DESIGN OF FLAPPING MECHANISM AND ANALYSIS ON THE LIFT FORCE OF THE WINGS

SAKTISHVIKMEND A/L ANBALAGAN

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2019

DESIGN OF FLAPPING MECHANISM AND ANALYSIS ON THE LIFT FORCE OF THE WINGS

SAKTISHVIKMEND A/L ANBALAGAN

RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2019

UNIVERSITY OF MALAYA
ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Saktishvikmend Anbalagan

Matric No: KQK160030

Name of Degree: Masters of Mechanical Engineering

Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"): DESIGN OF FLAPPING MECHANISM AND ANALYSIS ON THE LIFT FORCE OF THE WINGS

Field of Study: Flapping Unmanned Air Vehicle

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date:

Subscribed and solemnly declared before,

Witness's Signature Date:

Name:

Designation:

ABSTRACT

Development of flapping unmanned air vehicle (FUAV) has been of interest in the aerospace community with ongoing research. Most of the previous research were done on pitching and plunging motion of the FUAV. With pitching and flapping motion of FUAV, researchers usually study it by experiment such as wing tunnel. A few works were reported by numerical calculation.

In this paper, a flapping wing mechanism was developed and the capabilities of flapping was analyzed. A mechanical based mechanism is designed for the flapping motion. Three different shapes of wings were used in this project. Preliminary analysis has been done on the wings. Numerical analysis and structural analyses has been done on the mechanisms.

The model was designed in Solid Works. The mechanism uses gear and metal rods, shaft, spars, and a DC motor to drive the gear. The complete wing span used in the project is about 110 mm. Analyses were done based on Solid Works simulation analysis. This research is helpful to understand the flight mechanism of birds, thus improving the design of FUAV simulating birds.

ABSTRAK

Kenderaan udara sayap mengapung adalah penyelidikan yang berterusan dalam kalangan aeroangkasa untuk menguasai risalah semulajadi dengan banyak cara yang berbeza. Kebanyakan risalah yang dilakukan oleh penyedik adalah tentang gerakan angkat dan tujah oleh kenderaan mengepak udara tanpa manusia. Untuk pelajaran tentang angkat dan tujah, banyak penyelidikan diadakan melalui eksperimen seperti terowong udara dan kerja pengiraan adalah sedikit.

Tujuan projek ini adalah untuk membangun dan menguji keupayaan mekanisme sayap mengepak. Dalam ornithopter projek ini digunakan. Mekanisme berasaskan mekanikal direka untuk gerakan mengepak. Tiga sayap yang berbentuk lain antara satu sama lain digunakan. Analisis awal telah dilakukan pada sayap. Ciri-ciri prestasi aerodinamik dilakukan berdasarkan analisis berangka dan analisis struktur.

Model ini direka bentuk dalam Solid Works. Mekanisme itu menggunakan rod gear, serat besi, syaf dan DC motor untuk memacu sayap mengepak. Jangkauan sayap lengkap digunakan dalam projek itu adalah kira-kira 110 mm. Analisis dilakukan berdasarkan analisis simulasi Solid Works. Penyelidikan ini harap membantu memahami mekanisma menyepak, dan meningkatkan reka bentuk yang dipelajari dari simulasi burung.

ACKNOWLEDGEMENTS

I wish to express my profound appreciation and gratitude to Associate Prof. Dr. Poo Balan A/l Ganesan for suggesting the problems and providing generous assistance. His excellent guidance and knowledge sharing has made completion of this project work possible by providing profitable discussions.

I also wish to express my sincere gratitude to the mechanical department for providing necessary facilities for smooth completion of this project work.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

g	:	Grams
cm	:	Centimeters
cms	:	Centimeters square
m	:	Meters
Kg	:	Kilograms
CD	:	Coefficient of Drag
CL	:	Coefficient of Lift
T	:	Thrust
L	:	Lift
n	:	Flapping frequency
HIPS	:	High Impact Polystyrene
ABS	:	Acrylonitrile Butadiene Styrene
AR	:	Aspect Ratio
FUAV	:	Flapping Unmanned Air Vehicle
Hz	:	Hertz
MAV	:	Micro Air Vehicle

CHAPTER 1: INTRODUCTION

1.1 Background Study

Generally, nearly all airborne missions have been deployed with costly, large, and high-performance manned aircraft. Swiftly progressing technology and the aim to make things smaller, lighter, faster, and efficient have become the core points of all researches and experiments done recently. A flapping unmanned air vehicle (FUAV) is a conceptual aircraft that mimics the flapping mode of birds and insects. Micro Air Vehicle (MAV) is the pioneer name for many air vehicles whereby all MAVs are unmanned air vehicle (Tsai & Fu, 2009). Figure 1.1 below shows an example of a micro air vehicle.

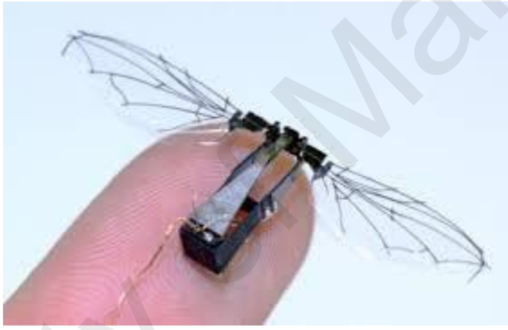
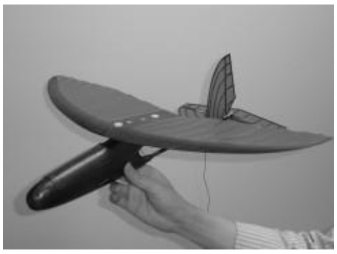


Figure 1.1: Micro Air Vehicle

Mankind is inspired by admiring the elements of the nature itself to create these agile robotic fliers. These fliers can solve or ease complex human tasks. Numerous missions has been accomplished utilizing MAVs especially in military surveillance and reconnaissance operations. Absence of the pilot on board favors this air vehicle to sustain higher g-loading and g-forces. Tactical aircraft's performance is limited by human physiology and it becomes heavier by carrying life support systems, pilot controls, ejection seat, and other hardware components (Kinkaid, 2006). The use of FUAV has become favorable due to few reasons. The air vehicle can be controlled by a ground control station such as a remote control. Reduced size requires less logistical support, thus cheaper. Advancement in technology in a certain fields including aerodynamics, micro-electronics, micro-electromechanical systems, and micro-manufacturing, is making it possible for the affordable and possible development. Tracking, targeting, and creation of small payloads are the few mission for could be useful in the future (Svanberg, 2008).

Flapping flight has the potential to benefit unmanned air vehicle technology as it provide improved aerodynamic performance over that of flight using conventional wings or rotors (George, 2011; Shyy et al., 2008). Fixed wing, rotary wing, and flapping wing MAVs are the main types of MAVs created by researches in recent years (Chen et al., 2016). All researches are done based on these trio. Table 1.1 below shows the three categories of MAVs.

Table 1.1: Types of MAVs

Category	Examples
Rotary wing	
Fixed wing	
Flapping wing	

Flapping wing air vehicle is also known as ornithopter which closely replicates the flying dynamics of a bird. This is because FUAV uses flapping as its primary source of lift and thrust (Parker & Borbone, 2010). Recent researches have revealed unknown unsteady aerodynamics mechanism of flapping wing. These incorporate the fling and clap, rotational lift, vortex generation, and wing-wing interaction components, which offer assistance clarify the essential principles of unsteady force generation in flight (Yu, Kim, & Zhao, 2014). These mechanism deliver the required kinematics at the fetched of complexity and weight. Be that as it may, the wing movement of natural characteristic fliers is a result of vibrant excitation of their aero-elastically made-to-order structure of the wing. However, these mechanism use piezoelectric actuators. This component expand and contract when electrical charges on flowed in it. This will require bulky control power. Moreover, these researches assume aerodynamic damping and linear spring stiffness. Many researchers have attempted to examine the springs to bring down the peak torques and power amid the flapping loop. However piezoelectric is not used in this project.

Due to the instinctive small scale of a FUAV, there are numerous innovative obstacles to be faced. FUAV will work at such a low Reynolds number and that cause flow field distribution to be of crucial significance. In conjunction with streamlined issues, researchers will need to overcome the sophisticated wing kinematics, volume and also weight limitations for control supplies and actuators, big value of power-to-weight proportion prerequisites, and the capacity to function in a broad range of conditions (Svanberg, 2008). There has been no such FUAV that imitates the storing of this versatile vitality. Due to trouble in putting away the flexible vitality, most FUAV have restricted flight continuance.

1.2 Problem statement

Most of the flapping unmanned air vehicles works only if there is an initial velocity. A model that takes off from zero velocity is yet to be designed. A normal flapping mechanism does not consider lifting off from its initial position with zero initial velocity.

