EXPERIMENTAL STUDY OF THE EFFECT OF WING ANGLE-OF-ATTACK AND STIFFNESS ON LIFT AND THRUST ON MODEL DRAGONFLY WINGS

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A thesis submitted for the degree of Master of Philosophy

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University or institute of higher learning. To the best of my knowledge, it contains no material previously published or written by any other person, except where due reference is made in text.

Yutong Wang

30/6/2009
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Abstract

Recent studies in flapping-wing aerodynamics have touched the edge of unsteady aerodynamics where a flexible flapping wing and passive wing rotation are involved. The research in this area is still in infancy and the experimental data and results are extremely sparse.

The current research investigates the effects of spring stiffness correlating to angle-of-attack and wing stiffness on related aerodynamic parameters. The research was performed on a novel experimental device characterized as having a dragonfly-like wing rotating passively with asymmetrical up and down angle-of-attack.

By statistically analyzing experimental data, the research found that optimal spring stiffness exists in generating resultant aerodynamic force as well as lower spring and wing stiffness yielding higher energy efficiency in the studied system. In addition, the research results include the relationships between spring stiffness or wing stiffness and lift, thrust, power and resultant force direction. These research conclusions are expected to be of benefit to future Micro-Air-Vehicles designs.
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## Terms and Abbreviations

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<td>6-DOF</td>
<td>Six degree of Freedom</td>
</tr>
<tr>
<td>Adj MS</td>
<td>adjusted mean squares</td>
</tr>
<tr>
<td>Adj SS</td>
<td>adjusted sum of squares</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
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<td>AOA</td>
<td>Angle-of-Attack</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<tr>
<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
</tr>
<tr>
<td>DF</td>
<td>Degrees of freedom</td>
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<td>EI</td>
<td>Flexural stiffness</td>
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<td>F</td>
<td>F-value</td>
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<td>FX</td>
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<tr>
<td>FY</td>
<td>Horizontal force</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<td>k</td>
<td>Reduced Frequency</td>
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<tr>
<td>LEV</td>
<td>Leading Edge Vortex</td>
</tr>
<tr>
<td>MAVs</td>
<td>Micro-Air-Vehicles</td>
</tr>
<tr>
<td>NACA0012</td>
<td>A wing profile</td>
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<tr>
<td>P</td>
<td>Power</td>
</tr>
<tr>
<td>PE</td>
<td>Power Economy</td>
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<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
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<tr>
<td>RANS</td>
<td>Reynolds-Averaged Navier-Stokes</td>
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<td>Re</td>
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<td>Sr</td>
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Publications

Accepted Conference Papers

39th AIAA Fluid Dynamic Conference & Exhibit (2009)*
Title: Effects of Flapping Wing Angle of Attack on Lift and Thrust

27th AIAA Applied Aerodynamics Conference (2009)*
Title: Effects of Flapping Wing Stiffness on Lift and Thrust

Title: Design and Fabrication of Dragonfly Test Bed for Aerodynamic Characterization

* American Institute of Aeronautics and Astronautics (AIAA)
In 1996, the Defense Advanced Research Projects Agency (DARPA, a US based agency) initiated a program of developing Micro-Air-Vehicles (MAVs). In this program, an MAV was defined as a flying device with no dimension greater than 6 inches and the overall weight less than 100 grams (McMichael and Francis 1997). An important application for MAVs is reconnaissance for military purposes, including deploying MAVs inside confined space structures such as buildings and tunnels. Since then, research to develop MAVs which meet the above mentioned requirements has intensified and spread globally.

Initial research efforts in this area quickly revealed that the fixed wing aircraft design is not suitable for application on the small scale requirement of MAV. Small scale fixed wing aircraft were unable to obtain sufficiently slow flight dynamics as the MAVs would encounter at quite low Reynolds number ($<10^5$) (Shyy 2008). Similarly, the fixed wing aircraft designs were not agile enough to deal with the cluttered 3D environment in which the MAVs will be required to fly. On the other hand, the flyers in nature such as birds, bats and insects have inspired the human imagination for as long as human history, but more recently interest has increased since insect flight displays all the requirements needed for the desired MAVs. Insects draw particular attention for their smaller size, hovering capability, agility and manoeuvrability. As a result, a large amount of effort has been put into the research on insect flight and it is acknowledged that professional development of MAVs will inevitably require a full understanding of insect flight. One other possible design strategy for the development of MAVs could be rotary wings which can provide agility and hovering capability. However, current research is directed towards the use of flapping wings for the development of MAVs.
Research on insect/insect-like flight in the recent past has determined the importance of unsteady aerodynamics in insect flight. Four unsteady mechanisms that have been identified to play an important role in insect flight are: leading edge vortex (Ellington 1996), rotational force (Dickinson 1999), wake capture (Dickinson 1999) and clap-and-fling (Weis-Fogh 1973). The main problem that remains to be solved is the exact explanation of how insects use them to generate sufficient lift force to keep them aloft. Among the investigated flight-related factors, the Angle-of-Attack (AOA) and wing stiffness are considered the important parameters, because AOA is associated with the flight control and wing stiffness is related to the power consumption. Geometrically, the Angle-of-Attack is used to describe the angle between the chord line of the wing of a fixed-wing aircraft and the vector representing the relative motion between the aircraft and the atmosphere. High values of AOA (angles greater than 15 degrees for typical airfoils) in a fixed-wing aircraft causes the sudden drop in the lift force which is referred to as stall. In contrast flapping wing flight at low Reynolds number and high AOA generates a leading edge vortex on the flapping wing that creates suction and results in lift enhancement and delays stall effects. The effects of the AOA associated with the different types of the wings/wing motions are reviewed in detail in Section 2.2. In comparison to AOA, the effect of wing stiffness has received less attention in the literature. However some researchers (Shyy 1997; Heathcote et al., 2004, 2007) have shown its importance in MAV flight, noting the obvious fact that all the natural flyers use flexible wings. For example, flexible membrane wings can increase the AOA stall margin and moderate flexibility in the wing can enhance the thrust force (Shyy 1999). The review of the studies related to wing stiffness is presented in Section 2.3. Previous research has largely been performed using wings which have been actively flapped by
external means such as the use of motors. The effect of wing flexibility of a passively rotated dragonfly-like wing on propulsive performance has never been explored. Further, the effect of the variation of the stiffness on the force generation of the same wing needed to be explored.

The research conducted here uses springs to passively control the angle-of-attack of the wing during the flapping cycle. It is the main aim of the current research to study the effects aforementioned on lift and thrust when the wing flaps actively but is rotated passively around the pitch axis. Specifically, the objectives of this study are:

- To investigate if there exists the optimal spring tension or wing stiffness in producing maximum aerodynamic force.
- To investigate the effects of the spring tension or wing stiffness on power economy.

The design of MAVs can be improved significantly if the above relationships are successfully determined. The current study was restricted to one particular flapping configuration, that is the hovering mode. The Reynolds number (Re) based on the average chord length was around 16000, which is within the range associated with MAVs flight (Re < $10^5$).

To achieve aforementioned aims, the experimental study was carried out with the aid of a novel developed mechanical test bench. The test bench produces a wing flapping motion in a vertical plane. In addition, the test bench allows the flapping wing to rotate passively about its longitudinal axis. The data of lift and thrust generated by the flapping wing were collected by a sensor mounted at the base of the wing. The effects
Chapter 1 Introduction

of different stiffness of the spring which allows wing rotation and wing stiffness were obtained in the post-test analysis. The full factorial experiment was run with three factors (two spring stiffness and one wing stiffness) and each had three levels.

As a document of the current research, the thesis is organized in the following way. After this introduction chapter, Chapter 2 first looks at the general research background related to flapping flight. Then the review of the study related to AOA and wing stiffness follows. Chapter 3 describes the design of an experimental device which was essential to carry out the current research. The device provided the desired motions for the tested wing and collected the experimental data simultaneously. Chapter 4 deals with the experimental methodology designed to study the effects of spring and wing stiffness on aerodynamics and the experiment results. Chapter 5 analyzes and discusses the experimental results. The last chapter, Chapter 6 Conclusion, summarizes the current research and indicates the research implications in future MAV designs.
Chapter 2

Literature Review

2.1. Flapping Wing Aerodynamics

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   2.1.1.1. Reynolds Number (Re)
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   2.1.3.3. Computational Fluid Dynamics (CFD)
   2.1.3.4. Physical Model Experiments

2.2. Angle-of-Attack

2.3 Wing Stiffness

2.4 Passive Wing Rotation

2.5 Conclusion
In this Chapter, the overall study of flapping wing aerodynamics is considered first, followed by a review of research done in studying the effect of AOA and wing stiffness, particularly on lift, thrust and power efficiency. Finally, passiveness of wing rotation (pitch) is covered at the end of the Chapter. A broader review of flapping wing flight at low Reynolds numbers can be found in papers (Jensen 1956; Maxworthy 1981; Wakeling 1993; Rozhdestvensky 2003; Sun and Lan 2004; Sane 2003; Wang 2005; Ansari 2006; Platzer 2008) and books (Pringle 1957; Norberg 1975a; Lighthill 1987; Dudley 1999; Azuma 2006; Shyy 2008).

2.1 Flapping Wing Aerodynamics

The corresponding Reynolds number for MAVs is in the range of less than $10^5$ (Shyy 2008). The application of this type of aircraft includes environment surveillance, military reconnaissance, traffic management and real-estate survey. MAVs are required to be able to work inside confined spaces such as buildings, caves, tunnels and wells. Therefore, MAVs could be characterized as having small size, slow speed, low noise and high maneuverability.

Driven by this motivation, research on MAVs was carried out and intensified globally by many research institutions across different disciplines. Fixed-wing aeroplanes need high speed to keep them aloft, in addition they lack agility. Rotary-wing aircraft can hover and fly in any direction, however they are not in the scope of the current study. On the other hand, if an MAV could fly like an insect or a small bird, it would satisfy all other requirements as well, such as size, weight, payload, flight endurance, etc. In
addition, the Reynolds number of MAVs is in the same magnitude as smaller birds or larger insects. Thus, the idea of mimicking nature has encouraged researchers to put effort into studying the flapping wing aerodynamics of biological flyers in the hope of gaining inspiration from nature. Insects in particular have received more attention than birds and bats for their smaller size, hovering and all-direction flight capability (Dudley 1999), notably high lift in some species (Ellington 1999), and simpler wing structures (no articulations).

The study of insect flight has revealed that insect flapping flight is far more complicated than the existing fixed-wing aeroplane flight. The unsteady aerodynamics for a flapping wing is still in its developing stage. For a fixed wing, lift can be calculated by the simple formula

$$L = \frac{1}{2} C_L \rho A v^2,$$

where $L$ is lift, $C_L$ the lift coefficient, $\rho$ air density, $A$ wing area, and $v$ wing velocity. However, for a flapping wing, lift is influenced by a large number of factors, including kinematic parameters: flapping frequency, forward speed, flapping amplitude, stroke plane direction, instantaneous angle-of-attack, as well as wing-property parameters: wing size, wing shape, wing surface structure, wing stiffness, wing inertia and many others. Therefore, although flapping wing propulsion aircraft has a promising future for MAV design, understanding the associated aerodynamic mechanism needs to be developed significantly.

Some tools have proven to be helpful in MAVs aerodynamics study. Scaling laws, Reynolds number, Strouhal number and reduced frequency are among them.
2.1.1 Scaling laws

Scaling laws have proved helpful in MAVs flight studies, especially in mechanical and computational modeling. They help to set up the models, identify flow patterns and predict lift and thrust. In MAVs flight, the Reynolds number, Strouhal number and reduced frequency are the three key dimensionless parameters. By applying these parameters certain aerodynamic similarities could be maintained. For a rigid flapping wing, it would be sufficient to define aerodynamic similarities within the above three parameters in addition to geometric and kinematic similarities (Shyy 2008).

2.1.1.1. Reynolds Number

The Reynolds number describes the ratio of the inertial force to the viscous force. In general, the Reynolds number is defined as

$$Re = \frac{U C_m}{\nu},$$

Where, $U$ is wing velocity, $C_m$ object characteristic length, $\nu$ kinematic viscosity. In flapping flight, $U$ is taken differently according to the flight mode. In forward flight, $U$ is the wing’s forward speed, $C_m$ the mean chord length, but in hovering flight, $U$ is wing flapping velocity. In the current research, $U$ represents the wing tip mean velocity. So, if $\Phi$ is the amplitude of flapping angle measured from peak upstroke position to peak downstroke position, then

$$U = 2\Phi f_j R C_m / \nu,$$

Where, $R$ is the wing length, and $C_m$ is the mean chord length.
2.1.1.2. Strouhal Number

The Strouhal number is used for forward flight, representing inertial force expressed as the ratio of two initial forces, i.e., that of the unsteadiness of the flow to the inertial force due to the change in velocity in the flow field. It provides an estimate of unsteadiness in the flow. The Strouhal number is defined as

\[ S_r = f_f H/U, \]

where, \( f_f \) is flapping frequency, \( H \) is wing tip excursion measured as the vertical distance traveled by the wing tip during flapping stroke, and \( U \) is forward velocity. The Strouhal numbers in natural flyers are found within a narrow range \( 0.2 < S_r < 0.4 \) (Taylor and Thomas, 2003). In hovering flight, if \( U \) is represented by the wing-tip mean velocity, then

\[ S_r = f_f H/U = f_f H/2\Phi f_f R C_m / \nu = v H/2\Phi R C_m, \]

which is the figure only related to the wing flapping amplitude and wing shape. In other words, \( S_r \) will be the same so long as the wing flapping amplitude and the wing are kept the same.

2.1.1.3 Reduced Frequency (k)

This parameter also characterizes the unsteady aerodynamics of the wing. It is defined as

\[ k = \omega C_m / U, \]

where \( \omega \) is the wing rotating angular velocity, \( C_m \) mean chord length, and \( U \) is forward speed. In hovering flight, \( U \) is the average tip velocity \( 2\Phi f_f R \), where \( \Phi, f_f, \) and \( R \) are
defined as before. Similar to Sr, it can be explained that $k$ could be the same as long as wing rotation amplitude and wing shape are kept the same.

### 2.1.2. Unsteady Aerodynamic Mechanisms

Despite the complexities and unsteady aerodynamic effects in insect flight, the flow around the wing can still be modeled by the unsteady Navier-Stokes equations. Ellington has showed his proof of this unsteadiness by “proof-of-contradiction” (Ellington 1984a; Ellington 1984b) and at the same time denied the quasi-steady theory which was used for explaining the lift generation by Weis-Fogh (1973) and Jensen (1956).

In his “proof-of-contradiction”, Ellington (1984a) argued that if the mean coefficient calculated by temporarily summing the lift in one flapping cycle divided by insect body weight exceeds the maximum steady-state lift coefficient, then unsteady aerodynamics must be involved. This means quasi-steady theory does not include the effect of unsteady aerodynamics. However, if the mean lift coefficient is not greater than the maximum lift coefficient measured, it only means quasi-steady theory cannot be discounted. Lift calculations have not shown significant discrepancies for certain insects such as the crane-fly (*Tipula oleracea*), and *Drosophila virilis*, but not for insects such as *Encarsia* and *Aeschna*. Therefore, insects must use unsteady aerodynamics to generate required lift. Evidence of the limitation of the quasi-steady theory was further provided by Ennos (1989), Dedley and Ellington (1990), and Zanker and Gotz (1990). Although quasi-steady theory is not applicable to all insect flight, it still sometimes provides a quick means of estimating lift or thrust.
Using unsteady aerodynamic mechanisms, insects enhance the forces generated by their wings. To date, four types of unsteady aerodynamic mechanism have been identified, namely leading edge vortex (LEV), rotational force, wake capture and clap-and-fling. These are reviewed briefly as follows.

### 2.1.2.1 Leading Edge Vortex

That high lift is the result of the existence of leading-edge-vortex (LEV) has been convincingly argued by Ellington et al., (1996), although that LEV could benefit lift was noticed earlier (Maxworthy 1979, Dickinson and Gotz 1993).

LEV is a flow phenomenon associated with wing flapping. When the wing moves with high AOA, the flow is separated into two parts, those above and below the wing. The flow above the wing forms a vortex near the leading edge of the wing. This vortex creates a low pressure region above the wing, which causes the high lift commonly found in insect flight.

LEV was undoubtedly observed when Ellington (1996) was studying the Flapper. The Flapper is an aerodynamically 10:1 scaled-up mechanical model having the wing planform of the hawkmoth, *Manduca Sexta*. It was driven mechanically by several servo motors via a reduction gear box. It was claimed that the wing geometrical planform, Reynolds number and Strouhal number were preserved during the experiments. A smoke pipe was installed on the leading edge and during the stroke, released smoke provided the distinguishable flow visualization. LEV starting from the wing root and spiraling towards the tip was found attached to the wing only in the downstroke. The
size of LEV increased gradually from wing root to wing tip and attached to the wing for up to 75% of the wing length and was temporally experienced for almost half the stroke. The LEV shed out eventually at the end of the stroke. The leading edge vortex was also observed by Dickinson et al. (1999) on their mechanical model Robofly.

Ellington (1996) suggested that the stability of LEV is enhanced by its spiral flow along the wing span, because it prevents the LEV being shed from the wing where the spiral span-wise flow of the LEV transfers the momentum radially. As a result, it reduces the momentum accumulation in the chord, which keeps the LEV smaller and bound more tightly and longer on the wing. Therefore the spanwise spiral flow serves as a stable means of maintaining the LEV on the wing. In further research on Flapper, Usherwood and Ellington (2002) also concluded that axial flow is the key factor for LEV remaining attached. In contrast to the downstroke, however, during the upstroke the Flapper produced much less aerodynamic forces and no LEV was observed on the wing. Apart from being noticed on mechanical models (Ellington, 1996; Dickinson et al. 1999), the LEV was observed directly from insects (Willmott et al. 1997a; Willmott et al. 1997b; Willmott et al. 1997c), with these observations leading to the belief that LEV is the predominant mechanism used in insects to produce high lift. Further confirmation came from another research line. By using CFD, Liu and Kawachi (1998) and Liu (1998) showed that their flow simulation results are consistent with those observed found on the Flapper.