The additional challenges include shape of the wings, the mechanism itself, and reducing the frictional parts. Therefore a simple or less parts needed to be used to reduce friction and wing spar designed in a way that creates more lift. The aim of this research is to manufacture and examine a flapping-wing model in arrange to gather information which can in the long run be improvised by other researches. In arrange to achieve these objectives, testing strategies required to be created that were able of computing the greatly fluctuating strengths related with a wing that flaps. The primary step was to sketch, plan and construct a fluttering instrument to imitate the characteristics of a bird. A model was planned and designed utilizing Solid Works and printed on a 3D printing machine. Different shapes of wings were designed to study on lift force stress and strain.

1.3 Objectives

The main objectives of the project are:

1. Investigate lift and thrust forces acting on flapping unmanned air vehicle with different wing shapes.
2. Analyze stress and strain analysis on hinge joint of the spars to the body.
3. Develop model of flapping wings of an unmanned air vehicle.

1.4 Thesis outline

There are five chapters in this report. Chapter 1 deals with the introduction of the flapping wing unmanned air vehicle. Literature review will be the second chapter of the project. The methodology of the FUAV including the designing and fabrication of the parts, steps of the analysis, and the calculation on the lift force are discussed in chapter 3. Chapter 4 is the result and discussion on the methodology used for the product development. Chapter 5 concludes the project report on the flapping wing unmanned air vehicle.

CHAPTER 2: **LITERATURE REVIEW**

2.1 Flapping air vehicle

All flying creatures of nature fly by fluttering their wings. Based on an investigation, flapping-wing flight is demonstrated to epitomize more points of interest than both fixed-wing flight and rotary-wing flight. These focal points conclude higher streamlined proficiency, greater load, high maneuver landing, higher elevation and medium speed (Liang, Cui, & Zhang, 2011). Numerous of the long-term goals will more likely need the capacity and capability of the air vehicle to stay moderately stationary, or remain in one place in the air, for any length of time. There are two essential ways for accomplishing hovering ability on a small scale. These ways are attained by either rotating or flapping the wings whereby fixed wing aircrafts does not comprehend this ability yet. On the other note, there is one prompting factor for flapping-wing mechanism to adapt this ability is that creatures depend on the same rule to achieve hovering flight in nature (Svanberg, 2008).

Scaling effect is found by using Reynolds number, a non-dimensional number which is very much incorporated with the research of ornithopters. It is suitable for flying insect models which are expected to perform exploring and monitoring to weigh less than 50g and span less than 25cm. This models are considered small-size micro aerial vehicles (Shyy et al., 2008). The Reynolds number for this modes is normally lower than 20,000 and there is an unsteady aerodynamic model often deployed (Muller, 2001). Ornithopters that are mid-sized which has a span larger than 30cm but less than 2m also have been researched for its system dynamics, movement control and aerodynamics (Grauer & Jr., 2009). A quasi-steady streamlined model is regularly utilized for middle size ornithopters and its Reynolds number is around 75,000 to 200,000. The requirement for MAVs are dimensions less than 15-20 cm with takeoff weights of less than 200g and flight speed of

10-15 m/s and also low Reynolds number (10,000-100,000) regime (Sai, et al., 2016). The bird mimicked air vehicle flaps at a frequency of about 7 to 14 Hz and with a small flapping angle range. This type of wing mechanism have a great payload and wider flying area and high cruise speed. In spite of the fact that the mid-size flights have the ability to hover, they cannot perform hovering in the air because to their quasi-steady aerodynamics (Chen et al., 2016).

The research on flapping wing micro air vehicle has been going on for a lot of years. But producing a fully functioning model has been achieved on the recent years. There are different modes of flight achieved by different researchers. There are many mechanisms that came in place but there are only a few functional mechanisms. There are different types of mechanism such as piezoelectric, fully mechanical, mechanical and electronics combined. This project focuses on fully mechanical.

2.2 Flapping flight aerodynamics

Flapping flight may give improved aerodynamic performance compared to conventional rotors and wings, thus it is considered to benefit MAV technology. There are two distinct lift-generating mechanisms, Clap-and-fling and Leading-Edge Vortex (LEV) that have been distinguished in nature that hold promise for air vehicle design. The clap-and-fling mechanism as the name says it, has dual wings which are clapped together and fling apart, creating a zone that is in low pressure between the wings (Phan, Au, & Park, 2018). There are two phases consisted in clap and fling mechanism, which are:

1. the leading edges of both wings are clapped together at the end of the upstroke and
2. the wings rotate around their trailing edges, thus flinging apart.

Figure 2.1 below illustrates clearly the two phases of clap-and-cling mechanism. Larger animals uses this method to flap, and study says a pigeon uses this mechanism when it wants to take-off. That is the reason for a sound that is created when the pigeon "claps" its wings together (Shyy et al., 2008).

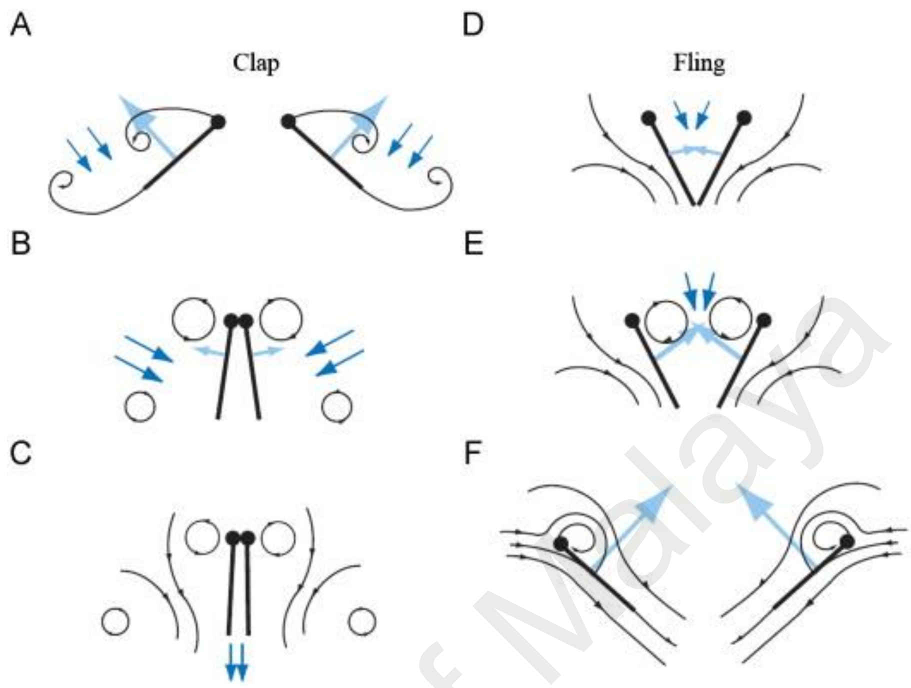


Figure 2.1: (a), (b), and (c) Clap condition and (d), (e), and (f) Fling condition

In the midst of the "fling" stage, or also known as the down stroke, the air streams that surrounds the leading edge of both wings makes a bound vortex on each wing that eventually acts as the starting vortex for the opposite wing. This grants a quick creation of circulation and an increase and improve total generation of lift (Miller & Peskin, 2009).

Leading-edge-vortex is created on wings with average aspect ratio, low Reynolds number and steadily revolving at high angles of attack (Nabawy & Crowther, 2017). Over the wide run of flight conditions of natural fliers and aircraft, an LEV's stability and capacity to expand lift depend on various factors. These variables regularly apply over the range, giving the potential for comparison, as well as kinematics, angle of attack, and wing shape (Muir & Viola, 2017). A LEV that creates on a flapping wing, as a result of an increase in angle between the wing and the oncoming air, develops in size and strength until it in the long run sheds from the wing with a loss of lift. In animals, the LEVs that create during a down stroke remains joined to the wing and do not shed until the end of the down stroke (Azuma et al., 1984). Clap-and-fling and leading-edge-vortex are the basis for augmented lift and thrust generation in flapping mechanisms. Figure 2.2 below shows the LEV mechanism.