2.1.2.2 Rotational Force

Dickinson et al (1999) were first to identify rotational force other than LEV as a mechanism for lift enhancement by insects. Rotational force was found from their
mechanical model, “Roboﬂy”, occurring near the end of a stroke when the wing underwent a rapid rotation. The rotational force appeared as a peak force recorded in the lift time history near each stroke end, where lift coefﬁcient, $C_L$, could be as high as 1.74 in some cases. The CFD results obtained by Ramamurti and Sandberg (2002) and Sun and Tang (2002) were consistent with the discovery reported by Dickinson, et al.(1999).

**2.1.2.3 Wake Capture**

The unsteady mechanism of wake capture was extensively studied by Dickinson et al (1999). Wake capture is a wing-wake interaction, occurring at the beginning of the stroke when the wing meets the wake from the previous stroke. They found that by using a wake capture mechanism the transient lift coefﬁcient $C_L$ could be up to 4 in some cases. Numerical studies (Wang 2004; Tang et al., 2007) on elliptic airfoils showed the existence of wake capture as well. The effect of different ﬂight parameters on the lift in wake capture was further studied by Sane and Dickinson (2001).

**2.1.2.4 Clap-and-ﬂing**

Clap-and-ﬂing is an unsteady aerodynamic mechanism only found in certain types of insects. Weis-Fogh discovered this when studying the chalcid wasp Encarsia formosa’s high-lift phenomenon (Weis-Fogh 1973). The chalcid wasp’s wings touch at their dorsal extreme position just before the end of the up stroke. This is called “clap”. Gradually the touch expands to the entire wing during pronation. The leading edges then suddenly separate and ﬂing apart downwards, with separation progressing from the leading to the trailing edge. During the clap phase, a jet of air caused by the clapping wings could
produce additional thrust for the insect. During the fling phase, a low pressure region generated between the wings accounts for the high lift of the insect.

Clap-and-fling may not only explain high lift for the wasp, but may also apply to other insects with a clap flight mechanism, including Drosophila (Gotz 1987), butterflies (Brodsky 1994), and locusts (Cooter and Baker, 1977).

Lighthill (1973) has modeled and theoretically analyzed the clap-and-fling mechanism, whereas Maxworthy (1979) and Spedding (1986) have studied it by experiments. Other studies of clap-and-fling can be found in the literature (Ellington 1984; Ennos 1989; and Lehmann et al 2005).

2.1.3 Research Approaches

In order to discover the principles underlying unsteady flapping flight, four research approaches are often used, these are theoretical analysis, biological study, CFD simulation, and physical model study. Theoretical analysis attempts to derive the analytic expression for lift and other aerodynamic forces. The biological studies seek the truth directly from the natural flapping flyers. CFD simulation solves Navier-Stokes/Euler equations to find aerodynamic forces, while the physical-model study extracts aerodynamic information from mechanical models which preserve some flight characteristics.

2.1.3.1 Theoretical Analysis
An incompressible, unsteady flow pattern is governed by Navier-Stokes equations (Kundu 1990). In differential form, it can be expressed as

$$\rho(Du/Dt) = -\nabla p + \rho g + \mu \nabla^2 u,$$

where \(u\) is particle velocity, \(\mu\) viscosity, \(g\) gravity acceleration constant, \(\rho\) density of fluid, \(p\) pressure, \(\nabla\) del operator.

Under no-slip conditions and no-penetration conditions, Wu (1981) derived a 2D analytic expression from Navier-Stokes equations to calculated the lift for an airfoil.

$$F = -\rho \frac{d\gamma}{dt} + \rho \frac{d}{dt} \int \gamma dA,$$

where \(\gamma = \int r \times \omega dR\),

Where \(F\) is lift generated by unit span, \(\rho\) density of fluid, \(\gamma\) first moment of vorticity, \(r\) distance form the origin, \(R\) area of region of interest, \(A\) cross-sectional area of the airfoil.

The above lift \(F\) includes the vorticity around the airfoil. However, it has no practical use in insect flight. First, an insect vortex spirals radially outwards, hence is 3D. The above force expression did not take this into account during derivation. Second, the flow in the vicinity of the wing must be known and this adds more difficulty to its use. Finally, the lift \(F\), was basically derived from the translating airfoil, not from a flapping wing.


$$F_x - iF_y = i \frac{\rho}{2} \int \left( \frac{dw}{dz} \right)^2 dz + i \rho \frac{\partial}{\partial t} \int w dz,$$
where \( w(z) = Ux(t) + iUy(t) \), \( \rho \) density of air, and * symbol for complex conjugate. This equation has its own limitations as it was derived from the Euler equation which implies that the fluid was considered as inviscid. The wing is regarded as a rigid plate and the vortex is in a sense 2D, which ignores the flow along the wing span. Only the LEV was considered during the derivation, while the other unsteady mechanisms such as rotational force, wake capture, and clap-and-fling were not considered. Although not including all the unsteady phenomena, the above formula is the most advanced analytical formula seen in the literature addressing unsteady aerodynamics in insect flight.

2.1.3.2. Biological Experiments

Biological experiments perform the studies of insect flight directly on insects’ wings through observing morphology, measuring kinematics and analyzing aerodynamics. This provides an ideal approach, because all the data obtained are true and direct without any modifications and thus reflect the true flight behavior of an insect.

In the insect world, the dragonfly has outstanding aerobatic skills. Equipped with four independent moving wings (Alexander 1984, 1986), dragonflies can not only hover steadily but can out manoeuvre most of the other insects in the air. Their maximum forward flight speed can reach 7m/s (Azuma 1988) and they can make a yaw turn in 2~3 wing beats (Alexander 1984). Serious research into dragonfly flight began with the advent of the high-speed camera in the 1950s (Nevile 1960). Finer flapping kinematic details were obtained gradually with the invention of more sophisticated cameras (Norberg 1975; Somps and Luttges 1984; Ruppell 1989; Wang 2002; Tsuyuki et al
2006). It was found that dragonfly flight is characterized by a nearly vertical stroke plane, independent control of each wing, hindwing leading forewing in hovering, and a different angle of attack during up and down stroke (Somps and Luttges 1985).

Studies in dragonfly aerodynamics have revealed that a dragonfly can generate extremely high lift. Somps and Luttges (1985) found the transient lift could be as high as 15–20 times body weight, while average lift was measured as 2–3 times body weight. Under quasi-steady theory, estimation of the lift coefficient, $C_L$, in dragonflies reached 2 (Weis-Fogh 1973) and 6.1 (Norberg 1975). Although quasi-steady theory overestimated $C_L$ at between 2.3 and 6.1, numerical studies showed that $C_L$ values remained at 2 (Gustavson 1991, Wang 2000, Sun and Lan 2004, Young et al. 2008). That leading edge vortex (LEV) is the cause of high lift in insects was argued by Ellington (1984a) and the existence of the LEV was demonstrated on the Flapper, a physical hawkmoth model (Ellington 1999). LEV on tethered dragonflies were observed by Savage et al (1979) and Somps and Luttges (1985). Other than LEV, the hindwing capturing the wakes shed from the forewing may also be responsible for the high lift (Maybury et al 2004). In addition to unsteady flow, the properties of the wing that may also contribute to high lift in dragonflies include wing flexibility (Combes and Daniel 2001; Combes and Daniel 2003) and wing roughness (Okamoto et al 1996).

In addition to lift, other characteristics of dragonfly flight also attracted researchers’ attention. Dragonflies usually have large wing-aspect ratios, with a ratio of 15.7 measured by Azuma (1988). Such high aspect ratios are typically used in gliders. Wakeling and Ellington (1997a; 1997b; 1997c) found during gliding that dragonfly
wings show exceptional steady-state aerodynamic properties in comparison with the wings of other insects. This viewpoint was shared by Kesel (2000). Wootton (1992) pointed out that the wing rotation in Odonata may be passive, which agreed with the findings by Ennos (1988b) and Newman and Wootton (1986). Azuma (1988) showed the twisting of the dragonfly wing must be adaptive.

2.1.3.3. Computational Fluid Dynamics (CFD)

With the development of solvers for Navier-Stockes equations, computational fluid dynamics (CFD) has become a powerful tool in MAV studies. It allows researchers to investigate flow details around the wing, find the relationship between flow fields and the aerodynamic forces generated by the wing, as well as to optimize the MAV’s design and improve its flight performance. Although CFD is a promising tool, CFD model establishment and its validation often requires detailed experimental kinematic data and long computing time. Despite the difficulties, much progress has been made in this area of study.

Liu et al (1998a; 1998b) applied Reynolds-Averaged Navier-Stokes (RANS) code to hawkmoth wing motion and found that they could match 2D force results, but were unable to match 3D force results because of lack of experimental 3D force data. They also confirm the existence of the LEV flow pattern which was found both on real hawkmoth wings and an aerodynamically scaled-up model Flapper by Ellington et al (1996). Ramamurti and Sandberg (2002; 2007) used a finite element solver to study Drosophila virilis, reporting matching in lift but not in thrust generation. Sun et al (2002; 2003; 2004) used self developed 3D RANS code on a Drosophila virilis. Their results
matched Dickinson’s Robofly results only moderately. Lian and Shyy (2006) studied membrane aerodynamics by CFD and concluded that a membrane wing and rigid wing exhibit similar aerodynamic performance but the former has a much larger stall margin. This conclusion is supported by the experiments of Waszak et al. (2002) and Galvao et al. (2006). Young and Lai (2007) showed that a plunging-pitching airfoil having a peak propulsive efficiency with a Strouhal number of 0.05~0.15, is consistent with experimental results of Anderson et al. (1998) and those in nature (Taylor and Thomas 2003). As a simulation tool, CFD also provides intuitive flow visualization. The vortices structures shed from the wing profile NACA0012 (Lai and Platzer 1998), near a flapping dragonfly wing (Wang 2000), around a pitch-up airfoil (Birch and Dickinson 2003), and during clap-and-fling (Lehmann et al. 2005) are among the remarkable results of flow visualization. In another example, the roles of vortices in a hawkmoth wing were clearly demonstrated by flow visualization and computed results (Aono and Liu 2006).

However, some interesting CFD results are lacking the experimental data necessary for validation. For example, the CFD results for dragonflies (Sun and Lan 2004; Wang and Sun 2004; Sun and Wang 2005; Isogai 2004) and bumble bees (Sun and Xiong 2005), as well as Wang et al’s (2007) results show that a dragonfly uses drag to support three quarters of its body weight and that the inclined stroke plane is more efficient than a horizontal stroke plane.
2.1.3.4. Physical Model Experiments

Despite biological experiments providing the most reliable insect flight kinematics and aerodynamics data, biologists often face challenges in obtaining detailed or systematic information about the kinematics of a wing, even with modern measuring technology. Dynamic scaled-up mechanical wings have provided another platform for insect-flight study, which in some sense could overcome the difficulties encountered when studying insects directly. Some research results from model wing studies have offered insights into unsteady insect aerodynamics. The discovery of the LEV mentioned previously is one example (Ellington 1996). In another example, Dickinson (1993) confirmed the existence of LEV at low Re (<10000) by studying his dynamic scaled model, Robofly. Experiments on Robofly were carried out in a mineral oil tank (Lauder 2001). Using Robofly, Dickinson (1994) also discovered that rotational force during stroke reversal may provide an important source of aerodynamic force in insect flight, and both rotational force and wake capture are the unsteady mechanisms for high lift in insect wings.

Other remarkable model experiment results were also reported in the literature. By revolving a model hawkmoth wing, Usherwood et al. (2002a; 2002b) noted that LEV is the source for high lift and the twist and cambered wings have no significant effect on lift. The effect of phase difference on lift in dragonfly’s ipsilateral wings was studied using two model wings arranged like dragonfly’s (Maybury et al. 2004). They concluded that the phase difference has no effect on the fore-wing. When the forewing lags behind the hind-wing by a quarter flapping cycle, the hind-wing resumes its performance as if the forewing didn’t exist. The clap-and fling mechanism discovered
by Weis-Fogh (1973) was mimicked by Robofly (Lehmann 2004; Lehmann and Sane 2005) who showed that it could enhance lift by 17%. They also noted that the angle separation of the two wings should be no more than 10°–12°. Double LEV was observed when carrying out experiments on a model flapping wing (Lu et al. 2006) with the aid of Digital Partical Image Velocimetry (DPIV).

Progress in mechanical model studies has demonstrated the unique advantage of employing models. Aerodynamical phenomena could be enlarged and wing motion operated in a controllable manner during experiments while preserving the flow patterns. In fact, much useful information has been extracted through the use of model studies.

### 2.2 Angle of Attack (AOA)

Angle of Attack plays an important flight controlling role in all types of flyers from fixed-wing airplanes to complicated flapping-wing insects existing in nature. This section reviews some AOA properties found in research into MAVs.

In a steady flow, insect wings stall at about 15° of AOA (Dudley 1999), which is similar to data for a rigid fixed wing. However, if the fixed wing surface is made of a membrane, the stall margin could be increased significantly (Waszak et al 2002). Torres and Muellers (2004) showed similar results in their experiment in which the stall angle reached 35° whereas the angle for a rigid wing was only between 12–15°. Their experiment was conducted on a low aspect ratio (~2) wing having Reynolds number 7x10^4. Based on the flexible fixed-wing study, a membrane-wing MAV was

The angle of attack in an insect wing during flapping is rather complicated compared with a fixed rigid wing. Insects vary the angle of attack during the stroke, Neivel (1960). “Methodologically, the wing angle of attack has proven to be difficult to quantify for arbitrary free motion.” (Dudley 1999). AOA twists along the wing span with the greatest value at the wing base when the wing flaps across the middle portion of the flapping stroke (Ellington 1984c). The twisted wing performs at its aerodynamic optimum, since the angle of attack of each section of the wing is adapted to the flow around at its best angular position.

Higher angle of attack characterizes the hovering flapping flight in nature. Experimental study of this phenomenon (Dickinson and Gotz 1993) in a sucrose tank with fixed AOA leads for the observation of the leading edge vortex (LEV) attached to a rigid 5x15mm rectangular wing for at least two chord lengths when AOA was set between 13.5° and 54°. The leading edge vortex is suggested as the cause of 80% lift increase when compared to that measured five chord lengths later.

Different from those methods used by Dickinson and Gotz (1993) using fixed AOA in their experiments, Hover et al (2004) added pitching motion in addition to plunging motion in studying the effects of pitching motion. Among the five studied pitching motions (simple harmonic motion, square, saw-tooth and cosine wave), saw-tooth has the highest thrust but cosine has high thrust with reasonable efficiency.
The effect of angle of attack on lift was studied by Lai et al. (2005) on a vertically flapping mechanical wing in a wind tunnel. The wing was made by bonding PVC film on a carbon fiber frame. In the range of 0 to 15°, AOA was fixed to a certain value for both up and down stroke for each individual test. Their results showed that lift increased with increase of AOA to between 0 to 15°, when flapping frequency was approximately 4Hz.

Very recently, Singh and Chopra (2008) studied the aerodynamics of seven horizontally hovering flapping model wings with passive pitching motion. In the hovering mode, pitch angle is a complementary angle of the angle of attack. Because of their symmetrical design of the pitching mechanism, the pitching motion in the up stroke is the same as that in the downstroke. From the test results of their third wing, with a 100mm span and 48mm chord length, made of an aluminum frame and Mylar membrane, it was found that the wing with a 45° pitch angle generated higher thrust than was the case for the 30° pitch angle. In addition, the power required was also found to be reduced.

The preceding review of angle-of-attack in MAVs has shown that AOA has been studied in various flight configurations, which include insect wings in steady flow states, flexible membrane wings, rigid heaving or plunging wings, forward flight flapping wings, and horizontally flapping wing. In general, aerodynamic force is the function of AOA (Azuma 2006). The relationship between the lift/drag coefficient and AOA in fixed rigid wings has been widely studied. However, there is a long way to go to achieve full understanding of the effect of AOA in insect-like flight. The relationship
between flapping-wing aerodynamics and AOA is measured on a case-by-case basis, and data in this field is still very limited. A similar situation exists in relation to the affect of wing stiffness on aerodynamics and flight efficiency.

2.3 Wing Stiffness

Wings in all natural flying animals exhibit flexible property (Swartz 1992, 1997, Tian et al 2006). Combes and Daniel (2001, 2003) studied flexural stiffness distribution and scaling rules in insect wings on 16 species from 6 orders, and determined that flexural stiffness in a single wing was distributed in such a way that it decreases exponentially either from wing base to tip or leading to tailing edge. It was also found that, between species, spanwise flexural stiffness was proportional to the cube of the wing span, whereas the chordwise flexural stiffness was proportional to the square of the chord length. The advantage with flexible wings is that the wing is enabled to adapt to its flow environment, which could lead to delayed flow separation in fixed membrane wings (Shyy and Berg 1999, Waszak et al., 2002).

The benefit of a flexible wing in control was found by Raney and Solminske (2004) who reported a that flexible wing can speed up transition between wing-beating modes.

Shyy (1997, 1999) and Waszak (2002) found that a flexible wing could improve its aerodynamic performance at high AOA when studying three artificial wings with different stiffnesses but the same shape. Their results show a larger delay of stall in a
flexible wing, whereas lift produced in the three wings was similar. This result was confirmed by Torres and Mueller (2004), Lian and Shyy (2003) and Galvao (2006).

Heathcote (2004) suggested that optimal wing stiffness exists to produce maximum propulsion after experiments in a water tank at zero-stream velocity, in which he tested three plunging rectangular wings where each had a different thickness. These rectangular plates with different thicknesses served as wings with different flexibilities. He also found that flexible wings improve power efficiency. By numerical analysis, Pederzani (2006) also showed that chordwise flexibility increases propulsive efficiency in a heaving motion. Heathcote (2008) advanced his experiments with spanwise flexible rectangular wings using the same experimental equipment at non-zero fluid-flow speeds and found results similar to those before, that modest flexibility is beneficial to thrust and power efficiency. He noted that this was observed when the Strouhal number was within the range 0.2–0.4. By simulation, Chimakurthi’ s (2008) computational results matched Heathcote’s (2008) experimental results.