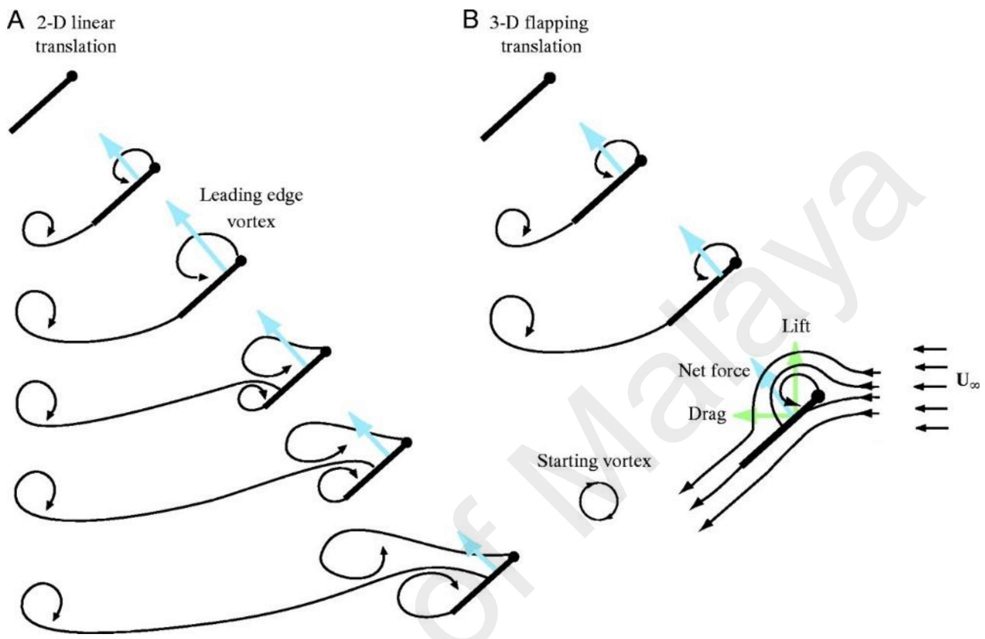


Figure 2.2: (a) 2-D linear translation and (b) 3-D flapping translation

The analysis of the flight dynamics of specific insect species were the initial studies of dynamics and stability of insect flight. (Taylor, Nudds, & Thomas, 2003) were the first one to do the analysis. The dynamics of desert locust schistocera gregoria were studied by (Taylor, Nudds, & Thomas, 2003). The mass of the wings were not taken into account because it is assumed that the wing beat is not fast enough to excite the rigid body.

The central body has the inertial and mass effects of the wings and by extension, the entire system. Different types of models do not consider the effects of inertia of the mass of the wing. A small perturbation theory can be extensively developed which includes the linearized model. This is used in the standard aircraft equations of motion (Reid & Etkin, 1996). The FMAV in hover condition are used to simulate the wing dimension from the mathematical; model and a robotic flapper. Control research conducts the standard aircraft flapping wing flight dynamics. For example, (Han, Lee, & Kim, 2008) developed the flight dynamics model for altitude control to incorporate in an ornithopter.

In (Sun & Xiong, 2005), also used the approximation method on the same rigid body for bumblebee hovering flight stability. The required data was obtained using the computational fluid dynamics. The moments and aerodynamic forces are cycle-averaged. Thus, determining the equilibrium condition of flight near the hover condition, the resultant forces for one flapping cycle is used.in loop setting the destabilization of longitudinal axis performed with the help of the aerodynamic pitching moment. The longitudinal axis in loop setting destabilizes the aerodynamic pitching moment. The phasing between the flapping motion and pitching should be exact otherwise the pitching moments of the wings will be enhanced to destabilizing effects.

Insects, birds and fist use a mode of locomotion for the flapping motion. The interaction between the flapping wings or tails in their surroundings generates lift and thrust. Leonardo da Vinci designed many types of ornithopters based on the bird flight which was inspired by the mist in the 1500s. The flapping wing is the most unsteady nature of flows, due to which the subject was difficult to achieve (Wang Z. J., 2000). Strouhal number is a non-dimensional quantity that is maintained by the natural flyer's in a range of 0.2 to 0.4. 'The propulsive efficiency which is defines as the ratio of the power produced by the wing to the power required to flap.' The Strouhal number range is maximized when the value of the thrust is also considered (Schouveiler, Hover, & Triantafyllou, 2005).

2.3 Flapping mechanism design

Although flapping wing mechanism in vital for furnishing a test bed for force analysis and wing kinematic optimization, it is more complicated than conventional wings such as fixed wings. This is because of the maneuverability of structure is high and thus the unsteady fluid dynamics are being created (Azuma et al., 1984). It is considered conventional planes are very simple due to its fixed wing. Lift is produced due to the forward motion relative to the air. Comparing to biological flight, it has to twist or flaps up and down, plunge, and sweep to produce lift. The wings needed to be flapped systematically so that enough force is generated to produce lift (Liang, Cui, & Zhang, 2011). Nevertheless, if the wings are stretched open and not flapping, the wings are actively generating only lift, not thrust. In order to maintain leveled flight, an air vehicle need to produce both lift and thrust to equalize the upward and horizontal forces, which are the gravity and drag respectively (Fenelon & Furukawa, 2010). For experiments on insects, the most favorite research subject would be the dragonfly due to its peculiar eight-figure flapping motion, forward flight, hovering, and wing profile (Abas, Rafie, Yusoff, & Ahmad, 2015).

2.3.1 Kinematics of wings

There are three basic flapping wing motion of wing with respect to axis based on the kinematic of motion (Sai, et al., 2016). They are:

- → *flapping,* as discussed earlier, the up and down plunging motion of the wing
- → *feathering,* pitching motion of the wing which varies along the span
- → *lead-lag,* which is in-plane lateral movement of the wing

The three flapping motions direction are shown in Figure 2.3 below.

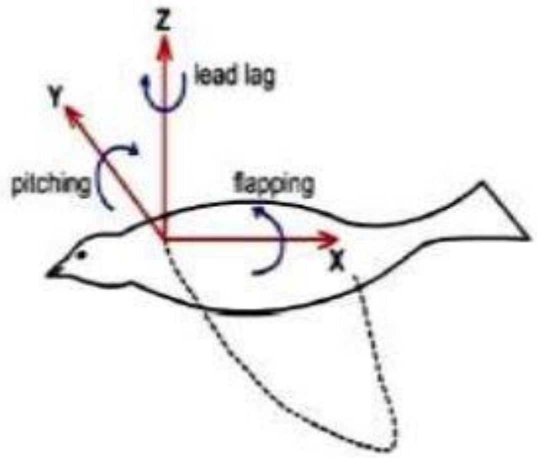


Figure 2.3: Ornithopter kinematics

When ornithopter which is also known as bird flight, flaps, the upstroke and down stroke both supplies thrust as well as develop lift to the flight. The wing is slightly bended inwards to diminish upward resistance. Ornithopters are brilliant in changing angle of attack between down stroke and upstroke. The angle of attack (AOA) increases during down stoke while upstroke it decreases (Wang Q. , 2017). Ornithopters has 2 degree-of-freedom (DOF). The ultimate is the main flapping motion, whereas the next is the small deviation from the stroke plane (Orlowski C. T., 2011). Comparing to flight of insects which has 3 DOF, the active rotation of the wing is substituted by passive wing rotation, which is produced by the mass inertial force during fluttering (Whitney & Wood, 2010). This reduction in DOF make it easier to understand the kinematics of ornithopter flying method. Birds flights is also accompanied with corresponding movement types of rotation and distortion. Moreover, wings that flaps up and down produces lift coefficient that is different thus contributes on adding the total lift (Liang, Cui, & Zhang, 2011). Figure 2.4 shows the direction of thrust and lift of flapping wing vehicle.

The aerodynamics of the flapping wing is characterized by the unsteady aerodynamics. Small birds and insects are less unsteady when compared to the large birds with slow flapping rate. The unsteady effect is created by the bound and trailing vortices, as the viscous flow regime increases it gets harder to produce vortices and thus a hard work for birds. Lift like clap and fling mechanism, rapid pitch up, wake capture and delayed stall are unsteady mechanisms used by the insects and other small birds to enhance their lift.

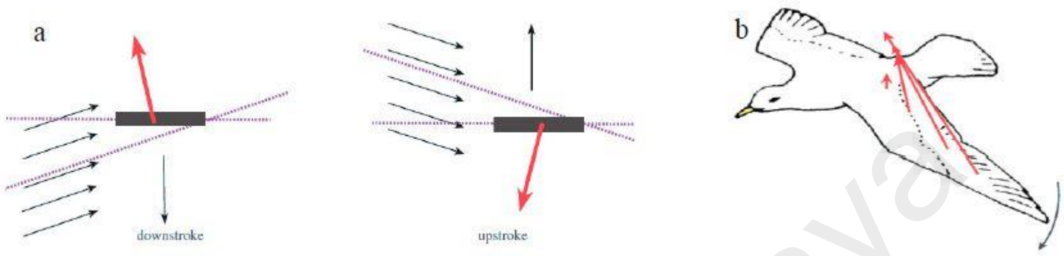


Figure 2.4: (a) flapping wing thrust and (b) flapping wing lift at down stroke

For a long time mankind has been engross with flight of natural animals. Researchers look for replication or mimicking what birds can do naturally. For an example, Airbus A380 was designed by studying the wings of a peregrine falcon. It has wings that change into a most aerodynamics shape (Sunderland, 2017). In-flight performance of a bird is vital in understanding the morphology of birds. This research only takes small birds as consideration. Due to adaptation to nature, wing of a small birds differ. Geometry analysis shows this relation (Singh, 2014). Figure 2.5 below shows different types of wings and wingtips.

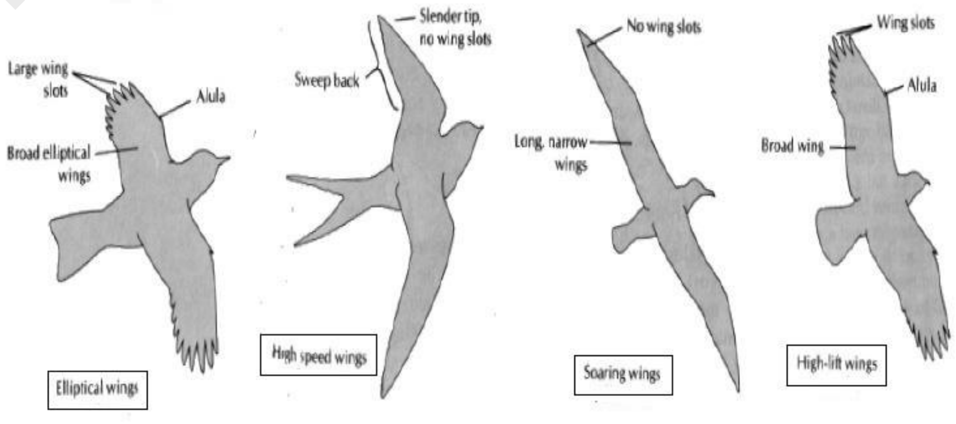


Figure 2.5: Various wing shapes of birds

Table 2.1 below shows purposes of different type of wings. This research shows studies on long and broad wing with slots.

Table 2.1: Purpose of different wing types

No	Type Of Wings	Purpose
1	Broad	Efficient power (soaring)
2	Long	Efficient lift (gliding)
3	Pointed	Reduced drag, speedy flight
4	Rounded or elliptical	Better maneuverability
5	Tapered	Extreme high speed

2.3.2 Aspect ratio and wing loading

The shape of the wing can be defined in terms of aspect ratio (AR). The ratio of the span to the mean chord of a wing is called aspect ratio. It is a factor that researches need to include into consideration because it affects the lift and drag created by the wing. An aircraft wing is said to have high aspect ratio when it has long narrow wings, whereas an aircraft with short and wide wing has a low aspect ratio (Kermode, 2006). Furthermore wings with high aspect ratio generate higher lift with induced drag which is low (George & Thomson, 2011). In aerodynamics, the aspect ratio is described as the square of wing span divided by the area of wing as given by AR= b^2/A. Here, AR is the aspect ratio, b is the wing span, and A is the area of the wing. High moment of inertia must be overcome by the high aspect ratio wing. In other case, (Sai, et al., 2016) in their research, assumed that the aspect ratio coefficient is 4 for a weight of 20 grams. And the positive angle of attack of the wing is 2^{o}.

However aspect ratio is considered useless if wing loading parameter is unknown (Singh, 2014). Therefore, the wing loading is described as the ratio of weight to the area of both wings as given by WL= mass/wing area. An air vehicle needs large wing loading to fly. Comparably, lower loading of wing reduces energy consumption, which means lower minimum velocity at which the flight is possible. Thus, flight take-off and landing distance are affected by wing loading. Thin and long wing has higher aspect ratio but it also causes high bending moment when in flight. Thus stronger material is needed to strengthen the wing (Cutler, 2015). They also might have torsion, which is undesirable in some applications.

2.4 Lift generation

It is advisable to understand the lift generation during the flapping cycle for flapping wing flight. As discussed earlier, upstroke and down stroke happen during one cycle of flap. Let's say the wing starts at the down stroke, where wing is in maximum height, the lift starts to increase. Then the middle of the stroke is where the aerodynamics force peaks. Third is when the lift force starts to decrease at the end of the down stroke. Finally when upstroke starts, the wing travels upwards where aerodynamic forces produces negative lift. Figure below shows a diagram to understand the cycle.

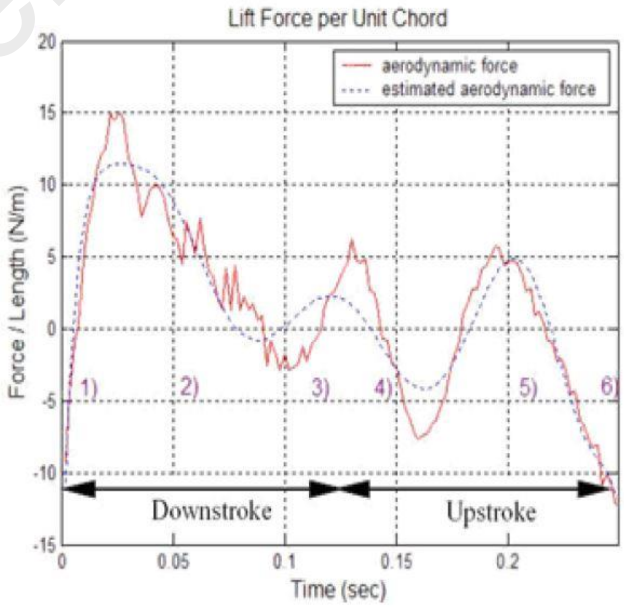


Figure 2.6: Unit Force versus time for up and down stokes

2.5 Thrust generation

Researches mentioned that to generate thrust, insects make use of unsteady aerodynamics phenomena. Thrust generation can be divided into four parts. Firstly, the down stroke where the wings translates fixed collective pitch angle, then at the end of down stroke, the wing bend so that AOA is positive, thirdly at the upstroke the AOA is positive. Lastly, the end of upstroke, where the AOA converts from positive to negative.

The phase of flapping airfoil plays important role in lift and thrust generation. An experiment was done by (Singh, 2014), which explains thrust generation in flapping wing. Figure below shows the results of the test. A wing was labelled at 18°, then proceeds to perform on complete flap or cycle by returning to its original position. The study shows that thrust is always being generated, however positive lift forces happens during down stroke. Figure 2.7 below shows the thrust that is produced while wing flaps.

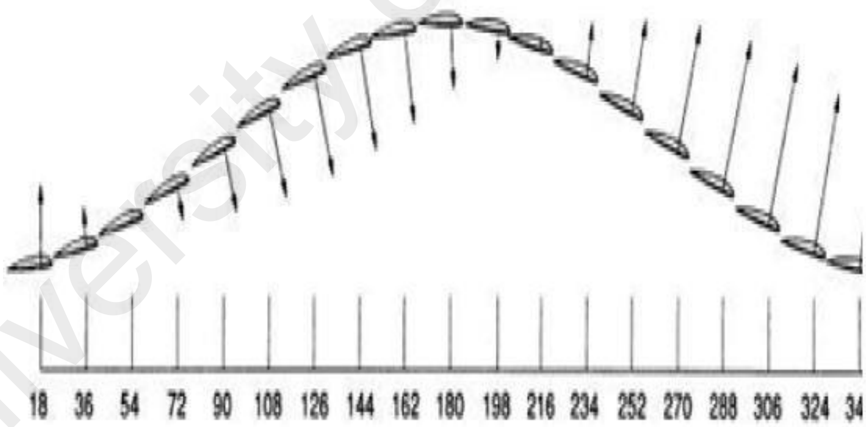


Figure 2.7: Thrust generation in flapping wing flight in one cycle

Every action has its opposite and equal reaction. The same applies to this phenomena whereby when there is thrust, there is drag. Thrust is forward force whereas drag is the opposing force. In other words, drag can be said as the aerodynamic force that oppose the velocity of an object moving through air (or any fluid). The unique part of drag is it comes in various forms. One of them being friction drag that is the result of the friction that is developed when surface of moving vehicle against molecule of the air. An aircraft wing with a smooth surface produce less skin friction compared to a rough one (Hedenstrom & Liechti, 2001). Rivets on aircrafts wings can produce skin frictions. An effective force is created when air flows around a body which change the local velocity and pressure. Figure below indicates the forces that play important roles on an air vehicle.

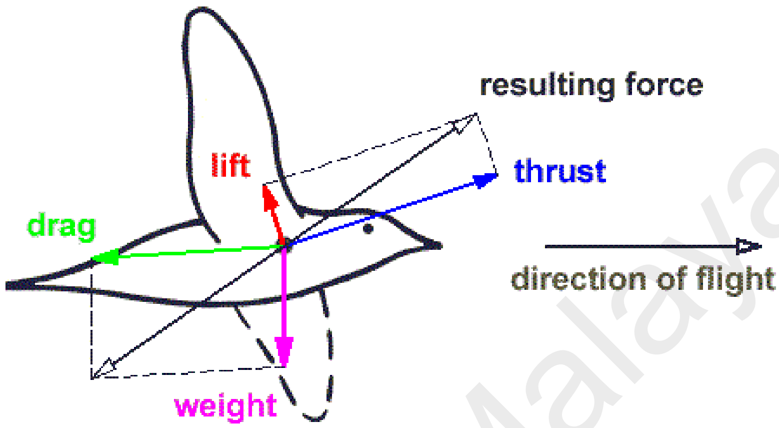


Figure 2.8: Multiple forces act on an air vehicle

2.6 Related works

An aerodynamic model for semi-elliptical wing was developed by (Malik & Ahmad, 2010) based on blade elemental analysis. Thorough study has been done to show the consequence of various parameters on lift, thrust and drag forces to understand ornithopters flight better. It was said that there are many possibilities of different inputs and obtaining different form of results. Furthermore, there are four points that has been concluded by doing this research (Ryan, 2012). Firstly the lift is influenced by incidence angle and forward speed, then the thrust is affected by flapping frequency and forward speed. Third is the drag force elevates in forward speed, flapping frequency, and incidence angle. Lastly increase in flapping angel, the total force increases.