2.4 Passiveness of Wing Rotation

Different from a fixed wing, an insect’s wings constantly change their speed and AOA in both magnitude and direction (Wootton 1992). Wing rotation is closely related to AOA, occurring more rapidly during pronation (wing top pitching reversal) and supination (wing bottom pitching reversal) than in the translational phase. Whether that rotation is active or passive remains uncertain. Some researchers (Ellington 1984; Miyan and Ewing 1985; Dickinson 1993) assume that the rotation is actively controlled
by wing base sclerites while others (Norberg 1972; Ennos 1988; Wang 2005; and Bergou et al., 2007) believe that it is passive. It is not difficult to assume it to be active, because insects are living creatures. But it is less obvious why it could be passive.

Norberg (1972) demonstrated that the mass centre of the wing in some dragonfly species is posterior to the rotation axis. At the end of each stroke, the inertia caused by the deceleration of the wing makes the wing rotate; hence the wing rotation is passive.

Ennos (1988b) proved inertial force alone is responsible for the rotation in Diptera by momentum conservation theory. He assumed that in the middle of the stroke there is no rotation but only flapping motion, therefore the wing only possesses linear momentum at this moment. But the virtual angular momentum about the rotation axis can be calculated as the product of this linear momentum and the distance between the mass centre of the wing and the rotation axis. This angular momentum will be conserved until the end of the stroke where the wing-flapping velocity becomes zero, the angular speed and average trailing edge speed, \( V_r \), can then be derived from the angular momentum. Take the ratio of \( V_r/V_t \), where \( V_t \) is the average speed of wing tip. Compare this calculated ratio to that measured from high-speed camera film. “If the calculated ratio is less than the observed values then inertia alone is unable to account for the speed of wing rotation” (Ennos 1988b). His results from observation of two species of \textit{Eristalis tenax} and four species of \textit{Calliphora} have shown “No active twisting of wing base need to be invoked” (Ennos 1988b).
From the viewpoint of the power requirement for wing rotation at end reversal, Bergou et al (2007) also proved that there is no need for the wing base to supply power to rotate the wing in the dragonfly, fruit fly and hawkmoth. Their method proposes that the power needed in a wing muscle should be that power needed to overcome the wing inertia in rotation minus the power generated by associated aerodynamics. In the case of the dragonfly, the authors used the kinematics measured by Russell and Wang (2004). Aerodynamic force was obtained by solving 2D Navier-Stokes equations described by Xu and Wang (2006a), where their results show that the power required from the wing muscle is negative. Its direct interpretation is that the aerodynamic force is injecting power into the wing, where, in fact, it signifies the passivity of the wing’s rotation. Similar results were found for fruitfly and hawkmoth.

2.5 Conclusion

In the preceding review, overall research into insect aerodynamics was discussed first, followed by present studies in AOA and wing stiffness, with the passive rotation reviewed last. The review shows that AOA is an important parameter closely associated with lift, thrust and power efficiency in all types of man-made aircraft and natural flyers. Wing stiffness is of particular importance for wings with low Reynolds numbers. Wing rotation passiveness could be true for some insects. From the viewpoint of making MAVs, passive rotation wing could potentially offer great benefits to MAVs, because a passive mechanism uses less mechanical components has fewer control requirements and needs less power; hence it could make MAVs simpler, lighter and more efficient.
This feature is crucial to an apparatus used in the air when payload, agility and power consumption are of paramount importance.

In a passive wing rotation system, how AOAs different in up and down strokes and how the wing stiffness of a dragonfly-like wing affects lift, thrust and power efficiency has been found to be largely unexplored in the published literature. This was the motivation for this research.

The results of the effect of spring stiffness and wing stiffness on different experimental output parameters are presented in Chapter 4 and discussed in Chapter 5. The design of the device will be presented in the next Chapter.
Chapter 3

Electro-Mechanical Experimental Device

3.1 Introduction
3.2 Requirements for the Experimental Device
3.3 Mechanical System
   3.3.1 Wing Flapping Motion Mechanism
   3.3.2 Wing Passive Motion Mechanism
   3.3.3 Support Structure
   3.3.4 Noise Removal
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   3.4.1 Electrical Control Components
   3.4.2 Force/Torque Data Acquisition Components
   3.4.3 Rotation Angle Measurement
3.5 Force/Torque Data Conversion
3.6 Conclusion
3.1 Introduction

Physical experiments have been a valuable means in studying of flapping unsteady aerodynamics. The discovery of the unsteady aerodynamic mechanism ‘rotational force’ (Dickinson and Gotz 1994) and the ‘leading edge vortex’ (Ellington 1996) are the two prominent examples. In other researches, experimental devices have been used in finding the optimal angle-of-attack (Sane and Dickinson 2001) and dual leading-edge-vortices (Lu et al., 2006), in verifying the ‘clap-and-fling’ mechanism (Lehmann 2004), and in providing flow visualization (Ellington 1996; van den Berg 1997; Willmott and Ellington, 1997). The effect of phase relation between two wings on lift was explored on a physical model as well (Mayburry and Lehmann 2004).

The above researches were concentrated on rigid wings. Recently, Heathcote (2004, 2008) explored the effect of wing flexibility on thrust of wings in plunging motion in a water tank. More recently, Singh (2008) studied a passively flapping wing in normal hovering (horizontal wing stroke plane). Despite these studies, research into the flexible wing is still in its infancy and many new aspects remain to be explored.

This Chapter describes the experimental platform developed to investigate passive flapping aerodynamics and its dependence on spanwise stiffness of the wing. The experiment uses three dragonfly-like wings with different flexibilities flapping in a vertical stroke plan and pitching with asymmetrical angle-of-attack in the upstroke and downstroke.
The experimental device is constructed with two major systems: a mechanical and an electrical system. The mechanical system includes the structure supporting the entire device as well as the functional mechanism to convert the motor rotation motion to the wing flapping motion. In addition, the wing is rotated passively during flapping, with the degree of rotation independently controlled by two springs in up and down stroke. The electrical system controls the flapping frequency via a servo amplifier and a personal computer and collects the force and torque data from a six degree of freedom (6-DOF) sensor placed at the base of the wing. The rotation angle of the wing base is measured via a Hall-effect sensor located at the end of the wing rotation shaft.

Two pictures of the finished test bench viewed from rear-side and from the side are shown in Figure 3.1 and 3.2. The schematic of the test bench is illustrated in Figure 3.3. The video footage of the wing in flapping is stored in the CD attached.
This chapter covers the requirements placed upon the device, followed by the detailed mechanical and electrical design description and components selection. The
force/torque data conversion from sensor coordinates on the wing to the ground coordinates is covered last.

### 3.2 Requirements for the Experimental Device

To achieve the objectives of the experimental program for the thesis, the test bench is mechanically required to provide two motions for the wing: an active flapping motion with a passive rotating motion. In addition, it should be possible to vary certain kinematical parameters of the flapping, such as flapping frequency, flapping amplitude, and angle-of-attack in either up- or down-stroke. The electrical system should offer the necessary control and power for the mechanical system so that it can flap at an accurate flapping frequency with sufficient torque. The data acquisition system should complete two tasks: one is to measure the force and torque generated by the wing and the other is to measure the rotation angle at the wing base. Apart from the objectives mentioned above, the test bench should be able to work with a wing of any shape.

To achieve the expected design aims for the experiment device as a whole, individual systems which make up the device should meet their own functional requirements separately. For clarity, these requirements are listed in detail as follows:

#### 3.2.1. Mechanical System Requirements

1) Provide solid structure support for the test bench.

2) Produce required wing motions, which are,
   - Flapping motion;
• Passive rotation motion while flapping

3) Contain adjustable flight parameters, which are,
   • Flapping amplitude: 0–60 deg, that covers the range found in most dragonflies.
   • Angle of attack: 10–90 deg, that covers the range in dragonflies as well.
   • Wing neutral flapping position, i.e. the azimuth of the wing rotation axis when
     the flapping angle is zero.

4) Minimizing mechanical noise in the 6-DOF force/torque sensor

5) Minimizing the inertia force contained in the force/torque data

3.2.2. Electrical System Requirements

1) Provide sufficient power to drive the experimental device (max 250w)

2) Control the flapping speed precisely (+/-0.02Hz)

3) Collect required force and torque data

4) Collect required wing rotational angle data

5) Record, process and convert the collected data

3.3 Mechanical System

The mechanical system in the designed test bench includes four major assemblies: the
wing flapping motion mechanism, the wing rotation mechanism, the model wing, and
the supporting structure. A noise reduction methodology is also designed for the test
bench.
3.3.1 Wing Flapping Motion Mechanism

The wing flapping motion is realized by employing a four-bar mechanical mechanism that converts the rotational motion of the driving arm to the swinging arm via a linkage, as illustrated in Figure 3.4. Mechanically, the wing base, the whole moving portion between the swinging arm and the connector into which the wing is inserted, is coupled with the swinging arm. Therefore the motion of the wing root is same as the oscillating motion of the swinging arm. Furthermore, since the wing is fixed on the wing base, the wing’s flapping motion is identical to the motion of the swinging arm. The physical four-bar mechanical mechanism is shown in Figure 3.5 in which the flange connected to the output shaft of the motor acts as the driving arm. The linkage between the driving arm and swinging arm is formed with three sections and the purpose of this design is to reduce the noise and will be discussed in Section 3.3.4.

![Figure 3.4 Schematics of four-bar mechanism](image1)

![Figure 3.5 Physical four-bar mechanism](image2)
There are two adjustable parameters in this four-bar mechanism. One is the length of the driving arm, and the other is the length of the linkage. Changing the driving arm length corresponds to changing the flapping amplitude of the wing. Changing the linkage length corresponds to changing the azimuth of the flapping wing when in its flapping neutral position. The length change of the driving arm is realized by placing the nearer linkage connector to the different holes that have different distances to the centre of the flange. The length change of the linkage is realized by turning the linkage, since the threads at two ends were designed being in opposite directions. Given a rotating driving signal at the input link, follower link will undergo a sinusoidal angular displacement. Experimental results obtained for the azimuth set to zero and flapping amplitude set to 52°, showed angle trajectories closely resembled a sinusoidal wave with R-squared value 0.9928.

### 3.3.2 Wing Passive Motion Mechanism

While flapping, the wing rotates passively in the current experimental device. The wing rotation axis flaps in the stroke plane (see Figure 3.6). Because the force \( F_{\text{total}} \) representing all the external forces on the wing is not acting on the rotation axis, a torque about the rotation axis is produced, which makes the wing rotate. Since this torque is not actively produced but caused by the wing flapping motion, the wing rotation is passive.

Two extension springs on each side of the wing work against the above torque. This limits the degree to which the wing can rotate in either direction. For both springs, one
end is fixed on the lever which rotates with the wing and the other end is tied with a soft string.

Figure 3.6 Illustration of the principle of the wing passive rotation mechanism, viewed from wing tip to root.

Figure 3.7 Photo of the wing rotation control unit
Another end of the string is fixed on the case of the Rotation Control Unit. This design allows only one spring to work after the wing passes its neutral position. During the up-stroke, the external force pushes the wing downwards. The wing tends to rotate clockwise from its neutral position as shown in Figure 3.6; spring-2 works against this rotation by pulling the lever, while spring-1 is in its idle state. In contrast, spring-1 works and spring-2 idles when the wing rotates anti-clockwise from its neutral position.

In flapping flight, the Angle-of-Attack (AOA) describes the position relationship between the wing orientation and the wing motion. For a wing in hover, the geometrical AOA is defined as the angle formed by wing chord pointing from the trailing edge to leading edge and the direction of the flapping motion. In the context of the current thesis, the AOA is referred to this geometrical AOA. As illustrated in Figure 3.8. In the up-stroke if the rotation angle is $\phi$, then AOA $\alpha$ is complementary to the rotation angle $\phi$.

![Rotation angle and AOA viewed from wing tip to root.](image)

Therefore changing the rotation angle is equivalent to changing the AOA. As
mentioned before, two springs work against the wing rotation. Hence, the controlling of AOA can be achieved by controlling the stiffness of the springs. In the down-stroke, the complementary relation between $\alpha$ and $\varphi$ still holds.

### 3.3.3 Support Structure

A robust metal table was built to provide a solid foundation for the experiments in order to prevent interference from an unstable base (see Figure 3.9). On top of the table there are two unconnected portions: one for supporting the motor and the other for supporting the wing. Each portion has a base made of a timber plate on top of 100mm thick foam. The gap between the two portions and the two foams serve to prevent vibration being transmitted from the motor to the force/torque sensor mounted on the wing. The details of noise attenuation are given in next Section. The motor holders and the support frame...
for flapping parts were bolted onto the timbers respectively. Glue was used to bind the foam with the timber and the metal table.

### 3.3.4 Removal of Mechanical Noise

After the device was assembled, significant mechanical noise was detected by the sensitive 6-DOF force and torque sensor mounted at the end of the wing. Noise was found to be generated from the motor-gearbox assembly when bolted onto a regular table. To reduce the noise, a very robust table was built using bulky steel bars and the noise path from motor-gearbox to sensor was cut off by using two big pieces of 100mm thick foam placed under the wing supporting structure and the motor-gearbox assembly. This management cut off the noise path from gearbox to sensor via the table.

Noise was also transmitted from the gearbox to the sensor via the four-bar linkage mechanism. To cut off this second path, the middle portion of the linkage was removed and replaced with a longer rod which overlapped the remaining two end portions of the linkage. Sponge rubbers were placed between the overlapped parts portions. Cyanoacrylate glue was found strong enough in bonding the rubber and metal. The finished linkage is shown in Figure 3.10.

![Figure 3.10 Vibration absorption Linkage](image)

Figure 3.10 Vibration absorption Linkage
In addition to this arrangement, a rubber grommet was inserted into the connection hole on the flange mounted on the output shaft of the gearbox. This arrangement provided a soft connection between the flange and linkage end rod as shown in Figure 3.11. As a result, noise transmitted in the linkage path was eliminated effectively.

![Figure 3.11 Flange and grommet](image)

After the two paths for noise transmitting were blocked, force/torque data became quite clean (see Figure 4.5 and Figure 4.6).

### 3.4 Electrical System

The electrical system provides two functions: (1) the control of the wing flapping of the experimental device and (2) the data acquisition of force/torque and the rotation angle of the wing. The control part of the electrical system consists of a driving motor, a reduction gearbox, a digital encoder, a servo amplifier, a power supplier and a personal computer program with a Graphical User Interface (GUI) for motor speed control. Most parts in the electrical system are commercial off the shelf components selected from Maxon Motor Pty Ltd. The schematic of the electrical control system is illustrated in
Figure 3.12. The data acquisition part of the electrical system has components of 6-DOF force/torque sensor, sensor interface and, acquisition card and rotation angle measuring unit. The major work carried out on the electrical system was to select the adequate components and integrate them into the desired system.

3.4.1 Electrical Control Components

(1) Motor-Gearbox-Encoder

Figure 3.13 Motor-gearbox-encoder assembly
A Maxon EC 45 250 watt brushless motor was chosen to drive the system, as shown in Figure 3.13. The motor has a maximum speed of 11000rpm with a nominal operating voltage of 48v. The motor draws continuous current of 8.2 A at a speed of 5000 rpm. This motor provides a reliable driving source.

The gearbox selected was a Maxon planetary gearbox GP 42C, with an output torque of 3~15Nm and a reduction ratio of 26:1. The gearbox transmits power effectively with the only disadvantage being the mechanical noise generated. Extra insulation effort had to be spent to remove the noise (See Section 3.3.4).

A Maxon digital encoder HP HEDS 6540 was employed to detect the rotor’s position and rotation direction for precise motor speed and position control.

(2) Servo Amplifier

A servo amplifier 4-Q-EC DEC 70/10 was used for the electrical driving system, Figure 3.14. It has the advantage of providing digital speed control as well as digital torque control. The control can be operated in both accelerating and braking directions.
(3) Power Supply and High Frequency Chokes

The power supply shown in Figure 3.15 used in the current test bench is a Parameters P4303, a dual-tracking DC power supply, which takes AC from the mains and transforms it to DC. Combining two channels in series, it provides a variable voltage between 0 and 60V and the total current output could reach 6A.

![Figure 3.15 Power supply](image1)

![Figure 3.16 High frequency chokes](image2)

High frequency chokes (Figure 3.16) were used between the motor and the servo amplifier to reduce the high frequency noise. Without using the high frequency chokes, an audible sharp electrical noise was generated by the motor. The high pitch noise was caused by the digitized motor supply power. By connecting 3 high frequency chokes between the 3 power cables to the motor and the servo amplifier the noise was eliminated and the motor worked in a quiet condition.

(4) Motor Control Program

A motor control program with a GUI specially written for Maxon Motor, was chosen to run the control operation. The gearbox output speed can be varied in the range of +/- 4000 rpm with the increment of 1 rpm, equivalent to 0.016 Hz. The flapping frequency in the experimental program is set at 1.25 Hz.
3.4.2 Force/Torque Acquisition Components

Data acquisition part is responsible to collect the desired data during the process of experiments. In the present experimental study, there are two types of data to be collected. One is the force and torque data from the 6-DOF force/torque sensor and the other is the wing rotational angle value measured by a Hall-effect sensor. The force/torque sensor records the force and torque at the wing base during flapping. The Hall-effect sensor measures the time history of the wing root rotation that occurs during flapping. Figure 3.17 shows the mechanical schematic diagram of the data acquisition system.

![Mechanical schematic diagram of the data acquisition system.](image)

(1) The 6-DOF Force/Torque Sensor

The electrical schematic diagram of force/torque acquisition is illustrated in Figure 3.18.
The force/torque acquisition part consists of 3 major parts: 6-DOF F/T sensor, sensor interface and the data acquisition card.