Natural bird make complicated maneuvers that are out of reach by FUAVs of comparable size. This capability is partly elated to the efficient flapping mechanism. A research was done that describes the flapping kinematics of bird-sized UAV relying on advanced kinematics analysis (Grand, Mouret, Martimelli, & Doncieux, 2008). It was mentioned that morphological and kinematical data have been used to wisely dimension a flapping mechanism. According to this model, a simple control rule for quasi-sinusoidal motions has been developed (Margerie, Mouret, Ravasi, Martinelli, & Grand, 2007).

All classes of MAV can operate outdoors and are believed to the same natural influences that keep birds and insects from flying efficiently whenever periods of high winds or thunder storms, the capacity of flapping wing FUAVs to securely arrange tight quarters is based on lift mechanism advanced which allow slow controlled flight over the surface of the wing. The reason that a flapping wing is more survivable than a rotor is that at either end of the flapping stroke, to its maximum at mid stroke its energy is dispensed over a wider chord and oscillates from a minimum of zero thrust and lift. Maneuverability derives from the flapping-wing's differential kinematics, which can vary in fluttering speed, point of assault, span, or cycle excursion (Michelson, 2010).

Folding wings are vital for birds because from a static position birds do not have the airstream flowing on the wings, thus lift must be augmented. Therefore birds fold their wings inwards during the upstroke, meanwhile re-extend wings during down stroke. The birds can get airborne by using this method during lift, then transition to standard flight (Gerdes, Gupta, & Wilkerson, 2012). In an experiment done, the researchers described a flying MAV which uses wing one-way compliance to obtain the folding effect (Thipyopas & Intaratep, 2011). The results shows that with slower forward speed the wings can lift the similar weight. There were other authors also tried similar style of wings in their report, resulting in augmented lift generation in non-moving air (Billingsley, Slipher, Grauer, & Hubbard, 2009; Wissa, Tummala, & J. E. Hubbard, 2012). Extreme amount of folding utilized by the wing disturbed the balance of forces in flight, thus flight was not achieved.

There a study done on stability during ornithopter in midair (Phan, et al., 2012). Most air vehicle use control system and actuations to regain stability in airborne which need multiple expertise. On the other hand, there were other authors who developed design that focuses on transition flight such as take-off and landing (Shyy et al., 2008; Bachmann, Frank J. Boria, Ifju, & Quinn, 2007). However none of those designs applied flapping wing mechanism. There are limited experiments on small scale ornithopters. Researchers are focused on large sized or insect-type (Pfeiffer, Lee, Han, & Baier, 2010).

In ornithopters, flow control and wing shape morphing are a bit tough to obtain. This would need much complicated multi-actuator design and multi-spar which is heavy and not reliable (C. & R., 2007). Mechanism with one hinge are normally not effective, because it increase the gliding ratio along restricted ability to climb. DeLaurier's design can be considered the most advanced mechanism because during flapping, the wing allows wing incidence variation and wing morphing. This produces a decent rate of climb, but the wing structure is very complicated (DeLaurier, 1999).

It was mentioned that fixed wing UAV is best developed and exhibit excellent forward flight capabilities as well as steady level flight. It has power loading in order of 13kg/kW. The Figure 2.9 below shows the power needed for UAV built in wing shape of delta with weight of 0.25kg and 0.45m span (C. & R., 2007). Figure 2.10 shows a fixed wing air vehicle.

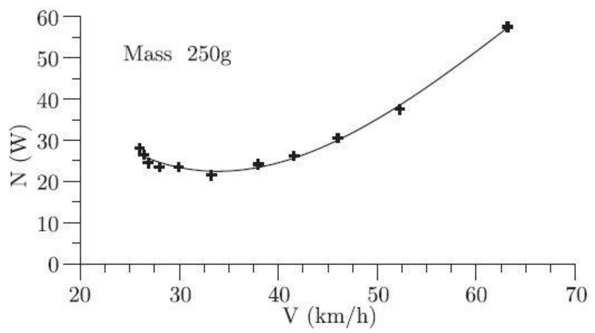


Figure 2.9: Power needed for flight of 250g fixed wing UAV

Figure 2.10: Design of fixed wing UAV

Rotary wing UAV on the other hand, are not particularly efficient similar to their larger originals. The smallest, lightest and advanced robot, Micro Flying Robot (μFR) developed by Seiko Epson is capable to fly controllably only for 3 minutes. Even though the propulsion efficiency doubled, the UAV will not fly more than 20 minutes. This configuration are capable to merge high and low speed feature counting in hovering as well (C. & R., 2007). A possible design of rotary wing unmanned air vehicle is as shown below in Figure 2.11.

Figure 2.11: Rotary wing UAV

2.7 Wing Structure

Commonly researchers are experimenting on flapping unmanned air vehicle by printing the parts as small as they could, assembles them and test on it. Basically it is converting the rotary motion into flapping action. One of the test that was done by (Gerdes J. , 2010) indicates that the mechanism is an effective design because of its reliability. Moreover to test the limits of functionality of this design, a couple of tests were done. It was proved that the flapping mechanism sustained the wind speed up to 15 mph for 20 minutes without any damage to the mechanism.

2.8 Material

There are wide variety of materials that have been used in many projects. Two main thermoplastics are studied and compared. There will be one material that is chosen and used in this work. Those two materials are:

1. High Impact Polystyrene (HIPS)
2. Acrylonitrile Butadiene Styrene (ABS)

2.8.1 High Impact Polystyrene (HIPS) Filament

This filament is suitable for Fused Deposition Modelling (FDM), but in most of the cases it is used as support material for an object that is being printed. HIPS can be dissolved in solvents such as limonene solution. Thus, it is used as supports. Most notably in terpene chemicals it dissolves easily. HIPS is ecofriendly because biodegradable solvent degrades it which can be diluted and handled by water treatment plants. Table 2.2 has summarized the properties of HIPS.

Features of HIPS Filament (Bates-Green & Howie, 2017):

→ Great impact strength

→ Good dimensional stability

→ Excellent machinability

→ Low shrinkage value

Table 2.2: Properties of HIPS

Property	Value
Ultimate tensile strength	32 MPa
Young's modulus	1.9 GPa
Poisons Ratio	0.41
Thermal conductivity	0.22 W/m-K
Density	1.0 g/cm^3
Tensile strength	21.5 MPa
Flexural modulus	2137.37 MPa

2.8.2 Acrylonitrile Butadiene Styrene (ABS)

ABS is the cheapest compared to HIPS or any other filaments. It can be sanded, can be easily stick together or smoothed to a glass-like finish. The most amazing mechanical properties of ABS are resistance and toughness. Although, it is has heat shrinkages and warping during printing, it produces smooth finishing and solidifies quickly (Saxena, 2016). It is tough, hard and rigid and has good chemical resistance and dimensional stability. A user who is a novice in dealing with ABS will find it tricky to use because the flow rate from the print nozzle is slow and it constricts as it cools down. Therefore, printing high precision products is not possible. Table 2.3 has summarized the properties of ABS.

Benefits of using ABS materials (Bates-Green & Howie, 2017):

- → Very hard and sturdy
- → Heat resistant
- → Ideal for mechanical parts
- → Durable and difficult to break

Table 2.3: Properties of ABS

Property	Values
Young’s modulus	2.5 GPa
Flexural modulus	7.6 GPa
Ultimate tensile strength	110 MPa
Density	1.4 g/cm^3
Poisson Ratio	0.35
Coefficient of thermal conductivity	90 $\mu m/m\text{-}^oC$

2.9 Solid Works

The Solid Works software is a mechanical design automation application that lets designers quickly sketch out ideas, experiment with features and dimensions, and produce models and detailed drawings. It is one of the many computer aided design (CAD) programs which runs in Microsoft Windows. It was founded by Massachusetts Institute of Technology (MIT) graduate Jon Hirschtick in 1993. Parts are the basic building blocks in the Solid Works software. Assemblies contain parts or other assemblies, called subassemblies. A Solid Works model consists of 2D and 3D geometry that defines its edges, faces, and surfaces (Islam, Hasan, Tamal, Mian, & Evan, 2013). Highly detailed parts and assemblies can be created using this computer program by designers. Solid Works is an excellent tool to cover a lot of stages of product development. This software provides tools needed to generate complex surfaces, structural welded assemblies, and others. Solid Works is used in this project to design the main parts.

2.10 3D Printing technology

It was 1980 when additive manufacturing was developed as a process to make three-dimensional objects (Sandeep & Chhabra, 2008). Subtractive manufacturing techniques create a lot of waste which the material that is cut off generally sent out as scrap. 3D

Printing uses software that slices the 3D model into layers (0.4mm thick used in this project). Each layer is then traced onto the build platform by the printer, once the pattern is completed, the build platform is lowered and the next layer is added on top of the previous one (Saxena, 2016).