A 6-DOF Force/Torque Sensor, Nano 43 from ATI Pty Ltd was selected and mounted at the wing base (see Figure 3.19).

The 6-DOF sensor collects the force $f_x$, $f_y$, $f_z$ and torque $m_x$, $m_y$, $m_z$ in xyz three directions with respect to the reference frame on the sensor. This reference frame is
defined as follows. The origin is at the centre of the one end of the cylindrical sensor. That end is facing the wing when the sensor is installed on the device. The z-axis corresponds to the sensor’s cylindrical axis pointing outwards from the wing root to tip, and it is also co-axial with the wing rotation axis. When the wing surface is horizontally placed, the x direction is pointing vertically upwards. The y direction can be found by the right hand rule.

(2) Sensor Interface

![Figure 3.20 Sensor Interface](image)

The sensor interface power supply box as shown in Figure 3.19, designed for small sensors like the Nano 43 also from ATI, provides the working power for the sensor as well as the electronics for cleaning the loading analogue signal collected from the same sensor before passing it onto the data acquisition card installed in the computer.

(3) Data Acquisition Card

The data acquisition card as shown in Figure 3.21 used in the current device bridges the conditioned data and the computer central processing unit, where the data are converted from the voltages to readable force and torque. The data acquisition card employed in
the current device is an M series NI PCI-6221, a fast yet low cost data acquisition card from National Instrument.

![Data acquisition card, NI-PCI 6221](image)

**Figure 3.21** Data acquisition card, NI-PCI 6221

### 3.4.3 Rotation Angle Measurement

Rotation angle measurement was achieved using a Hall-effect sensor configuration. This sensor had the advantage of low cost, light weight and zero mechanical friction. The principle of the current rotation angle measuring device with hall sensor can be described with the aid of Figure 3.22.

![Hall-effect sensor and magnet for rotation angle measurement](image)

**Figure 3.22** Hall-effect sensor and magnet for rotation angle measurement

Viewed from wing root to tip as shown in Figure 3.22, the middle of a magnetic bar is
mounted onto the end of wing rotation shaft, the Hall sensor is placed at about 10mm off the rotation axis. When the wing is in its neutral position, as shown in Figure 3.22, there is no magnetic field strength detected by the Hall-effect sensor. Its output voltage is about 2.63v.

When the wing rotates clockwise, N-pole moves closer to the Hall sensor and the output voltage of the sensor is increased above 2.63v. In contrast, negative magnetic strength is detected and the output voltage of the sensor is decreased from 2.63v when the wing rotates count-clockwise from its neutral position. The larger the degree the wing rotates, and the stronger the strength the sensor detected, in either direction. The rotation angle +/-90 degree corresponds to the Hall-effect sensor output voltage 0–5v, conversion between the rotation angle and Hall sensor output voltage is shown in Figure 3.23.

Figure 3.23 Conversion between the rotation angle and Hall sensor output voltage.
3.5 Force/Torque Data Conversion

The data collected from the 6-DOF sensor are with respect to the sensor reference. Because the sensor is mounted on the wing root, it flaps and rotates with the motion of the wing root. To gain the aerodynamic force with respect to the ground, the data collected from the sensor must be converted to the ground reference frame. This conversion was carried out in the post-test data process program written in Matlab.

![Diagram of Sensor Reference Oxyz and Ground Reference OXYZ](image)

Figure 3.24 Sensor reference oxyz and ground reference OXYZ

The sensor and ground reference coordinates are illustrated in the Figure 3.24. Sensor
reference was determined when the sensor was manufactured with the origin at the centre of the one end of the sensor and z axis is coaxial to the axis of sensor cylinder and x axis was marked on the sensor. When installed in the current experiment device, it was arranged such that the z axis was coaxial to the wing rotation axis pointing from wing root to tip, and x axis pointing vertically upwards when the wing was at horizontal position. Ground reference is defined such that X axis has the positive direction upwards and Y axis has the positive direction same as the sensor y axis in its neutral flapping position. As a result, the positive direction of the Z axis is same as the sensor z axis when the wing is in a horizontal position.

The side views of the wing in Figure 3.25 and 3.26 illustrate the flapping and rotation angle $\theta$ and $\phi$ respectively, which are the only two angles involved in the conversion.
The flapping angle $\theta$ is measured between main spar and its horizontal position and it is positive when the wing flaps upwards. The rotation angle $\varphi$ is defined as zero when the surface of wing is parallel to the horizontal plane and is positive when the wing rotates clockwise, viewed from wing tip to root.

Having defined two references and two angles, the conversion matrix from sensor reference to ground reference was found as:

$$
\psi = \begin{bmatrix}
\cos \varphi \cos \theta & \sin \varphi \cos \theta & \sin \theta \\
\sin \varphi & \cos \varphi & 0 \\
-\cos \varphi \sin \theta & -\sin \varphi \cos \theta & \cos \theta
\end{bmatrix}
$$

Hence, $\vec{F} = \psi * \vec{f}$, where $\vec{F} = [F_x \ F_y \ F_z]^T$ and $\vec{f} = [f_x \ f_y \ f_z]^T$.

$\vec{F}$ is the force in ground reference, and $\vec{f}$ is the force in sensor reference.

To remove the inertial force the wing generated, experiments were conducted under two situations: wing with membrane and wing without membrane. Two sets of test data were collected. The AOA was detected by a Hall-effect sensor and displayed and recorded in oscilloscope Agilent 54624A; data for force and torque was recorded through ATI software in LabView.

A Matlab program, whose flow chart is shown in Figure 3.27, was written to process the collected data to obtain the aerodynamic force in ground reference. In the program, AOA, force with membrane and force without member were phase averaged first. Then the inertial effect was subtracted from the total force measured. And the resultant data
were converted to the ground reference frame.

![Diagram of flow chart of post-test data analysis program]

Figure 3.27 Flow chart of post-test data analysis program

The Matlab program is attached in the Appendix A. It is noticed that the sensor reference and ground reference have different origins. This does not affect the force conversion, but will change the results of torque conversion slightly. However, the calculation with real experimental data has shown that the differences in results are negligible. Therefore, the conversion matrix is also valid for torque.

### 3.6 Conclusion

An electro-mechanical test bench using passively rotating wing concept with angle-of-attack controllable at the end of wing rotation shaft was successfully designed. The mechanical, electrical and data acquisition system all function as expected. The mechanical vibration noise problem generated in the gearbox was completely solved by blocking the noise transmitting paths. The 27 slow wing motions movies depicting the
different combinations of up and down angle-of-attack and wing stiffness can be viewed in the CD attached.
Chapter 4

Experiments and Results

4.1 Introduction

4.2 Fabrication of Flexible Wings

4.3 Reynolds Number

4.4 Experimental Platform

4.5 Data Processing
    4.5.1 Force and Power
    4.5.2 Minimization of Inertial Effect

4.6 Experimental Methods

4.7 Results

4.8 Conclusion
4.1 Introduction

Most research has been focused on rigid wings (Dickinson et al., 1999, Usherwood and Ellington 2002a, b; Wang 2004; Ramamurti and Sandberg 2007), although the importance of wing flexibility was noticed much earlier (Wootton 1992). Among the few researchers working on wing flexibility effects, Heathcote (2004, 2008) experimentally showed the benefits of the flexible wing in thrust and power efficiency when the tested wing was in heaving motion. His results were matched numerically by Pederzani (2006) and Chimakurthi (2008).

Active or passive-wing rotation is another issue drawing researchers’ attention. Although insects are capable of rotating their wings actively (Bottiger and Furshpan 1952, Ellington 1984, Dickinson and Gotz 1993), Bergou et al., (2007) have shown that the rotation could be passive based on their finding of the negative power requirement for rotation in some insects such as the dragonfly. The negative power requirement not only implies that the wing is passively rotated but also that passive-wing rotation is an energy-saving mechanism.

The dragonfly is well known for its superior aerobatic skills. It hovers with the angle-of-attack asymmetrical in up and down stroke, which differs from other normal hovering insects which have a horizontal stroke plane and the same AOA in up and down strokes. Experimental research into an asymmetrical angle-of-attack in up and down stroke has not been reported.
The current experimental configuration involves the bio-mimetic wing features found in the dragonfly, i.e., the wing is flexible and passively and asymmetrically rotated. Under such configuration, how the spring stiffness and wing stiffness affect the aerodynamic force and power economy has not been explored. The goal for this research is to extract insights potentially beneficial to the design and development of dragonfly-like MAVs. Specifically, as stated in Chapter 1, the objectives of this study are:

- To investigate if there exists an optimal spring tension or wing stiffness to produce maximum aerodynamic force and power economy.
- To show that a certain degree of chordwise wing flexibility improves the overall aerodynamic force and power economy in passive wing rotation.

This Chapter describes the methodology used in this research, followed by the presentation of data processing and results. Analysis and discussion is presented in Chapter 5.

### 4.2 Fabrication of Flexible Wings

A series of five wings, with stiffness ranging from rigid to soft were built, which are numbered as 1, 1.5, 2, 2.5 and 3. However, only wing 1, 2 and 3 were chosen for experimentation. All wings used in the experiments had the same planform that is shown in Figure 4.1. The factors considered during wing design included: shape, weight, flexural stiffness and its variation in chord direction.
The planform of a dragonfly wing was chosen because of the dragonfly’s recognized aerial maneuverability, with the model wing having the shape of an enlarged version of the *Aeschna* dragonfly’s hind wing (Norberg 1975b). With a span of 499 mm, measured from wing root to tip, the third rib from the wing base has a maximum length of 145 mm. The third rib has the longest length of 136 mm measured from the rotation axis to the trailing edge. (see Figure 4.1).

A light-weight wing was desirable so that the flapping inertial effect could be as small as possible. Carbon fiber was selected as the material of the wing veins due to the advantage of its lightness and strength. Wing membranes were made of cello sheet, with a thickness of 0.03 mm, with the cello sheet being so thin that its stiffness in comparison with that of the carbon fibre veins could be ignored. Therefore the stiffness of the wing was primarily determined by its vein material.

In the model wing, the veins were arranged as shown in Figure 4.1. A main spar runs...
spanwise, while seven ribs run chordwise and are evenly spaced. Because of the trivial effect of the cello sheet, the flexural stiffness of the wing in span and chordwise were determined by the main spar and ribs. The main spar is tapered from wing root to tip when viewed from top as shown in Figure 4.1, but has the same thickness everywhere if viewed from side. Although the main spar is tapered, the spanwise stiffness was designed being very stiff for all five wings so that there is no visible bending of the wing in the span direction during experiments. The ribs were made with rectangular strips. In the same wing, seven ribs have the same height, but their widths decrease from the chord near the wing root to the chord near the tip. For each rib at the corresponding position for all wings, their width and length are the same, although the height of ribs is different from wing to wing.

The wing’s main spar and ribs were joined together by super glue to form its vein structure. The membrane was formed by cello sheet cut to the shape of the *Aeschna* dragonfly’s hind wing, but was enlarged 12 times. The wing was completed by bonding the wing-vein structures and membrane with double-sided clear adhesive tape. The mass properties of the fabricated wings are listed in Table 4.1.

<table>
<thead>
<tr>
<th>Wing</th>
<th>Mass [g]</th>
<th>Centre of Mass [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>1</td>
<td>16.8</td>
<td>194</td>
</tr>
<tr>
<td>1.5</td>
<td>9.8</td>
<td>186</td>
</tr>
<tr>
<td>2</td>
<td>7.8</td>
<td>186</td>
</tr>
<tr>
<td>2.5</td>
<td>4.8</td>
<td>187</td>
</tr>
<tr>
<td>3</td>
<td>2.8</td>
<td>186</td>
</tr>
</tbody>
</table>

Table 4.1: Mass properties of five flexible wings
To obtain a measurement of the wing stiffness, the wing is treated as being an equivalent beam with one end fixed. A series of deflections were then measured along the beam where force was applied. Given the applied force and deflection, the flexural stiffness of the beam can be calculated. The wing spanwise stiffness measurement was performed by clamping the horizontal wing where the first chord from the wing base is located, applying the force vertically and then measuring deflection. Chordwise stiffness was measured by clamping the horizontal wing at its rotation axis, placing a blade across the horizontal wing surface and parallel to the wing-rotation axis, thus applying force vertically to the blade and allowing measurement of deflection. Wing flexural stiffness $EI$ was calculated by treating the wing as an equivalent cantilever beam with one end fixed, by

$$EI = \frac{Pl^3}{3y},$$

where $P$ is the force applied on the wing, $l$ is the distance from the point where the force is applied to the first chord from the wing base and $y$ is deflection at the point where the force is applied. Figure 4.2 and 4.3 show the plots of $EI$ in spanwise and chordwise.
Chapter 4 Experiments and Results

Figure 4.3: Wings’ chordwise stiffness. The distance is normalized to the longest chord. (Wing 1, 2, 3, 4 and 5 in legend of this figure corresponds to wing 1, 1.5, 2, 2.5, and 3).

4.3 Reynolds Number

In this section, the Reynolds Number is first revisited followed by a review of the Scaling laws that have proved to be helpful in MAV flight studies, especially in mechanical and computational modeling, helping to set up models, identify flow patterns and predict lift and thrust. In MAV flight, the Reynolds number, Strouhal number and reduced frequency are the three key dimensionless parameters. By applying these rules certain aerodynamic similarities can be maintained. For a rigid flapping wing, it would be sufficient to define aerodynamic similarities within the above three parameters in addition to geometric and kinematic similarities (Shyy 2008). Since this
research is focusing on the hovering motion of the wing and forward velocity is zero, only the Reynolds number is of interest and both Strouhal number and the reduced frequency could be ignored.

The Reynolds number describes the ratio of inertial force to viscous force. In general, the Reynolds number is defined as

\[ \text{Re} = \frac{U C_m}{\nu}, \]

where, \(U\) is wing velocity, \(C_m\) object characteristic length (averaged chord length is used in the thesis), and \(\nu\) kinematical viscosity. In flapping flight, \(U\) is taken differently according to the flight mode. In forward flight, \(U\) is the wing’s forward speed. In this research, \(U\) represents the wing-tip mean velocity, hence, if \(\Phi\) is the amplitude of flapping angle measured from peak upstroke position to peak downstroke position, then

\[ U = 2\Phi f_j R C_m / \nu \]

where, \(R\) is the wing length, and \(C_m\) is the mean chord length.

The Defense Advanced Research Projects Agency (DARPA) defined Micro-air-vehicles (MAVs) as the flying vehicles with physical dimensions not larger than six inches (15cm) and flying speeds less than 10 m/s (McMichael and Francis 1997). Therefore, MAVs can be characterized as having small size, slow speed, low noise and high maneuverability. The corresponding Reynolds numbers for MAVs is in the range less than \(10^5\) (Shyy 2008) The Reynolds number for this study’s experimental wings is 16500, which is within the range of MAVs. Therefore, the results obtained from these experiments could serve as a reference for MAVs with similar Reynolds numbers.
4.4 Experimental Platform

Figure 3.24 is redisplayed as Figure 4.4 below to illustrate the set-up of the experimental apparatus omitting the flapping driving mechanical which is represented by the Y-axis. The ground reference frame is marked with capital letters OXYZ, while the sensor reference is identified by the lower-case letters oxyz. The explanation of forces/torques and other variables related to both references are listed as follows.

![Diagram of Experimental Set-up](image)

**Figure 4.4: Diagram of Experimental Set-up**
1. **Ground Reference, OXYZ**

The origin of the ground-reference coordinates is placed on the intersection of the wing flapping and rotation axis. The X-axis points upwards and the Y-axis points horizontally from the trailing edge to the leading edge of the wing when wing is horizontal.

2. **Sensor Reference, oxyz**

The origin of the sensor reference coordinates is placed at the centre of the end of the cylindrical sensor closer to the wing. When the wing surface rests horizontally, the x-axis points upwards and the y-axis points horizontally from the trailing edge to the leading edge. The sensor reference frame moves with the wing.

3. **Lift (N)**

Lift $\mathbf{FX}$, in ground reference, is defined as the aerodynamic force in the X-axis.

$FX = |\mathbf{FX}|$. Lift $\mathbf{fx}$, in sensor reference, is defined as the aerodynamic force in the x-axis.

4. **Thrust (N)**

Thrust $\mathbf{FY}$ in the ground reference is defined as the aerodynamic force in the Y-axis. $FY = |\mathbf{FY}|$. Thrust $\mathbf{fy}$ in the sensor reference is defined as the aerodynamic force in the y-axis.
5. **Resultant Force (N)**

Resultant Force $\mathbf{FR}$ is defined as the vector sum of lift and thrust in ground reference. $\mathbf{FR} = \mathbf{FX} + \mathbf{FY}$, $FR = |\mathbf{FR}|$.

6. **Resultant Force Direction (deg)**

Resultant Force Direction $\beta$ is defined as the angle between $\mathbf{FR}$ and the X-axis where $\beta = \arctan(FY/FX)$.

7. **Torque (N-mm)**

In the ground reference, $MX, MY, MZ$ are the aerodynamic torques about $X, Y$ and $Z$ axes. In the sensor reference, $mx, my$ and $mz$ are torques about $x, y$ and $z$ axes.

8. **Angular Speed $\omega$ (rad/s)**

Angular speed refers to the flapping angular speed,

$$\omega = 2\pi f_f \phi \cos(2\pi f_f t + \pi / 2)$$

where, $f_f$ is flapping frequency (Hz), and $\Phi$ is flapping amplitude (rad).

9. **Power, $P$ (mW)**

Power $P$ is defined as the power required in generating aerodynamic force, that is the product of torque about Y axis and angular speed, $P = (MY)*\omega$.