. There are many methods of 3D printing, but the most commonly utilized is called Fused Deposition Modelling (FDM). The two materials discussed above are used in this method. A single nozzle is used to extrude melted material which is supplied through it. The melted plastic is build layer by layer onto a heated platform according to the design that is done using Solid Works. The SLDPRT (part file) is converted into STL (.stl) in Solid Works itself. STL file can be read by the 3D printer. Figure 2.12 below shows the growth of 3D printing industry (Mawere, 2014).

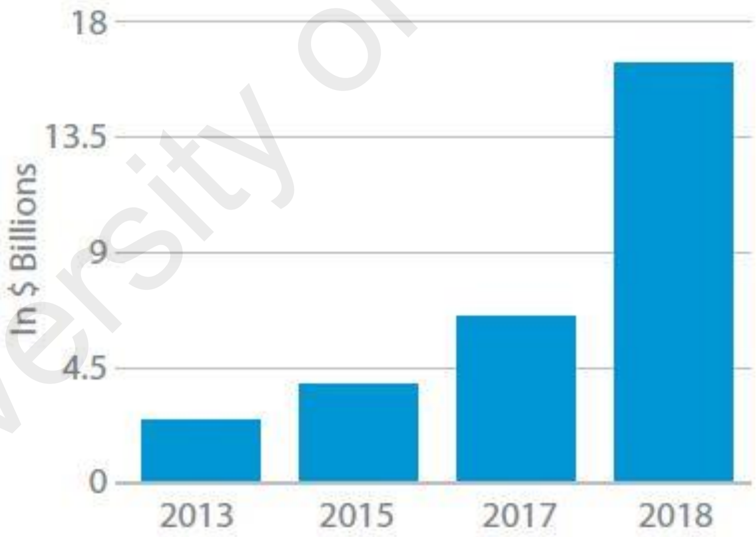


Figure 2.12: 3-D printing industry growth from 2013-2018

CHAPTER 3: **METHODOLOGY**

In some academic contexts, the word 'methodology' is sometimes reserved for the theoretical study of methods. Methodologies may be described as structured sets of steps, techniques, design products and processes, components and perspective. Furthermore, a methodology can be regarded as a generalized description of the activities of a series of design projects, together with a theory that explains why those projects were successful, and it may be seen as an abstraction for good practice. A methodology is usually presented not as a description but as a prescription, a recommendation that projects should follow the generalized task structures. A methodology is created which ultimately studies the objectives of this project.

3.1 Process Flow Chart

The Figure 3.1 shows the flow of the project. It is in a linear flow. It starts with the design phase. In this process the parts are drawn and mechanism is created. Next, in the development phase, thermoplastic is selected, parts are printed using 3D printer, assemble, and rendered. Lastly, will be the analysis on the stress and strain of the wings.

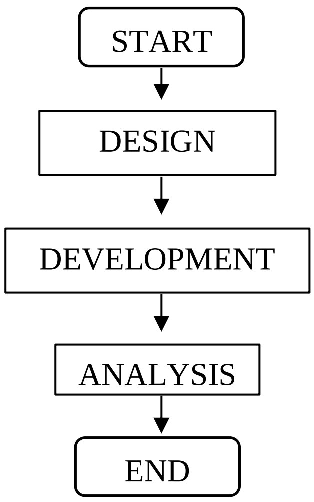


Figure 3.1: Research flow chart

3.2 Design of flapping wing

It is because of extreme complexities involvement and weight restriction of an ornithopter, the kinematics of small birds are tough to be mimicked. To create required lift and thrust, simple flapping mechanism with suitable parameter and overall light weight are needed. This project designed a simple half wing mechanism to be studied on. Consequently many successful ornithopters are designed with flapping mechanism with flexible membrane and piezoelectric, which were not used in this experiment.

Separate parts were designed, and then brought together into the final assembly. There are four (Sandeep & Chhabra, 2008) main parts were created. Those parts are the body, gear, connecting shaft, and wing rod.

3.2.1 Body

The main body or also can be said as the chassis, that was designed in Solid Works is as shown in Figure 3.2 below. This part will assist on holding the gear which is mounted to this part fixed firmly with small metal rods. The idea of having the motor mounted to the body part is to hold the motor firmly so that the shaft is perpendicular to the body structure.

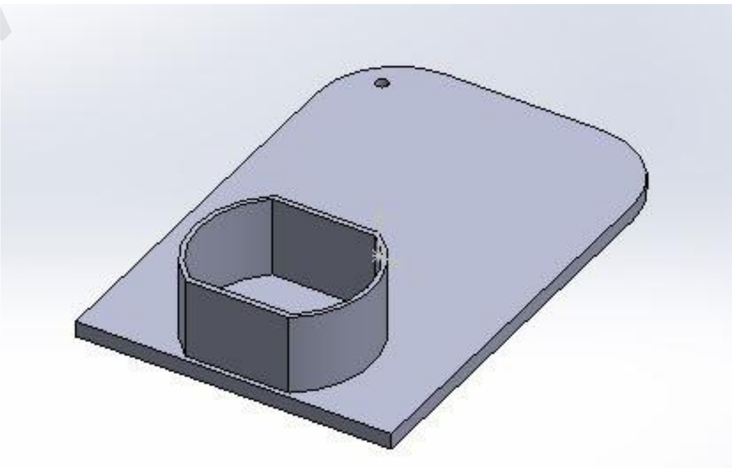


Figure 3.2: Main body

3.2.2 Gear

The gear shown in Figure 3.3 below is based on a wheel that is needed to fix the shaft coming from the motor. In other words, the gear act as a wheel, nothing more. The wheel rotates when the motor is turned on. So, it produces oscillations or rotation that will convert to linear motion like a slider-crank mechanism. Figure below depicts the mechanism utilized as a system that converts the reciprocating rotary motion into linear motion.

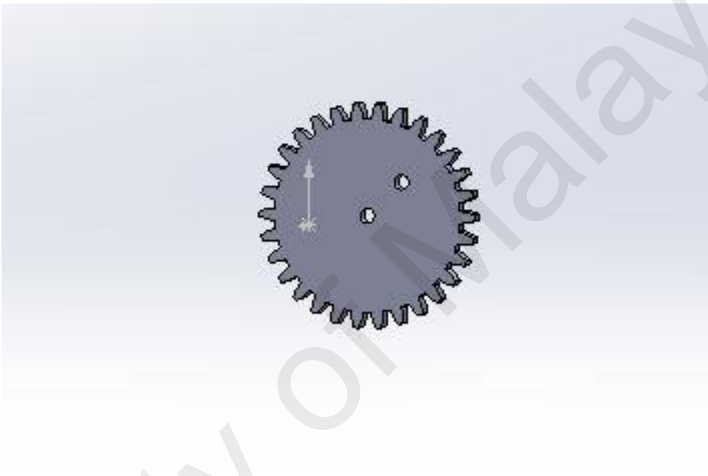


Figure 3.3: Gear

3.2.3 Gear-spar connection shaft

The gear-spar connecting rod is as shown in Figure 3.4 below. This is a crucial part because this helps the motion from the gear to the spar. Without this part the wings wouldn’t even move. As mentioned in earlier, this shaft is connected to the gear by hinge pin (metal rods) so that there is free movement by the gear to the shaft.

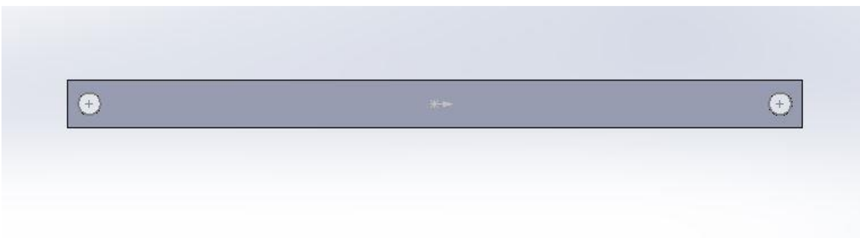


Figure 3.4: Gear-spar shaft

3.2.4 Wing spars

The wing spars are designed in two distinct shapes and one conventional shape as shown below in Figure 3.5, Figure 3.6 and Figure 3.7 for spars A, B and C respectively. These spars will assist the wings to be place on it. Different shapes of wings will be stick on these spars which later will be analyzed. This wing spar is directly attached to the mechanism for it to flap. The design of the spars A and B is slightly different than spar C. The wing spars A and B are not straight part but it has a bend in the midsection. The bend angle is 155°. For wing spar A, the bend is downwards whereas spar B bends inwards and C is just straight without any bends. Studies will be done on these three types of wing spars in this project.