10. **Power Economy, $PE$ (N/mW)**

Power economy is defined as the ratio of the resultant FR and the power $P$, that is,

$PE = FR/P$. 
4.5 Data Processing

4.5.1 Force and Power

The raw data of force and torque, from flapping and rotation of the wing, were initially acquired in the sensor reference frame, while the pure aerodynamic data in the ground reference frame were obtained and processed by a specially written Matlab program, (see Appendix A). The outcomes of the Matlab program calculations are the means of the desired parameter values. Results are tabulated at the end of this Chapter. The following demonstrates the data processing using Run 6 that is group 123 as an example. Group 123 symbolizes the use of level 1 down-spring tension, level 2 up-spring tension and level 3 wing stiffness.

Four types of raw data are needed: force/torque, inertial force, rotation angle and flapping angle. Figure 4.5 shows force data with membrane on the wing in 12 flapping cycles collected from a force/torque sensor and includes aerodynamic force, gravity and inertial force.

![Graph of Measured Force with Membrane on the Wing](image)

Figure 4.5 Raw force data with membrane on the wing, 12 flapping cycles for run 6.
Figure 4.6 shows the force measured without a membrane on the wing and represents the force generated by inertia and gravity but not aerodynamic force.

Figure 4.6 Raw force data without membrane on the wing, 12 flapping cycles for run 6.

Figure 4.7 shows the rotation angle in 12 cycles measured by the Hall-effect sensor.

Figure 4.7 Rotation angle of Run 6 measured in Hall-effect sensor.

Flapping angle data is generated by the computing program as the 4-bar linkage mechanism produces a sinusoidal function for wing flapping. It was found that the measured-time history of the flapping angle is very close to a sinusoidal function with an $r$-squared value of 0.9928.
During initial data processing, the raw data for force and rotation angle were first phase-averaged, with all phase-averaged data collected from the beginning of the down stroke. The rotation angle was then converted from voltages $V$ to radians $\varphi$. The conversion curve of a $6^{th}$ order polynomial was obtained by curve fitting to the measured data with r-squared value of 0.9956 during calibration (see Figure 4.8).

$$\varphi = 0.0519V^6 + 0.6847V^5 - 14.560V^4 + 80.086V^3 - 220.64V^2 + 275.33V - 134.11$$

![Rotation Angle Conversion](image_url)

Figure 4.8 Rotation-angle conversion chart.

Having phase-averaged all data of multiple cycles into one cycle period, the aerodynamic forces $f_{xa}$, $f_{ya}$, and $f_{za}$ at any data point in the cycle in the sensor reference frame are calculated by subtracting gravity and force measured without
membrane from the force measured with membrane on the wing by using the derived formulae on each data point,

\[
\begin{align*}
  f_{xa} &= f_x - fxi \cos \varphi + fyi \sin \varphi - G + G \cos \varphi , \\
  f_{ya} &= f_y - fyi \cos \varphi - fxi \sin \varphi + G \sin \varphi , \\
  f_{za} &= f_z - fzi ,
\end{align*}
\]

where \( f_x, f_y \) and \( f_z \) are forces in the \( x, y \) and \( z \) direction in the sensor reference when the wing has a membrane; \( fxi, fyi \) and \( fzi \) are forces in the \( x, y \) and \( z \) direction in the sensor reference when the wing has no membrane; \( G \) is the weight of the tested wing and its associated mounting structure.

The aerodynamic forces, \( F_{xa}, F_{ya} \) and \( F_{za} \) in the ground reference frame, are obtained by converting \( f_{xa} \) and \( f_{ya} \) and \( f_{za} \) from the sensor reference through the conversion matrix, that is,

\[
\vec{F} = \psi \star \vec{f} ,
\]

\[
\psi = \begin{bmatrix} 
  \cos \varphi \cos \theta & \sin \varphi \cos \theta & \sin \theta \\
  \sin \varphi & \cos \varphi & 0 \\
  -\cos \varphi \sin \theta & -\sin \varphi \cos \theta & \cos \theta
\end{bmatrix}
\]

where \( \vec{F} = [F_{xa} \ F_{ya} \ F_{za}]^{-1} \) and \( \vec{f} = [f_{xa} \ f_{ya} \ f_{za}]^{-1} \);

\( \theta \) is the flapping angle when positive and measured from the azimuth upwards;

\( \varphi \) is the rotation angle when positive and measured from the 3 o’clock position when viewed from wing tip to base.

The above force evolution from raw data are phase-averaged to the final aerodynamic data in the ground reference are illustrated in Figure 4.9.
Figure 4.9: Force evolution for run 6, group123
Each subplot represents the phase-averaged values of the relevant data from the beginning of the down stroke. Subplot (a) is for flapping angle; subplot (b) for rotation angle; subplot (c) for force measured in the sensor reference with membrane on the wing; subplot (d) for the force measured in the sensor reference without membrane on the wing; subplot (e) for pure aerodynamic force in the sensor reference frame and, finally, subplot (f) for pure aerodynamic force in the ground reference frame. For all 27-run force-evolution graphs see Appendix B.

In order to estimate the power economy of the flexible wing, the power consumed by the aerodynamic force needs to be determined. In general, power is the product of torque and angular speed. Since the wing rotation mechanism is passive, only the flapping moment measured at the sensor is used to calculate the power required. In addition, since the wing only rotates about the Y-axis, torque about the X-axis does not consume power. Therefore, the power required in generating aerodynamic forces is the product of the aerodynamic torque about the Y-axis and the flapping angular speed.

Similarly to determine pure aerodynamic force, aerodynamic torque is calculated by subtracting the torque caused by gravity and inertia from the torque measured when a membrane is on the wing. The formulae derived for this procedure is as follows,

\[
m_{za} = m_z + m_{zi} \sin \varphi - m_0 \cos \theta \sin \varphi,
\]

\[
m_{ya} = m_y - m_{yi} \cos \varphi + m_0 \cos \theta \cos \varphi,
\]

\[
m_{za} = m_z - m_{zi}.
\]
where $m_{xa}$, $m_{ya}$ and $m_{za}$ are aerodynamic torque about the $x$, $y$, $z$ axes in the sensor reference frame; $m_0$ is the torque about the $y$-axis that is measured when the wing is in a still, horizontal position. The torque $m_x$, $m_y$ and $m_z$ are the torque about the $x$, $y$, $z$ axes in the sensor reference frame that is measured when the wing has a membrane. Torque, $m_{xi}$, $m_{yi}$ and $m_{zi}$ is that torque about the $x$, $y$, $z$ axes in the sensor reference frame that is measured when the wing has no membrane. $\theta$ and $\varphi$ remain as previously defined.

The aerodynamic torque $M_{xa}$, $M_{ya}$ and $M_{za}$ in the ground reference frame is obtained through converting $m_{xa}$, $m_{ya}$ and $m_{za}$ using the converting matrix. That is,

$$
\bar{M} = \psi ^* \bar{m},
$$

$$
\psi = \begin{bmatrix}
\cos \varphi \cos \theta & \sin \varphi \cos \theta & \sin \theta \\
\sin \varphi & \cos \varphi & 0 \\
-\cos \varphi \sin \theta & -\sin \varphi \cos \theta & \cos \theta
\end{bmatrix}
$$

where $\bar{M} = [M_{xa} \ M_{ya} \ M_{za}]^{-1}$ and $\bar{m} = [m_{xa} \ m_{ya} \ m_{za}]^{-1}$.

The angular speed $\omega$ of the flapping wing is obtained by taking the derivative of the angular displacement of the wing, which is a known sinusoidal function.

The power $P$ required in generating the aerodynamic force can then be calculated by

$$
P = M_{ya} * \omega
$$

Figure 4.10 shows a power evolution process for group 123. Similar to the force-evolution graph, each subplot represents phase-averaged data starting from the beginning of the down stroke, in which subplot (a) is for flapping angular speed; subplot (b) for aerodynamic torque about the $Y$-axis; subplot (c) for aerodynamic torque $M_{ya}$;
and finally subplot d) for the power $P$. The 27-run force power graphs are shown in Appendix C.
Chapter 4 Experiments and Results

Figure 4.10 Power evolution graph for Run 6, group 123
4.5.2 Minimization of Inertial Effect

A means of minimizing the inertial effect during data processing has also been developed. When the wing flaps the force/torque data collected contains inertial effects due to the wing mass. The removal of those inertial effects is always a difficult issue in experimental studies, especially in flapping wings. The following method used in these experiments has not been reported by other researchers.

The removal of inertial effects requires the wing to flap twice with membrane attached in the first run and without its membrane in the second. The data without-membrane is then subtracted from that gathered from the wing with-membrane. The remaining data will be without inertial effects. This simple approach will lead to a larger error, as the wing rotates while flapping with membrane, but with almost not rotation at all when the membrane is removed from the wing. This rotation-motion difference will cause some of the rotational inertial force to remain in the collected data.

This problem may be overcome by attaching a small mass to the wing-without-membrane in order to create a rotational wing motion to match that of the wing-with-membrane. A disadvantage of this method is that the two motions may sometimes be poorly matched, with certain inertial forces remaining.

The method used in the current experiments requires placing a weight on the wing, such that the centre of the mass of the wing is shifted to its rotational axis. Theoretically there should be no rotational inertial force generated throughout the flapping cycle, provided
that the spanwise stiffness of the wing is high enough. With this configuration, the inertial forces in both runs (with and without membrane) are only caused by the flapping motions and there is no rotational inertial force involved. Hence, the inertial force generated during flapping can be removed by subtracting the corresponding forces measured in two flapping sessions regardless of the rotational-motion difference.

### 4.6 Experimental Methods

To achieve the goal of this research, a total of 27 runs were conducted covering a full-factorial experimental space with 3 input factors and 3 levels for each of the factors. In each run, force/torque data across 12 flapping cycles were recorded through a 3-dimensional sensor located at the wing base. At the same time, the wing-rotation angle was also recorded. In order to remove inertia force in later data processing, the above procedure, see Section 4.5.2, was executed twice, once for the wing with membrane and for the other without. The multi-cycle force/torque data and rotation-angle data were first phase-averaged, with gravity and inertial forces then subtracted. Finally, pure aerodynamic force was converted to lift and thrust in the ground-reference frame. The effects of the three factors, spring stiffness for both up and down strokes and wing stiffness on net aerodynamic force and power economy, were calculated. The effects of the above factors on net force angle and power required were also obtained.

The 27 runs based on the 3 factors and their 3 levels were conducted randomly to minimize the systematic error. Flapping frequency was fixed at 1.25 Hz throughout the
experiments. In each run, 12 flapping cycles’ data points were collected. In data processing, the raw data for 12 cycles collected in sensor coordinates were phase-averaged to one cycle, followed by the subtraction of gravity and inertial effects to produce pure aerodynamic force in the ground-reference frame. The mean values of the aerodynamic forces, power and other desired parameters were calculated by averaging the phase-averaged instantaneous values in one flapping cycle. The effects of the factors on desired parameters are investigated based on these mean values. The results are presented in Section 4.7 and analyzed in Chapter 5.
4.7 Results

The mean values of the results of 27 runs are tabulated in Table 4.2, with statistical analyses in Chapter 5 based on these data.

Table 4.2 Results Table

<table>
<thead>
<tr>
<th>Run</th>
<th>Group</th>
<th>FX (N)</th>
<th>FY (N)</th>
<th>FR (N)</th>
<th>Beta (deg)</th>
<th>P (mW)</th>
<th>PE (N/mW)</th>
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<td>-0.0034</td>
<td>0.0720</td>
<td>0.0721</td>
<td>92.7410</td>
<td>-0.6706</td>
<td>0.1075</td>
</tr>
<tr>
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<td>0.0763</td>
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</table>
4.8 Conclusion

This Chapter described the methodology used to develop the current experimental research. A 27-run full factorial experiment was employed, in which up and down spring stiffness and wing stiffness were chosen as the experimental factors with 3 levels for each. The fabrication of the flexible wings was detailed. A data processing method was developed to extract the information about the pure aerodynamic force and power from the raw data. The final results were presented in the form of means which are ready for statistical analysis detailed in Chapter 5.
Chapter 5

Analyses and Discussion

5.1 Introduction

5.2 Analyses

5.2.1 Effects of the Factors on Resultant Force, FR

5.2.2 Effects of the Factors on Power Economy, PE

5.2.3 Effects of the Factors on Resultant Force Direction, $\beta$

5.2.4 Effects of the Factors on Power, P

5.2.5 Effects of the Factors on Lift, FX

5.2.6 Effects of the Factors on Thrust, FY

5.3 Discussion

5.4 Conclusion
5.1 Introduction

Understanding the role of wing flexibility in passive flapping aerodynamics is an important step in developing model of insect flight and possibly building micro MAVs with flapping wing propulsion system. Although there only limited papers published, research has shown the benefits of using flexible wings in force generation and the power efficiency in passive wing rotation. Recent work (Heathcote 2004) in heaving chordwise flexible wing in water tank indicates that certain amount of wing stiffness yields the greater thrust and power efficiency. Following up results (Heathcote 2008) indicate that a certain degree of the flexibility in spanwise is also beneficial to the thrust and power efficiency but an over-flexible wing is detrimental. A computational analysis (Miao and Ho 2006) on a plunge motion flexible airfoil also shows the enhancement in the propulsive efficiency with certain degree of flexure amplitude. The experimental study (Singh and Chopra, 2008) of symmetrical flapping wing in hovering motion has found that a soft torsion spring for passive wing rotation produces more thrust at slightly lower power than the stiff spring and that elasticity of the wing increases the thrust as well.

The current experiment research considers a scaled model of a dragonfly-like wing that flaps actively but rotates passively with asymmetrical up and down angle-of-attack. Chapter 4 presented details of a full factorial experiment that varied spring stiffness in both up and down stroke, as well as wing flexibility. This chapter produces an analysis of the experimental results presented in Table 4.2 in Chapter 4.
The analysis results show that flexible wing increases total aerodynamic force generated independent of angle-of-attack associated with upstroke and downstroke spring stiffness. The results also show that flexible wing improves power economy of flapping propulsion. Further more, the analysis results also reveal the relationships between the factors (up and down spring stiffness, wing stiffness) and the resultant force direction, power, lift and thrust. These findings are potentially useful in MAVs design.

5.2 Analyses

In order to obtain the information on the effects of spring stiffness and wing stiffness on Resultant force, Power economy, Resultant force direction and Power, Vertical force (Lift) and Horizontal force (Thrust) statistical analyses was carried out on the data listed in Table 4.2 in Chapter 4. The effect of a given factor at a particular level on interested parameter is calculated by computing the average of the values of the interested parameter obtained in all the runs with the given factor at that level. The statistical analysis was done using MiniTab (www.minitab.com). The statistical analyses include the plots of the main effects of the factors and the interaction plot and analyses of variance of means. Throughout the statistical analysis in this Chapter, the factor of spring stiffness for up stroke is denoted as A, the factor of spring stiffness for down stroke is denoted as B, and the factor wing stiffness is C. The numbers 1, 2, 3 are their 3 levels with 1 representing ‘stiff’, 2 ‘medium’ and 3 ‘soft’. In the tabular results of the analysis of variance for means following the interaction plots, the meaning of the components and abbreviations are explained as follows:
• Source - indicates the source of variation, either from the factor, the interaction, or the error. The total is a sum of all the sources.

• DF - degrees of freedom from each source. If a factor has three levels, the degrees of freedom is 2 (n-1).

• Adj SS – adjusted sum of squares between groups (factor) and the adjusted sum of squares within groups (error).

• Adj MS – adjusted mean squares are found by dividing the adjusted sum of squares by the degrees of freedom.

• F - calculate by dividing the factor Adj MS by the error Adj MS.

• P – computed from the F-distribution, the value of P is used to determine whether a factor is significant. In this work, a significant level of 0.05 is used; that is the effect is to be considered significant if its P-value is less than 0.05.

5.2.1 Effects of the Factors on Resultant Force Magnitude, FR

In this section, the analysis of Resultant force, the vector sum of vertical force (Lift) and horizontal force (Thrust), is presented. The magnitude of the Resultant force is denoted as FR. The analysis undertaken is an analysis-of-means (Mendenhall and Terry 2007) based on the full factorial experiment described in Chapter 4. In particular, data for this analysis were taken from the column headed by FR in Table 4.2 in Chapter 4.

Figure 5.1 shows the plots for effects of two spring stiffness and one wing chordwise flexural stiffness on Resultant force. The left most plot corresponds to factor A, the
strength of the down spring. This factor is correlated angle-of-attack with down stroke. The middle plot corresponds to factor B, the strength of the up spring. This factor is correlated angle-of-attack with up stroke. The right most plot corresponds to factor C, the wing chordwise flexural stiffness. This factor is more complex, but at a naive level will also contribute to the angle-of-attack (varying along the chord) in both up and down stroke.

![Main Effects Plot for Mean Resultant Force FR (N)](image)

**Figure 5.1** Main effects plot for resultant force, FR

![Interaction Plot for Mean Resultant Force FR (N)](image)

**Figure 5.2** Interaction plot for resultant force, FR
The left plot in Figure 5.1 shows a peak value at level 2. This indicates that in the passive rotation wing system, there exists optimum spring stiffness in down stroke for force generation, although there are only 3 spring stiffness considered. Since this down spring is related to the down stroke angle-of-attack, hence these exists optimum angle-of-attack for resultant force generating. The above result is to be expected and is consistent with one’s intuition. The current experiment has shown that horizontal force (thrust) (see Figure 5.11 left) is the dominant force when forming the resultant force with vertical force (lift) (see Figure 5.9 left plot). Consider the down stroke situation. When factor A is at level 1, the thrust hence the resultant force is small because of stiffer spring hence large angle-of-attack. When factor A is at level 3, the thrust hence the resultant force is also small because of a soft spring hence small angle-of-attack. When factor A is between level 1 and 3, the thrust hence the resultant force is large hence there exists a peak value. This effect corresponds to a P-value of 0.002 in the ANOVA analysis and is strongly supported by the data as significant effect.

Similar information can be extracted from the middle plot for up stroke spring stiffness, i.e. there is an optimum spring stiffness and angle-of-attack exist for resultant force...
generating in up stroke. The P-value for this effect is 0.016 and again the data support this. One may expect the upstroke and down stroke results to be identical. However, due to small varieties in spring tensions and the different texture on two sides of the wing, there are expected differences.

The right plot in Figure 5.1 shows the relationship between the resultant force FR and the wing stiffness levels. It is noticed that the resultant force increase with the decrease of the wing stiffness from level 1 to 3. Consider the down stroke again. When the tail of the wing is slightly bent in the down stroke, the leading-edge-vortices generated on the up surface of the wing are less easily to be shed from the trailing edge. This will ensure the vortices are attached to the wing more strongly and remain attached longer. As a result, the increase in strength of vortices yields stronger resultant force. The upstroke is a similar mechanism and the average resultant is increased.

Although leading-edge-vortex formation is the most likely cause of increased thrust, there are other aerodynamics effects that may be active. It is possible that the effect of wake-capture (one of the unsteady aerodynamic mechanisms) capturing more air flow may be presented. Conversely, it is unlikely that the rotational force (another unsteady aerodynamic mechanism) is involved since the wing rotates passively. Whether wake-capture is also the cause for the enhancement of aerodynamic force in flexible wing can be further investigated with the flow visualization in the future.

It is clear from these plots and the associated ANOVA results that the three factors are all statistically significant (P-values of 0.002, 0.016 and 0.033). Figure 5.2 shows the
plot for the interactions between factor A, B and C. With P-value for A*B of 0.102 and P-value for A*C and B*C of 0.825 and 0.913, more importantly, it shows that the factors A, B and C are independent. The slightly lower P-value of A*B could possibly be related to wake capture aerodynamic effects. However, the data is insufficient in itself to support any such hypothesis.

Overall, the experiment shows an expected correlation of angle-of-attack with force generation (factors A and B), along with new evidence of unsteady aerodynamics interaction with a flexile wing to generated higher force (factor C).

5.2.2 Effects of the Factors on Power Economy, PE

In this section, the analysis of power economy PE, is presented. Power economy is the ratio of the resultant force magnitude FR and the power P required in generating the resultant force, FR/P. Power economy is a good meter to measure efficiency of a flight regime. Flight regimes that generate high total force may require excessive power and result in inefficient flight. It is to be expected that any insect, such as dragonfly will have evolved to have an efficient flight regime as well as one that provides high force generation when required. The analysis method adopted is same as the one described in the previous section for resultant force. The data for this analysis were taken from the column headed by PE in Table 4.2 in Chapter 4.

Figure 5.3 shows the plots for effects of two spring stiffness and one wing chordwise flexural stiffness on power economy, PE. The left most plot corresponds to factor A, the
strength of the down spring. This factor is correlated angle-of-attack with down stroke. The middle plot corresponds to factor B, the strength of the up spring. This factor is correlated to angle-of-attack with up stroke. The right most plot corresponds to factor C, the wing chordwise flexural stiffness. This factor affects the angle-of-attack in both up and down stroke.

![Main Effects Plot for Mean Power Economy PE (N/mW)](image)

**Figure 5.3** Main effects plot for power economy, PE

![Interaction Plot for Means Power Economy PE (N/mW)](image)

**Figure 5.4** Interaction plot for power economy, PE
Chapter 5 Analyses and Discussion

### Analysis of Variance for Means

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<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
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</thead>
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<td>0.33480</td>
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<td>B</td>
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<td>0.32019</td>
<td>0.160095</td>
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<td>0.003</td>
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<tr>
<td>C</td>
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<td>0.23700</td>
<td>0.23700</td>
<td>0.118501</td>
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In figure 5.3, the three subplots show that the power economy increases with all three factors A, B and C from level 1 to 3 (stiff to soft). It indicates that more flexible wing rotation and more flexible wing yields better power efficiency. This could be the result that the softer springs and wing allow the wing to be easily compliant to the flow around the wing hence less energy is used to overcome the resistance of the air when the wing is moving through it. Thus, reduction in actuation force results in lower power efficiency, even though the total force generated is lower also (see Figure 5.1).

It is also noticed that in Figure 5.3 that PE increases faster from level 1 to level 2 than from level 2 to 3 in both left and middle plots. In the right plot, PE increases faster from level 2 to 3 than from level 1 to 2. This could be explained as follows.

When down spring is in level 1, i.e. having larger stiffness, the AOA during down stroke is large. Therefore the vertical force (lift) is large but horizontal force (thrust) is small. The resultant force is almost same as the vertical force. When down spring is level 2, i.e. having medium spring stiffness, the angle-of-attack is medium during down stroke. As discussed in previously for the resultant force, in this case the resultant force
has a peak magnitude. On the other hand, the power requirement, P, (shown in Figure 5.7, negative sign means drawing power) is reduced when compared to the case in spring level 1, because of the smaller angle-of-attack and the power is normally consumed in the lift. Therefore the power economy, FR/P, increase sharply.

When the down spring is in level 3, i.e. having soft spring, the angle-of-attack is very small during down stroke. The resultant force decreases sharply. However, on the other hand, the power required also drops sharply because of the small angle-of-attack and hence the less lift. The ratio FR/P, changes not much. This is why the slow increase is shown from level 2 to 3. The similar explanation can be applied in the middle plot in Figure 5.3, representing the case for up stroke spring stiffness.

The right plot in Figure 5.3 shows the power economy increases with the increase of wing flexibility. Especially, it increases sharply from level 2 to 3. This could be explained as follows.

When the wing is rigid, i.e. in level 1, the resultant force generated is small and the power requirement is medium (see in Figure 5.7). When some flexibility is added in the wing, i.e. level 2, the resultant force increases but the power required is also increased. Therefore the ratio of FR/P is not changed much. When the wing becomes more flexible, i.e. level 3, the resultant force becomes very large. However, the power requirement drops dramatically (see Figure 5.7). Hence power economy, the ratio of FR/P, becomes very large. This is shown by sharp increase from level 2 to level 3 in the right plot of Figure 5.3.
Analysis of variance (ANOVA) for power economy shows the significance of the major factors A, B and C by displaying the P-values (0.002, 0.003 and 0.007) less than 0.05. On the other hand, it once more demonstrates the independence between the factors by showing the P-values (0.444, 0.543 and 0.679) larger than 0.05.

5.2.3 Effects of the Factors on Resultant Force Direction, $\beta$

In this section, the analysis of resultant force direction $\beta$ is presented. Resultant force direction is the angle between lift and resultant force measured from 12 o’clock anti-clockwise. The analysis method adopted is same as the one described in the previous two sections. The data for this analysis were taken from the column headed by Beta in Table 4.2 in Chapter 4.

Figure 5.5 shows the plots for effects of two spring stiffness and one wing chordwise flexural stiffness on resultant force direction. The meanings of the symbols A, B and C in the plot are same as the previous two sections. The left most plot corresponds to factor A, the strength of the down spring. This factor is correlated angle-of-attack with down stroke. The middle plot corresponds to factor B, the strength of the up spring. This factor is correlated angle-of-attack with up stroke. The right most plot corresponds to factor C, the wing chordwise flexural stiffness. This factor affects the angle-of-attack in both up and down stroke.
Chapter 5 Analyses and Discussion

Figure 5.5 Main effects plot for resultant force direction $\beta$

![Main Effects Plot for Mean Beta (deg)](image)

Figure 5.6 Main effects plot for resultant force direction $\beta$

![Interaction Plot for Mean Beta (deg)](image)

**Analysis of Variance for Means**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>9469.6</td>
<td>9469.6</td>
<td>4734.8</td>
<td>34.10</td>
<td>0.000</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>13085.7</td>
<td>13085.7</td>
<td>6542.8</td>
<td>47.12</td>
<td>0.000</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1408.7</td>
<td>1408.7</td>
<td>704.3</td>
<td>5.07</td>
<td>0.038</td>
</tr>
<tr>
<td>A*B</td>
<td>4</td>
<td>905.9</td>
<td>905.9</td>
<td>226.5</td>
<td>1.63</td>
<td>0.257</td>
</tr>
<tr>
<td>A*C</td>
<td>4</td>
<td>620.9</td>
<td>620.9</td>
<td>155.2</td>
<td>1.12</td>
<td>0.412</td>
</tr>
<tr>
<td>B*C</td>
<td>4</td>
<td>1116.6</td>
<td>1116.6</td>
<td>279.2</td>
<td>2.01</td>
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<td>1110.7</td>
<td>1110.7</td>
<td>138.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>27718.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The left plot in Figure 5.5 shows Beta increases with the decrease of the down spring stiffness. This phenomenon can be explained in terms of the angle-of-attack of the wing. When the down spring stiffness is at level 1, the angle-of-attack is large. This large angle-of-attack yields large lift but small thrust. Since the resultant force is the vector sum of lift and thrust, the resultant force is close to lift hence Beta is small. When down spring stiffness decreases, the smaller angle-of-attack results in the increase in thrust and decrease in lift. Therefore Beta is increased.

Similar situation occurs for factor B, but in the opposite direction since B controls the wing angle-of-attack in up stroke, as shown in the middle plot in Figure 5.5.

Wing flexural stiffness seems having no strong trend from level 1 to level 3 shown in the right plot in Figure 5.5. This can be explained as follows. The wing tends to bend upwards in down stroke but downwards in up stroke. Therefore the wing bending effects on the resultant force direction tend to cancel out in one flapping cycle.

The ANOVA results basically examine two things in our experiments. One is whether the effects investigated are significant statistically. The other is whether the factors under examined are independent to each other. The result for resultant force direction once more indicates there is no strong evidence suggesting that the factors are interacted (P-values are 0.257, 0.412, 0.186 are greater than 0.05). and the effects obtained are significant (P-values are 0.000, 0.000, 0.038 are less than 0.05). The interpretation for ANOVA in the coming sections will be even simpler.
5.2.4 Effects of the Factors on Power, P

In this section, the analysis of power P, is presented. Power P is the power required in generating the resultant force. The analysis method adopted is same as the one described in the previous section for resultant force (Section 5.2.1). The data for this analysis were taken from the column headed by P in Table 4.2 in Chapter 4.

Figure 5.7 shows the plots for effects of two spring stiffness and one wing chordwise flexural stiffness on power, P. Same as in the described in Section 5.2.1. The left most plot corresponds to factor A, the strength of the down spring. This factor is correlated angle-of-attack with down stroke. The middle plot corresponds to factor B, the strength of the up spring. This factor is correlated angle-of-attack with up stroke. The right most plot corresponds to factor C, the wing chordwise flexural stiffness. This factor affects the angle-of-attack in both up and down stroke.

![Main Effects Plot for Mean Power P (mW)](image)

Figure 5.7 Main effects plot for power, P
Figure 5.8 Interaction plot for power, P

**Analysis of Variance for Means**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
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<th>Adj MS</th>
<th>F</th>
<th>P</th>
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<td>0.229418</td>
<td>0.229418</td>
<td>0.114709</td>
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</tr>
<tr>
<td>B</td>
<td>2</td>
<td>0.374823</td>
<td>0.374823</td>
<td>0.187411</td>
<td>91.47</td>
<td>0.000</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>0.047218</td>
<td>0.047218</td>
<td>0.023609</td>
<td>11.52</td>
<td>0.004</td>
</tr>
<tr>
<td>A*B</td>
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<td>0.005365</td>
<td>0.001341</td>
<td>0.65</td>
<td>0.640</td>
</tr>
<tr>
<td>A*C</td>
<td>4</td>
<td>0.004337</td>
<td>0.004337</td>
<td>0.001084</td>
<td>0.53</td>
<td>0.718</td>
</tr>
<tr>
<td>B*C</td>
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<td>0.011552</td>
<td>0.011552</td>
<td>0.002888</td>
<td>1.41</td>
<td>0.314</td>
</tr>
<tr>
<td>Residual Error</td>
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<td>0.016391</td>
<td>0.016391</td>
<td>0.002049</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>0.689104</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is noticed that the values on y-axis in Figure 5.7 are negative. The negative sign indicates that the power is drawn from the power source.

All three subplots in Figure 5.7 show that factor A, B and C at their level 3 (softest) consumes minimum power. As explained in Section 5.2.2 for power economy, this could be the result that the softer springs and wing allow the wing to be easily compliant to the flow around the wing hence less energy is used to overcome the resistance of the air when the wing is moving through it. As previous sections the ANOVA results show the significance of the factors and the independence of each other.
5.2.5 Effects of the Factors on Lift, FX

In this section, the analysis of lift (more precisely its magnitude, FX), is presented. Lift is the aerodynamic force generated by the flapping wing in the vertical direction in ground reference. The analysis method adopted is same as the one described in the previous section for resultant force (Section 5.2.1). The data for this analysis were taken from the column headed by FX in Table 4.2 in Chapter 4.

Figure 5.9 shows the plots for effects of two spring stiffness and one wing chordwise flexural stiffness on lift, FX. Same as described in Section 5.2.1. The left most plot corresponds to factor A, the strength of the down spring. This factor is correlated angle-of-attack with down stroke. The middle plot corresponds to factor B, the strength of the up spring. This factor is correlated angle-of-attack with up stroke. The right most plot corresponds to factor C, the wing chordwise flexural stiffness. This factor affects the angle-of-attack in both up and down stroke.

![Figure 5.9 Main effects plot for lift, FX](image-url)
The left most plot in Figure 5.9 shows the lift FX monotonically decreases with the decrease of the down stroke spring stiffness. This can be explained as follows. When factor A is at level 1, the angle-of-attack is high and hence the leading-edge-vortices can easily be produced. Further more, at large angle-of-attack, the wing effective area is large and hence the wake-capture effect is strong. Therefore large lift was observed. When factor A is at level 3, the angle-of-attack is small and hence the leading-edge-vortices are difficult to be produced or easily to shed off the wing. Also when factor A is at level 3, the wing effective area is small and hence the wake-capture effect is week.
Therefore small lift was observed. In the same manner, the explanation can be made for factor B shown in the middle plot in Figure 5.9.

The effects of wing stiffness on lift shown in the right plot in Figure 5.9 appear having not strong trend and close to zero. This means the effects of the wing stiffness variation on lift is small. The explanation of this phenomenon is that the effect of the wing bending on FX in up stroke is canceled out by the effect of the wing bending in the down stroke. Ideally, level 1, 2 and 3 are expected on the zero line. This small variation is because of the slightly asymmetrical Angle-of-attack in up and down stroke caused by the deviation of the springs’ stiffness and wing different surface texture on two sides (Membrane was glued onto the carbon fiber so one side is smooth the other side has carbon fiber).

Once more, ANOVA shows the significance of the factors and no interactions between them by presenting the P-values less and greater than 0.05 respectively.

### 5.2.6 Effects of the Factors on Thrust, FY

In this section, the analysis of thrust (more precisely its magnitude, FY), is presented. Thrust is the aerodynamic force generated by the flapping wing in the horizontal direction in ground reference frame. The analysis method adopted is same as the one described in the previous section for resultant force (Section 5.2.1). The data for this analysis were taken from the column headed by FY in Table 4.2 in Chapter 4.

Figure 5.11 shows the plots for effects of two spring stiffness and one wing chordwise flexural stiffness on thrust, FY. Same as in the described in Section 5.2.1. The left most
plot corresponds to factor A, the strength of the down spring. This factor is correlated angle-of-attack with down stroke. The middle plot corresponds to factor B, the strength of the up spring. This factor is correlated angle-of-attack with up stroke. The right most plot corresponds to factor C, the wing chordwise flexural stiffness. This factor affects the angle-of-attack in both up and down stroke.

![Main Effects Plot for Mean Thrust FY (N)](image1)

**Figure 5.11** Main effects plot for thrust, FY

![Interaction Plot for Means Thrust FY (N)](image2)

**Figure 5.12** Interaction plot for thrust, FY
Chapter 5 Analyses and Discussion

### Analysis of Variance for Means

<table>
<thead>
<tr>
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<th>Adj SS</th>
<th>Adj MS</th>
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<td>0.056777</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.11 shows the plot of effects of factor A, B and C on thrust FY. Because the thrust FY is the dominant component in forming the resultant force FR, the interpretation for the effects is similar to FR (Section 5.2.1) and no longer discussed any more in this section. Same to ANOVA results, the explanation is omitted.

### 5.3 Discussion

In this section, the overall outcomes for the experiment undertaken are discussed. The experimental results described in Section 5.1~5.6 demonstrate that the three factors considered,

- Factor A, down stroke spring stiffness
- Factor B, up stroke spring stiffness
- Factor C, chordwise stiffness of wing

act significantly and independently on the passive flapping flight regime considered. It is not surprising that the effects of factors A and B are very similar and are decoupled
since these factors predominately correlate to angle-of-attack in downstroke and upstroke of the wing independently.

It is more interesting and an important contribution of the this thesis, that the wing flexibility (factor C) acts independently of factor A and B has a significant positive effect on total force generated and on power economy in a passive flapping flight regime. It is difficult, if not impossible, to explain this effect using traditional quasi-steady aerodynamic analysis, and the only reasonable explanation of these effects must rely on unsteady aerodynamic effects.

There are several possible unsteady aerodynamic effects that have been discussed in the literature that could be active in the flight regime considered. Of these possible effects as was thoroughly discussed in Chapter 2, Literature Review (Section 2.1.2), two effects of most interest are leading-edge-vortex and wake capture. To investigate the processes of these effects a qualitative flow visualization experiment was undertaken. In the flow visualization experiment, a laser sheet was projected down onto the wing and interacting along the chord direction. Smoke was pumped below the wing. The videos of flow situations were recorded using Sony HDR-SR7. Due to the limitation of the laser equipment, only half the chord length of the wing was able to be imaged. Moreover, turbulence of the flow led to considerable confusion of the images and limited the information that could obtained. Nevertheless, although the flow patterns recorded are not very clear, the existence of a leading edge vortex is clearly visible in Figure 5.13.
Figure 5.13 Image from flow visualization experiment.