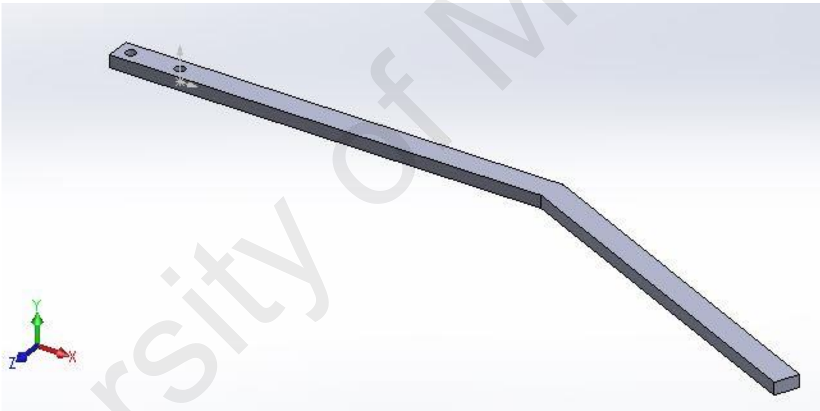


Figure 3.5: Wing spar A

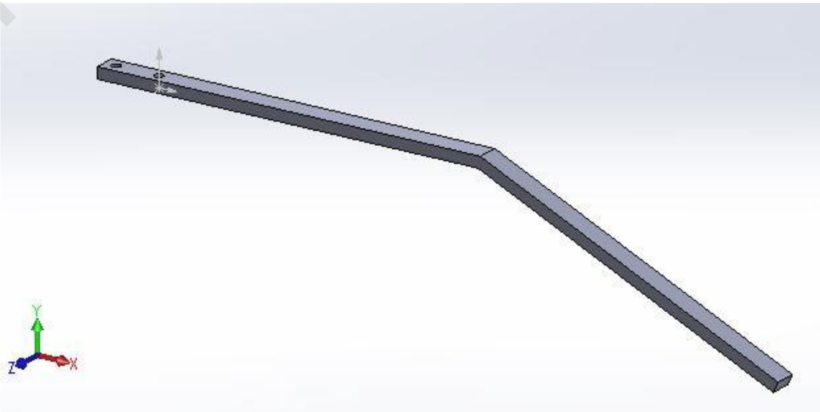


Figure 3.6: Wing spar B

Figure 3.7: Wing spar C

3.2.5 Complete assembly

The complete assembly of the individual parts are as shown in Figure 3.8, Figure 3.8 and Figure 3.10 below.

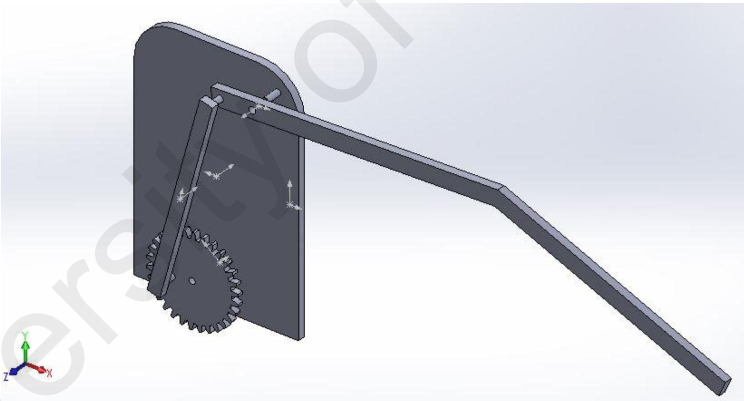


Figure 3.8: Complete assembly of wing spar A

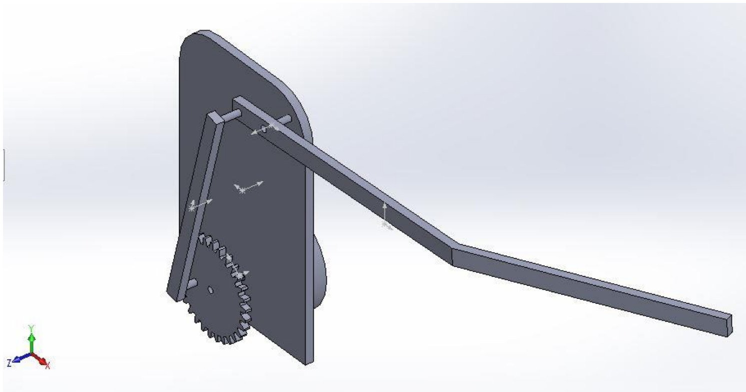


Figure 3.9: Complete assembly of wing spar B

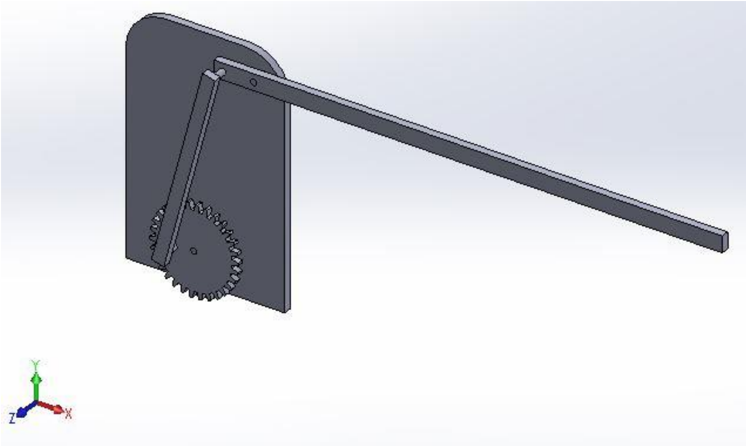


Figure 3.10: Complete assembly of wing spar C

Motion analysis has also been done with the help of solid works. The DC motor parameter with five revolutions per minute (5 RPM) is given to the center of the gear in anti-clockwise direction.

3.3 Parts printing

There are several methods of 3D printing. Fused Deposition Modeling (FDM) is the most popularly known method compared to others like Stereolithography (SLA) and Selective Laser Sintering (SLS). FDM uses a single nozzle head to extrude melted material, typically plastic, layer by layer onto a build platform according to the 3D design files that has been translated into instruction to the printer (Bates-Green & Howie, 2017). FDM is cheaper than SLA as it uses actual plastic instead of simulating plastic like material by projecting laser on resin (Jasveer & Jianbin, 2018). One of the most familiar printers in this space, the MakerBot, uses the FDM method. The model of the 3D printer that was used in this experiment was MakerBot Replicator 2X as shown below in Figure 3.11.

Figure 3.11: MakerBot Replicator 2X

3.4 Material Selection

The filament that is used in this project shall be ABS. ABS is an oil-based plastic, has high melting point, strong and sturdy material that is widely used for creating things such as plastic parts, toys and electronic housings. That was the reason why this material was used. ABS was supplied to the nozzle then shall be heated to 230°C whereby the platform surface shall be 110°C. The filament would warp if cooled while printing therefore a hot platform is needed (Sandeep & Chhabra, 2008). ABS that was chosen and used in this experiment is as shown in Figure 3.12 below.

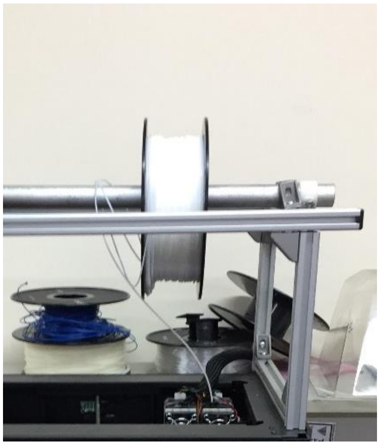
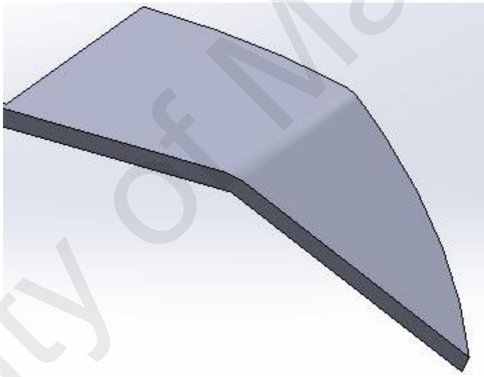
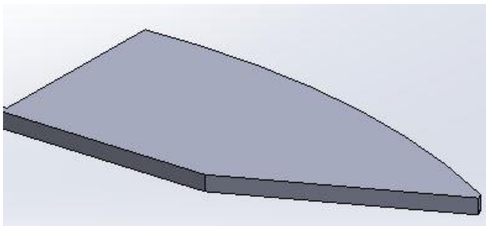
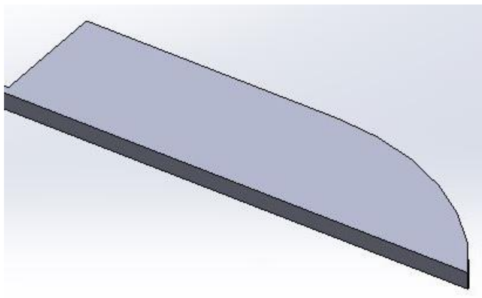