A laser beam is projected down from above. Wing spars are retraced with white lines because the black carbon fiber spars are hardly to be visible on the black background. The laser sheet has illuminated on the membrane. The intersection line of the laser sheet and membrane traced a grey sheet in the centre of the image because of the camera exposing time length. Below the leading edge strut is a column of shadow due to light blocking by the main spar. The leading edge vortex is clearly visible in the laser sheet. The full vortex would extend along the leading edge of the wing. The size of the leading edge vortex visible would indicate that it is likely to be the major cause of aerodynamic forces applied to the wing in this flight regime. Clearly, this is just one example, however, it is reasonable to conclude that leading edge vortex generation is one of, if not the dominant force effects in passive flapping wing.
This point of view is also supported by and visualization of the flapping motion considered. Frame by frame, images for cases 111, 221, and 331 are shown in Figure 5.14, 5.15 and 5.16. Note that even with soft spring and rigid wing (as 331) the effective AOA of the wing chord is still greater than $20^\circ$. That is the airfoils operating constantly in the stall regime.
<table>
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<tr>
<th>a1</th>
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<th>a3</th>
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<td><img src="a5.png" alt="image" /></td>
</tr>
<tr>
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<td><img src="a7.png" alt="image" /></td>
<td><img src="a8.png" alt="image" /></td>
<td><img src="a9.png" alt="image" /></td>
<td><img src="a10.png" alt="image" /></td>
</tr>
</tbody>
</table>

Figure 5.14 A series of pictures of one flapping cycle. Group 111
Figure 5.15  A series of pictures of one flapping cycle. Group 221
Figure 5.16 A series of pictures of one flapping cycle. Group 331
Returning to the experimental results, it is of interest to consider whether leading edge vortex generation provides a means to explain the thrust generation and power economy observed and initially consider the effects of factors A and B for a stiff wing. Increasing the stiffness of factor A and B increase the AOA of the wing during stroke. Clearly, for low AOA their less opportunity for generation of LEVs and force generation would be low. For very high angle of attack large forces are generated due to large vortices. This effect can be seen clearly when comparing the phase averaged force generation shown in Figure 5.17, 5.18 and 5.19.

![Figure 5.17 Force generated from group 111](image-url)
Figure 5.18 Force generated from group 221

Figure 5.19 Force generated from group 331
Moreover, for very high AOA the force generated is mainly in the stroke plane. The symmetric flapping motion of the wing then leads to an averaging effect of total force and the low mean resultant force seen in Figure 5.1. The power economy of this regime is particularly poor due to the high power required to flap the horizontal wing back and forth (Figure 5.3). The peak force is obtained for medium spring stiffness (Figure 5.1) associated with the orientation of the force seen to be toward to thrust direction that is FY is larger (Figure 5.11). Due to the high angle-of-attack involved in the flapping these effects can not be explained by classical quasi-stationary flow analysis.

The results for factor C, wing flexibility can also be explained through LEV effects. Recent studies have indicated that flexibility in wing may allow vortices to attach more tightly to a wing surface. (Heathcote 2004). Based on this observation, and then adding flexibility to a wing should lead to more effective bonding of LEVs to the wing.

When the wing is flexible to a certain degree, the leading-edge-vortices (LEV) tends to be bonded on the wing longer and tighter rather than shed off easily. This is beneficial in generating larger thrust hence the resultant aerodynamic force. Moreover, the flexible wing tends to adapt to the flow pattern around the wing. This could lead to the reduction of the flow resistance during flapping. The property of flexible wing of adapting the surrounding flow pattern leads to the reduction in power requirement. With stronger bonding vortices and less power requirement flexible wing should yield much higher power efficiency than its rigid counterpart. This explains the independent increase in total force with factor C seen in Figure 5.1 as well as the improved power economy in Figure 5.2.
If the wing’s flexibility is increased further to a level such that AOA is almost zero, the PE could be expected to decrease again, because of very low resultant force generation. If this is the case, there could be an optimum PE for the wing flexibility. This was documented in Heathcotte (2008). This could be a subject for further research in flexible wing effect on PE to cover a wider range.

5.4 Conclusion

The following hypotheses have been statistically accepted based on the analysis of the results of a 27-run full factorial experiment over 3 factors and 3 levels:

1. The medium stiffness spring produces maximum aerodynamic resultant force;
2. Lower spring tension and more flexible wing could yield higher Power Economy.

However, there is no peak found in the 3rd subplot for the resultant force. Therefore the hypothesis that the wing with the medium stiffness generates maximum resultant force is rejected. A possible reason that the peak does not appear could be due to the wing stiffness range was not big enough. Future investigation in this direction should include wider wing stiffness range.
The current research results have drawn some useful conclusions which could benefit the future flapping MAVs design and development featuring passively rotated wing motion.

1. **Relationship between Lift and Spring Stiffness**: The lift monotonically decreases with the decreasing stiffness of the down stroke spring, but increases with the decreasing stiffness of the up stroke spring.

2. **Relationship between Thrust and Spring Stiffness**: Maximum thrust on both up and down stroke is obtained for moderate spring stiffness.

3. **Relationship between Lift and Wing Stiffness**: Wing stiffness has no effect on Lift.

4. **Relationship between Thrust and Wing Stiffness**: Thrust increases with the decreasing wing stiffness.

5. **Relationship between Resultant Force and Spring Stiffness**: The resultant force increases with the decreasing wing stiffness.

6. **Relationship between Resultant Force Direction and Spring Stiffness**: Decreasing the spring stiffness A or increasing the spring stiffness B rotates the resultant force about Z-axis clock-wise.

7. **Relationship between Power Economy and Spring and Wing Stiffness**: Softer springs and wings improve the Power Economy.

8. **Peak mean thrust could be as twice large as the peak means Lift**.

9. **Rigid Wing Should Be Avoided**: Rigid wing is no good for MAV design from the perspectives of both maximum force generation and higher Power Economy yielding.
10. *Thrust is Much Larger Than Lift*: Thrust generated by horizontal stroke plane could be much easier to balance the body weight than using Lift. In fact, many insects do use normal hovering mode (a type of hovering mode using horizontal stroke plane). Note that the peak mean thrust measured is 2 times as big as peak mean Lift.
Conclusion
This research experimentally studies unsteady aerodynamics associated with flapping wings. The research was performed on wings with the properties of a dragonfly-like planform, with each having different chordwise flexural stiffnesses. The wings flapped actively but rotated passively with asymmetrical up/down angle-of-attack.

Confined to this flapping wing configuration, the research was intended to:

1. Investigate the hypothesis that optimum spring stiffness (associated with angle-of-attack) and wing stiffness exist in aerodynamic-force generation.
2. Investigate the hypothesis that lower spring stiffness and lower wing stiffness yield higher power economy.

The research experiment was conducted on a novel electro-mechanical device designed to be capable of performing the required functions. Experimental data were processed using a self-developed Matlab program and statistically analyzed in MiniTab.

The conclusions of the experimental research are:

1. Optimal spring stiffness exists in aerodynamic force generation but optimal wing flexibility was not found within the tested range.
2. Lower spring stiffness and lower wing stiffness yields higher power economy.
The research not only successfully examined the above hypotheses, but also generated results which could be used as references for relevant MAV design. These results already mentioned in Chapter 5 are restated as follows:

1. **Relationship between Lift and Spring Stiffness**: The lift monotonically decreases with the decreasing stiffness of the down stroke spring, but increases with the decreasing stiffness of the up stroke spring.

2. **Relationship between Thrust and Spring Stiffness**: Maximum thrust on both up and down stroke is obtained from moderate spring stiffness.

3. **Relationship between Lift and Wing Stiffness**: Wing stiffness has no effect on lift.

4. **Relationship between Thrust and Wing Stiffness**: Thrust increases with decreasing wing stiffness.

5. **Relationship between Resultant Force and Spring Stiffness**: The resultant force increases with decreasing wing stiffness.

6. **Relationship between Resultant Force Direction and Spring Stiffness**: Decreasing the spring stiffness A or increasing the spring stiffness B rotates the resultant force clock-wise about the Z-axis.

7. **Relationship between Power Economy and spring and Wing Stiffness**: Softer springs and wings improve power economy.

8. Peak mean thrust could be twice large as the mean peak lift.

In summary, a rigid wing is not applicable to MAV design from the perspectives of both maximum force generation and higher Power Economy yielding. Thrust generated by the horizontal stroke plane could be applied to balancing body weight rather than by the
use of lift. In fact, many insects in nature do use normal hovering mode (a type of hovering mode using horizontal stroke plane) to generate aerodynamic forces to offset their body weights.
References


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Appendix A:

Data Processing Program
This program FTsensorToGroundFullRun_FT_final converts the data of force in sensor reference frame to ground reference frame in all 27 runs. Phase-averaged aerodynamic forces and power it requires are plotted.

clc % clean command window
cIff % clean figures
close all % close all figures
clear all % clear variables
delete('Results.txt'); % delete the Results.txt from previous run
delete('meanFXFYFZ.txt'); % delete the meanFXFYFZ.txt from previous run
delete('meanTXTYTZ.txt'); % delete the meanTXTYTZ.txt from previous run
%========================================================================
%========================================================================
% inputs: Rotation Angle, Force and Torque, Inertia, Flapping frequency and Divider.

%TrialNumber=input('TrialNumber =    '); % for test purpose for RunNumber=1:27; %RunNumber=8; TrialNumber=1; Ff=1.25; % Flapping frequency Hz
mainFolder='E:\Experiment Files\Experiment Final 2009\',
FTfolder='Force-Torque\';
InertiaFolder='Inertia\';
RotationAngleFolder='Rotation Angle\';
surfix1='.txt';
surfix2='ang.txt';

FileMatrix={
'111','C111b','C111c','IH31'; % (A, B, C)=flapping frequency=0.75,1,1.25Hz; (a,b,c)=trial 1,2, 3;
'114','C113b','C113c','IH34'; % 111, 113, 114......= spring controlling down stroke angle, spring controlling up stroke angle, wing (number) stiffness.
'115','C114b','C114c','IH35';
'
'131','C131b','C131c','IH31';
'134','C133b','C133c','IH34';
'135','C134b','C134c','IH35';
'
'151','C151b','C151c','IH31';
'154','C153b','C153c','IH34';
'155','C154b','C154c','IH35';
'
'311','C311b','C311c','IH31';
'314','C313b','C313c','IH34';
'315','C314b','C314c','IH35';

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FTname=FileMatrix{RunNumber,TrialNumber}; % get file names for force/torque, inertia and rotation angle.
InertiaName=FileMatrix{RunNumber,4};
RotationAngleName=FileMatrix{RunNumber,TrialNumber};

ForceTokFileAt=strcat(mainFolder,FTfolder,FTname,surfix1); % files' locations
InertiaFileAt=strcat(mainFolder,InertiaFolder,InertiaName,surfix1);
RotationAngleAt=strcat(mainFolder,RotationAngleFolder,RotationAngleName,surfix2);

ForceTorPlusMem=dlmread(ForceTokFileAt, '\t'); % input F/T with membrane data
ForceTorNoMem=dlmread(InertiaFileAt, '\t'); % input F/T with No membrane data
anglevolts=dlmread(RotationAngleAt, '\t'); % input angle data (with Membrane) from tab delimited txt file.

Fs=200; % Sampling Rate of Force/Torque sensor Hz
if Ff>1 % If Ff> 1 Hz, use 201; otherwise 200.
    NF=201;
else

NF=200;
end

N1=220; % first N1 data in force/torque data;
N2=220; % first N2 data in inertial data;
K1=320; % first K1 data in rotation angle data;

% derived number
N=floor(Fs/Ff); % data length in one cycle of Force

%Constants
T=200;
t=(1:T)/200;

%========================================================================
%========================================================================
% Rotation angle phi2 without membrane.

phi2=zeros(1,200); % Inertia caused by rotation is small compared to flapping motion, ignored.

%========================================================================
% finding out numbers of completed cycles in collected rotation angle (phi) data for the wing with Membrane
% (1) when rotation angle with membrane has already been phase-averaged before input and the data length is 200.
% phi=anglevolts;

%========================================================================
% (2)Calculating the phase average of the rotation angle phi (with membrane) from the beginning of downstroke,

% Starting point and repeated times
firstK1data=anglevolts(1:K1,1); % get first K1 data from flapping angle., in 1st column
[Fmax ko]=max(firstK1data); % get the max flapping angle data Fmax and its index ko.
k=floor((length(anglevolts(:,1))-ko)/N); % k= the number of complete cycles in anglevolts array
% Phase averaging
anglevolts2=anglevolts(:,2); % extract 2nd column
for i=1:N % repeat in one cycle

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Phisum(i)=0; % set initial to zero
for j=1:k
    Phisum(i)=Phisum(i)+anglevolts2(ko+i+N*(j-1)); % sum phi corresponding points in each cycle
end
    Phiav(i)=Phisum(i)/k; % find average value of the corresponding points
end

% Converting Voltage to Radian
p1 = 0.051938; % found from Figure after running; curve fitting with 6th order polynomial
p2 = 0.68466;
p3 = -14.566;
p4 = 84.086;
p5 = -220.64;
p6 = 275.33;
p7 = -134.11;
P=[p1 p2 p3 p4 p5 p6 p7]; % coefficients of voltage to angle trend line r-square = 0.9956
phi= polyval(P,Phiav); % convert voltages to rotation angle (rad).

% Interpolating such that data in one phase averaged cycle have 200 points.
x=1:length(phi); % 1:(phi length)
y=phi;
xi=1:length(phi)/NF:length(phi); % plan to interpolate phi to 200 data
y_interp=interp1(x,y,xi,'spline');

phi=y_interp; % phi is filled with interpolated data to 200.

for i=1:length(phi),
    if phi(i)>90/180*pi,
        phi(i)=90/180*pi;
    end
    if phi(i)<-90/180*pi,
        phi(i)=-90/180*pi;
    end
end

% Plot rotation angle with membrane
figureNumber=(TrialNumber-1)*27+RunNumber;
str=num2str(RunNumber);
str2=FileMatrix(RunNumber,TrialNumber);
if 0
    figure(figureNumber)
    subplot(3,2,2)
    plot(t,phi*180/pi,'k-','LineWidth',2),
    hold on
    plot(t,0,'k-','LineWidth',0.5),
    set(gca,'XLim',[0,1]);
    set(gca,'XTick',[0:0.5:1]);
    set(gca,'YLim',[-90,90]);
    set(gca,'YTick',[-90:45:90]),
    % set(gca,'YTickLabels',[-90; -45; 0; 45; 90]),
    title(strcat('Rotation Angle (deg), 'RunNumber=', str))
end

% Find out the number of complete cycles in collected force and torque data from Fz
% with membrane. (Fz has minimum at the beginning of downstroke)

firstN1data=ForceTorPlusMem(1:N1,3); % get first N1 data from Fz in 3rd column.
[Fzmin No]=min(firstN1data); % get the smallest data Fzmin and its index No.
m=floor((length(ForceTorPlusMem(:,1))-No)/N); % m= the number of complete cycles in ForceTorPlusMem array

% Calculate the phase-average of the F/T data with Membrane.
for i=1:length(ForceTorPlusMem(1,:)) % l: row number
    FTmsum=ForceTorPlusMem(:,i); % pick up one of Fx Fy Fz
    Mx My Mz to calculate
    for j=1:N % pick up one of the data in a cycle for phase average
        FTmsum(j)=0; % set initial to zero
        for k=1:m
            FTmsum(j)=FTmsum(j)+FTmsum(No+j+N*(k-1)); % sum corresponding points of every cycle
        end
        FTmpa(i,j)=FTmsum(j)/m; % find average value of the corresponding point
    end
end

% Interpolate FTmpa to make its data length of 200, same as the one for rotation angle data.
x=1:length(FTmpa(1,:)); % l:(Fx length)
y=FTmpa;  % 6x(Fx length) data matrix
x=1:length(FTmpa(1,:))/NF:length(FTmpa(1,:));  % plan to interpolate
for i=1:length(FTmpa(:,1))  % select Fx Fy Fz Mx My Mz
  y_interp=interp1(x,y(i,:),x,'spline');
  FTmpa_temp(i,:)=y_interp;
end
clear FTmpa;  % clear FTmpa old values
FTmpa=FTmpa_temp;  % Ftmpa is filled with interpolated
data to 6x200.

% if 0
subplot(3,2,3)
plot(t,FTmpa(1,:),'k-','t',FTmpa(2,:),'k--','t',FTmpa(3,:),'k:','LineWidth',2),
hold on
plot(t,0,'k-','LineWidth',0.5),
ylim([-1.5,1.5]),
set(gca,'XLim',[0,1]);
set(gca,'XTick',[0:0.5:1]),
title(' Force Phase-averaged in Sensor Reference (N)'),
h_legend=legend('Fx', 'Fy', 'Fz', 1);
set(h_legend,'FontSize',7);
% end

% Find out number of complete cycles in collected Inertia
% from Fz in NO membrane case.

firstNomN2data=ForceTorNoMem(1:N2,3);  % get first N2 data from
Fz in 3rd column.
[Fzmin No2]=min(firstNomN2data);  % get the
smallest data Fzmin and its index No2.
m2=floor((length(ForceTorNoMem(:,1)))-No2)/N);  % m2= the number of
complete cycles in ForceTorNoMem array.

for i=1:length(ForceTorNoMem(1,:))  % row number
  FTnomsum=ForceTorNoMem(:,i);  % pick up one of Fx Fy Fz
  Mx My Mz to calculate
  for j=1:N  % pick up one of
    the data in a cycle for phase average
    FTnomsum(j)=0;  % set initial to zero

for k=1:m2
    FTnomsum(j)=FTnomsum(j)+FTnomsum(No2+j+N*(k-1));  % sum corresponding point in each cycle
end
FTnompa(i,j)=FTnomsum(j)/m2;                 % find average value of the corresponding point
end

% interpolate FTnompa to make its data length of 200, same as the one for rotation angle data.
[x]=1:length(FTnompa(1,:));             % 1:(Fx length)
y=FTnompa;                               % 6x(Fx length) data matrix
[xi]=1:length(FTnompa(1,:))/NF:length(FTnompa(1,:));    % plan to interpolate FTmpa to 6x200 data matrix
for i=1:length(FTnompa(:,1))            % select Fx Fy Fz Mx My Mz sequentially
    y_interp=interp1(x,y(i,:),xi,'spline');
    FTnompa_temp(i,:)=y_interp;
end
clear FTnompa;                           % clear FTmpa old values
FTnompa=FTnompa_temp;                    % FTmpa is filled with interpolated data to 6x200.

% if 0
subplot(3,2,4)
plot(t,FTnompa(1,:),'k-',t,FTnompa(2,:),'k--',t,FTnompa(3,:),'k:','LineWidth',2),ylim([-1.5,1.5]),
set(gca,'XLim',[0,1]);%
set(gca,'XTick',[0:0.5:1]);
title('Inertia Phase-averaged in Sensor Reference (N)'),
h_legend=legend('Fx','Fy','Fz',1);
set(h_legend,'FontSize',7);
%end

%========================================================================
% Generate flapping angle theta starting from the beginning of downstroke
% And Generate angular speed

A=52*pi/180;     % flapping amplitude = 52 deg = 52*pi/180 rad.
for i=1:Fs/Ff    % T=data number in one cycle
    theta(i)=A*sin(2*pi*Ff*i/Fs+pi/2);   % theta=0 when wing is horizontal, positive: upwords; pi/2 is at up peak.
    w(i)=A*(2*pi*Ff)*cos(2*pi*Ff*i/Fs+pi/2);  % flapping angular speed
end

% interpolate theta to make its data length of 200, same as the one for rotation angle data.
x=1:length(theta);                      % 1:(theta length)
y=theta;                               % theta
xi=1:length(theta)/NF:length(theta);   % plan to interpolate theta to
1x200 data matrix
%for i=1:length(theta)  % theta
    y_interp=interp1(x,y,xi,'spline');
    % theta_temp(i,:)=y_interp;
%end
clear theta;                           % clear theta old values
theta=y_interp;                        % theta is filled with interpolated data
to 1x200.

% interpolate w to make its data length of 200, same as the one for
rotation angle data.
x2=1:length(w);                       % 1:(theta length)
y2=w;                                % theta
xi=1:length(w)/NF:length(w);         % plan to interpolate theta to 1x200 data
matrix
%for i=1:length(w)  % w
    y2_interp=interp1(x,y2,xi,'spline');
    % theta_temp(i,:)=y_interp;
%end
clear w;                               % clear theta old values
w=y2_interp;                           % w is filled with interpolated data to
1x200.

%if 0
subplot(3,2,1)
plot(t, theta*180/pi,'k-','LineWidth',2),ylim([-90, 90]),
hold on
plot(t,0,'k-','LineWidth',0.5),
set(gca,'XLim',[0,1]);
set(gca,'XTick',[0:0.5:1]);
title('Flapping Angle for All Runs (deg) ')
%end

%========================================================================
%========================================================================
% Subtract inertial force and gravity from total force in sensor
reference.

% force without the affect of inertia
%pureForce=(FTmpa-FTnompa); % force without the affect of inertial, convert to columns

G1=0.58; % weight including wing, connector between wing and sensor, part of sensor structure
%G2=0.43;
%G3=
G4=0.44;
G5=0.42;
if mod(RunNumber+2,3)==0
    G=G1;
end
if mod(RunNumber+1,3)==0
    G=G4;
end
if mod(RunNumber,3)==0
    G=G5;
end

pureForce(1,:)=FTmpa(1,:)-FTnompa(1,:).*cos(phi)+FTnompa(2,:).*sin(phi)-G*(1-cos(phi));
pureForce(2,:)=FTmpa(2,:)-FTnompa(2,:).*cos(phi)-FTnompa(1,:).*sin(phi)+G*sin(phi);
pureForce(3,:)=FTmpa(3,:)-FTnompa(3,:);

% if 0
subplot(3,2,5)
plot(t,pureForce(1,:),'k-','t',pureForce(2,:),'k--','t',pureForce(3,:),'k:','LineWidth',2),
hold on
plot(t,0,'k-','LineWidth',0.5),
ylim([-2,2]);
set(gca,'XLim',[0,1]);
set(gca,'XTick',[0:0.5:1]);
title('Force without Inertia in Sensor Reference (N)');
h_legend=legend('Fx','Fy','Fz',1);
set(h_legend,'FontSize',7);
xlabel('Nondimension Time');
%end

%========================================================================
%==
% Convert the pure force from sensor reference to ground reference.
%       P=[ cos(phi(i)).*cos(theta) sin(phi(i)).*cos(theta(i))
%         sin(theta(i)) ;
%         -sin(phi(i)) cos(theta(i))
%         0 ;
%         -cos(phi(i))*sin(theta(i)) -sin(phi(i))*sin(theta(i))
%         cos(theta(i))
%] ;
% This is the converting matrix.

for i=1:T
    P=[ cos(phi(i)).*cos(theta(i)) sin(phi(i)).*cos(theta(i))
        sin(theta(i))
        -sin(phi(i)) cos(theta(i))
        0 ;
        -cos(phi(i))*sin(theta(i)) -sin(phi(i))*sin(theta(i))
        cos(theta(i))
    ];
Force_xyz=[pureForce(1,i);pureForce(2,i);pureForce(3,i)];
Force_xyz=[fx; fy; fz] are forces in sensor reference
Force_XYZ(i,:)=(P*Force_xyz)';
Force_XYZ=[Fx Fy Fz] are forces in ground reference
end

%if 0
subplot(3,2,6)
plot(t,Force_XYZ(:,1),'k-',t, Force_XYZ(:,2),'k--',t, Force_XYZ(:,3),'k:','LineWidth',2),
hold on
plot(t,0,'k-','LineWidth',0.5),
ylim([-2,2]);
set(gca,'XLim',[0,1]);
set(gca,'XTick',[0:0.5:1]);
title('Aerodynamic Force in Ground Reference (N)'),xlabel('Nondimensional Time')
h_legend=legend('FX','FY','FZ',1);
set(h_legend,'FontSize',7);
%end

M1=55.8;  % N-mm, initial torque in My when wing1 flapping and rotating angles are both zero.
M4=34;    % N-mm, initial torque in My when wing4 flapping and rotating angles are both zero.
M5=32.4;  % N-mm, initial torque in My when wing5 flapping and rotating angles are both zero.
if mod(RunNumber+2,3)==0
    M0=M1;
end
if mod(RunNumber+1,3)==0
    M0=M4;
end
if mod(RunNumber,3)==0
    M0=M5;
end

pureTorque(1,:)=FTmpa(4,:)+FTnompa(5,:).*sin(phi)-M0.*cos(theta).*sin(phi);
pureTorque(2,:)=FTmpa(5,:)-FTnompa(5,:).*cos(phi)+M0.*cos(theta).*cos(phi);
pureTorque(3,:)=FTmpa(6,:)-FTnompa(6,:);
%if 0
figure(figureNumber+28)
subplot(3,1,2)
plot(t,pureTorque(1,:),'k-',t,pureTorque(2,:),'k--',t,pureTorque(3,:),'k','LineWidth',2),
ylim([-400,400]);
set(gca,'XLim',[0,1]);
set(gca,'XTick',[0:0.5:1]),
title('Aerodynamic Torque in Sensor Reference (N-mm)'),
h_legend=legend('Tx','Ty','Tz',1);
set(h_legend,'FontSize',7);
xlabel('Nondimension Time');
end

%========================================================================
%========================================================================

% Convert the pure Torque from sensor reference to ground reference,
origin at sensor.

    P=[  cos(phi(i)).*cos(theta(i))         sin(phi(i)).*cos(theta(i))
        -sin(phi(i))                              cos(theta(i))
        0                                          0]
    % This is the converting matrix.

for i=1:T
    P=[  cos(phi(i))*cos(theta(i))    sin(phi(i))*cos(theta(i))
        sin(theta(i))                  -cos(phi(i))
        -sin(phi(i))                              cos(phi(i))
        0                                          0]
    Torque_xyz=[pureTorque(1,i);pureTorque(2,i);pureTorque(3,i)];
    Torque_XYZ(i,:)=(P*Torque_xyz);
end

%if 0
figure(figureNumber+28)
subplot(2,2,2)
plot(t,Torque_XYZ(:,2),'k-','LineWidth',2),
hold on
plot(t,0,'k-','LineWidth',0.5),
ylim([-400,400]);
set(gca,'XLim',[0,1]);
set(gca,'XTick',[0:0.5:1]),
title('Aerodynamic Torque (Ty) in Ground Reference, Origin at Sensor (N-mm)'),
```matlab
L = 34.2; % mm, distance from sensor origin to the wing flapping axis.
Torque_XYZ(:,2) = Torque_XYZ(:,2) + L * Force_XYZ(:,1) .* cos(theta)';

Power = Torque_XYZ(:,2) .* w' / 1000; % [Watts] Power needed for producing the aerodynamic force
```

h_legend=legend('Angular Speed',1);
set(h_legend,'FontSize',7);

% if 0
subplot(2,2,4)
plot(t,Power,'k-','LineWidth',2),
hold on
plot(t,0,'k-','LineWidth',0.5),
ylim([-2,2]),
set(gca,'XLim',[0,1]);
set(gca,'XTick',[0:0.5:1]),
TITLE('Power Required in Generating Aerodynamic Forces (Nalts)'),
xlabel('Nondimension Time')
h_legend=legend('Power',1);
set(h_legend,'FontSize',7);
% end

% ===========================================================================
% ===========================================================================
% Calculate average pure Force in Ground reference

meanFX=mean(Force_XYZ(:,1));             % average of Fx in ground ref
without inertial
meanFY=mean(Force_XYZ(:,2));             % average of Fy in ground ref
without inertial
meanFZ=mean(Force_XYZ(:,3));             % average of Fz in ground ref
without inertial

% if 0
% Write meanFx meanFY and meanFz to Excel file
meanFXFYFZ=[meanFX,meanFY,meanFZ],
OutPutFileAt=strcat(mainFolder,'meanFXFYFZ',suffix1);
if TrialNumber==1;
    startingColumn=0;
else
    startingColumn=TrialNumber+3;
end
dlmwrite(OutPutFileAt,meanFXFYFZ,'-append','delimiter','\t','coffset',startingColumn);  % output to Excel as DLM file
% dlmwrite(OutPutFileAt,meanFXFYFZ,'\t');  % output to Excel as DLM file
for Matlab older version 6.5
% end

% ===========================================================================
% ===========================================================================
% Calculate average pure Torque in Ground reference

meanTX=mean(Torque_XYZ(:,1));            % average of TX in ground ref
without inertial
meanTY=mean(Torque_XYZ(:,2)); % average of TY in ground ref without inertial
meanTZ=mean(Torque_XYZ(:,3)); % average of TZ in ground ref without inertial
W=max(w);
%if 0
%Write meanFx meanFy and meanFz to Excel file
meanTXTYTZ=[meanTX,meanTY,meanTZ,W];
OutPutFileAt=strcat(mainFolder,'meanTXTYTZ',surfix1);
if TrialNumber==1;
    startingColumn=0;
else
    startingColumn=TrialNumber+3;
end
dlmwrite(OutPutFileAt,meanTXTYTZ,'-append','delimiter','\t','coffset',startingColumn); % output to Excel as DLM file
% dlmwrite(OutPutFileAt,meanFXFYFZ,'\t'); % output to Excel as DLM file for Matlab older version 6.5
%end

meanFr=sqrt(meanFX^2+meanFY^2); % resultant aerodynamic force
beta=atan2(meanFY,meanFX)*180/pi; % viewed from wing tip to root: North= 0 deg. West= 90 deg. East= -90 deg.
meanPower=mean(Power); % mean power calculation
powerEconomy=meanFr/abs(meanPower); % mean Power Economy
peakLift=max(abs(Force_XYZ(:,1)-meanFX)); % Peak Lift Magnitude in Groud reference
peakThrust=max(abs(Force_XYZ(:,2)-meanFY)); % Peak Thrust Magnitude in Groud reference

Results=[meanFX,meanFY,meanFr,beta,meanPower,powerEconomy,meanTY];
OutPutFileAt2=strcat(mainFolder,'Results',surfix1);
dlmwrite(OutPutFileAt2,Results,'-append','delimiter','\t'); % output to Excel as DLM file
% dlmwrite(OutPutFileAt2,Results,'\t'); % output to Excel as DLM file for Matlab older version 6.5

clear F* T* m*%Clear all F* T* variables
clear
clear all
Results=dlmread('E:\Experiment Files\Experiment Final 2009\Results.txt','\t');

%if 0
peakFn=abs(Results(:,3)-mean(Results(:,3))); % Peak Resultant force Magnitude in Groud reference
figure(60)
subplot(3,2,1)
stem(Results(:,3),Results(:,4),'k-','LineWidth',2), % resultant force and its angle. North is 0 deg; West is 90 deg; Viewed from wing tip to root.
title('Resultant Force and Direction'),
subplot(3,2,2)
stem(1:27,peakFn,'k-','LineWidth',2), % resultant force and its angle. North is 0 deg; West is 90 deg; Viewed from wing tip to root.
title('Peak Resultant Force Magnitude (N)'),
xlim([0,28]),

subplot(3,2,3)
stem(1:27,Results(:,5),'k-','LineWidth',2), % mean power
title('Mean Power (mW)'),
xlim([0,28]),

subplot(3,2,4)
stem(1:27,Results(:,6),'k-','LineWidth',2), %power economy
title('Power Economy (N/mW)'),
xlim([0,28]),
subplot(3,2,5)
stem(1:27,Results(:,7),'k-','LineWidth',2), %mean MY
title('mean MY Nmm'),
xlim([0,28]),
xlabel('27 Runs with Full Factorial of 3 Factors and 3 Levels ')
if 0
subplot(3,2,6)
stem(1:27,Results(:,8),'k-','LineWidth',2), %peakThrust
title('Peak Thrust Magnitude (N)'),
xlim([0,28]),
xlabel('27 Full Factorial Runs with 3 Factors and 3 Levels ')
end

end
Appendix B:

Force Evolution Graphs
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=1

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number =1.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=2

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number = 2.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=3

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=3

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number =3.
Force evolution graph, Run number = 4.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=5

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number =5.
Force evolution graph, Run number =6.
Force evolution graph, Run number = 7.
Force evolution graph, Run number = 8.
Force evolution graph, Run number = 9.
Force evolution graph, Run number =10.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=11

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number = 11.
Force evolution graph, Run number =12.
Force evolution graph, Run number =13.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=14

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number =14.
Force evolution graph, Run number =15.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=16

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number =16.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=17

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number =17.
Force evolution graph, Run number = 18.
Force evolution graph, Run number =19.
Force evolution graph, Run number = 20.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=21

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number =21.
Flapping Angle for All Runs (deg)

Rotation Angle (deg), RunNumber=22

Force Phase-averaged in Sensor Reference (N)

Inertia Phase-averaged in Sensor Reference (N)

Force without Inertia in Sensor Reference (N)

Aerodynamic Force in Ground Reference (N)

Force evolution graph, Run number = 22.
Force evolution graph, Run number = 23.
Force evolution graph, Run number = 24.
Force evolution graph, Run number = 25.
Force evolution graph, Run number =26.
Force evolution graph, Run number = 27.
Appendix C

Power Evolution Graphs
Power evolution graph, Run number =1.
Power evolution graph, Run number =2.
Power evolution graph, Run number = 3.
Power evolution graph, Run number = 4.
Power evolution graph, Run number =5.
Aerodynamic Torque (Ty) in Ground Reference, Origin at Sensor (N-mm)

Angular Speed of Wing Flapping (rad/sec), RunNumber=6

Aerodynamic Torque (TY) in Ground Reference, Origin at Flapping Axis (N-mm)

Power Required in Generating Aerodynamic Forces (Watts)

Power evolution graph, Run number =6.
Power evolution graph, Run number = 7.
Power evolution graph, Run number = 8.
Power evolution graph, Run number =9.
Angular Speed of Wing Flapping (rad/sec), RunNumber=10

Aerodynamic Torque (Ty) in Ground Reference, Origin at Sensor (N-mm)

Aerodynamic Torque (TY) in Ground Reference, Origin at Flapping Axis (N-mm)

Power Required in Generating Aerodynamic Forces (Watts)

Power evolution graph, Run number =10.
Aerodynamic Torque (Ty) in Ground Reference, Origin at Sensor (N-mm)

Angular Speed of Wing Flapping (rad/sec), RunNumber=11

Aerodynamic Torque (TY) in Ground Reference, Origin at Flapping Axis (N-mm)

Power Required in Generating Aerodynamic Forces (Walts)

Power evolution graph, Run number =11.
Power evolution graph, Run number =12.
Power evolution graph, Run number =13.
Aerodynamic Torque (Ty) in Ground Reference, Origin at Sensor (N-mm)

Angular Speed of Wing Flapping (rad/sec), RunNumber=14

Aerodynamic Torque (TY) in Ground Reference, Origin at Flapping Axis (N-mm)

Power Required in Generating Aerodynamic Forces (Watts)

Nondimension Time

Power evolution graph, Run number =14.
Power evolution graph, Run number =15.
Power evolution graph, Run number = 16.
Angular Speed of Wing Flapping (rad/sec), RunNumber=17

Aerodynamic Torque (Ty) in Ground Reference, Origin at Sensor (N-mm)

Aerodynamic Torque (TY) in Ground Reference, Origin at Flapping Axis (N-mm)

Power Required in Generating Aerodynamic Forces (Watts)

Power evolution graph, Run number =17.
Power evolution graph, Run number =18.
Power evolution graph, Run number = 19.
Power evolution graph, Run number = 20.
Power evolution graph, Run number = 21.
Power evolution graph, Run number = 22.
Power evolution graph, Run number = 23.
Power evolution graph, Run number = 24.
Power evolution graph, Run number = 25.
Power evolution graph, Run number = 26.
Power evolution graph, Run number = 27.