Figure 3.12: ABS filament

3.5 Wing designs

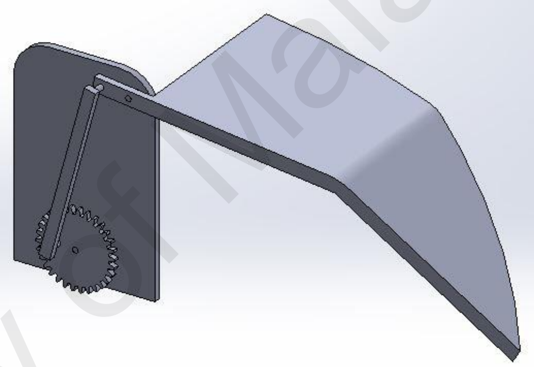
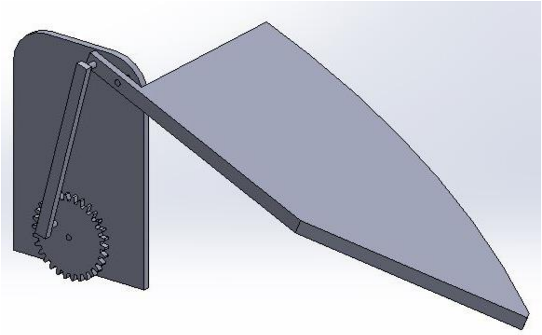
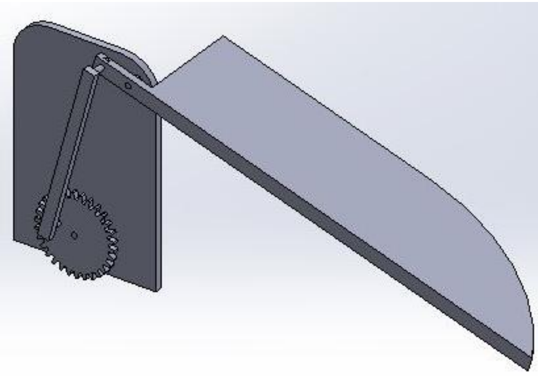
There are three different shapes of wings that will be studied in this projects based on spar that were designed above. This is to find out which wing shape will be suitable to be used in flapping unmanned air vehicle for this design. All of the shapes have been shown below in Table 3.1 as well as the areas. These wings will be used on the assembly shown above to find the efficient lift force that will be suitable to be used on an unmanned air vehicle.

Table 3.1: Wing shapes and area

No	Description	Shapes	Area (cm^2)
1.	Wing 1 to accommodate spar A		56
2.	Wing 2 to accommodate spar B		50
3.	Wing 3 to accommodate spar C		43

The area for wing 1 and 2 are the same. Therefore the wing span for wing 2 has been reduced so find out the difference in aspect ratio. The material that will be used in this experiment shall be plastic sheet with thickness of 0.5mm. Plastic was decided to be used because it is light weight, not rigid, has high strength-to-weight ratio, and good durability. Nevertheless, material for wings were taken less consideration since shape of the wings are being investigated. Once the wings are attached to the spars, the assembled mechanisms are as shown below in Table 3.2. Thus, in the next chapter, the actual printed models shall be looking like this once the parts are assembled.

Table 3.2: Wings assembled models

No	Name	Model
1.	Design 1	
2.	Design 2	
3.	Design 3	

3.6 Analytical Calculations

3.6.1 Masses of components

Admiring the fact that a flapping robot is now commonly studied on, it take researches a great challenge to reduce the size of it. The mechanism is necessarily to be as light as possible. The weight of each component is weighed using a digital scale measuring device. It has a precision of up to 0.01 grams. The masses of the composing parts are as shown in the Table 3.3 below.

Table 3.3: Masses of parts

No	Components	Mass (g)
1.	Body/Chassis	2.26
2.	Gear	0.44
3.	Connecting Shaft	0.32
4.	Wing Spar A	0.61
5.	Wing Spar B	0.61
6.	Wing Spar C	0.61
6.	DC Motor	15.14
7.	Metal rods	0.48

As this are only masses of the parts that are printed, bearing in mind that a full ornithopter that needed to fly will need two of wing spar A, B or C. It comes to about 19.86g each complete mode with wings at both side. Therefore, in the next sub-chapter, this weight is needed to be considered into the calculations. The mass of the wings or the plastic sheet is negligible but the thickness is assumed as 0.001mm. The total weight of the complete design shall be 19.86 grams.

3.6.2 Flapping Frequency

There are few theories and formulas used by researches in order to obtain flapping frequency of unmanned air vehicle by studying bird's motion. Experimental studies conducted by (Hu, Kumar, Abate, & Albertani, 2010) on birds for multiple regression and dimensional analysis by utilizing wing beat frequency formula which is:

$$\mathbf{f} = \mathbf{1.08}(\mathbf{m}^{\frac{1}{3}} * \mathbf{g}^{\frac{1}{2}} * \mathbf{b}^{-1} * \mathbf{A}^{-\frac{1}{4}} * \rho^{-\frac{1}{3}}) \tag{3.1}$$

The m is the mass of air vehicle's body, g is the acceleration due to gravity, b is the wing span, A is the wing area, and ρ is the density of air.

On the other hand, there was another formula for flapping frequency that was mentioned in the same experiment. The relation for different sizes are:

$$\mathbf{f}\ (\mathbf{large\ birds}) = \mathbf{116.3}(\mathbf{m}^{\frac{-1}{6}}) \tag{3.2}$$

$$\mathbf{f}\ (\mathbf{small\ birds}) = \mathbf{28.73}(\mathbf{m}^{\frac{-1}{3}}) \tag{3.3}$$

The f is the flapping frequency and m is the mass of the air vehicle (Hu, Kumar, Abate, & Albertani, 2010). Equation 3.6 is most suitable to be used in this work because the size of the FUAV in this experiment is considered to be small.

3.6.3 Lift force formula

For the air vehicle to have upward motion, the lift force should be higher than the weight of the vehicle itself. That is to overcome the force to move forward or lift off from its initial position or ground position. The force equation (Hall, 2015) is as shown below:

$$\mathbf{F} = \rho \mathbf{A} \boldsymbol{V}^{\mathbf{2}} \tag{3.4}$$

The value for density of air, ρ is 1.1839 kg/m^3. A is the area of the wings and V is the velocity of air vehicle. The density value is taken at 25°C and pressure at 101.325 kPA or 1 atm. This formula is actually derived from the Newton’s second Law of motion where aerodynamic force is directly related to the change of momentum of the fluid (Hall, 2015). Density can be define by volume divided by mass but when it comes to moving fluid the mass in taken in terms of mass flow rate. So, the aerodynamic force is equals to the mass flow rate multiplied with the velocity. This formula is used to find the force needed for all three designs in this project.

The velocity of the flapping model is assumed to be 20 m/s. The area of the wings are shown in Table 3.1. The above equation is compared to another lift equation given in a research (Hodanbosi, 1996). The lift equation given is as:

$$\mathbf{Lift} = \left(\frac{\mathbf{1}}{\mathbf{2}}\right) * \mathbf{A} * \mathbf{CL} * \boldsymbol{\rho} * \boldsymbol{V^2} \qquad \textbf{(3.5)}$$

The A is the wing area, CL is the coefficient of lift, ρ is the density of air, and V is the velocity of an air vehicle. CL is a variable to deal the complex dependencies and in most cases is it determined experimentally. This variable favors the researchers to gather the effects, simple complex, in an individual formula. The value of CL varies depending on many factors such as AOA, Reynolds number and thickness of airfoil (Subramanian, 2016). There is a curve obtain regarding CL which are shown in Figure 3.13 below.

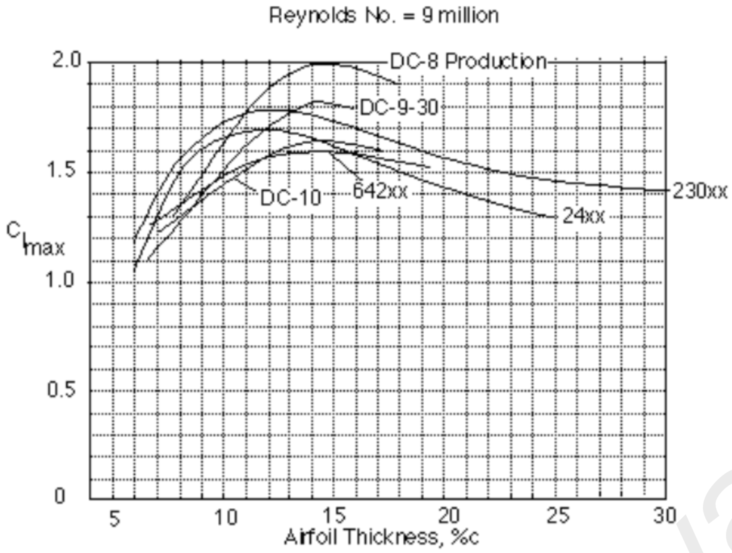


Figure 3.13: CL against airfoil thickness

This parameter is needed to be computed in order to find lift force. But in this experiment, the CL will be calculated using the equation above. Then the obtained CL will be compared to the area of the wings.

3.6.4 Drag force formula

The airflow over the air vehicle wing generates force of drag which the formula (Sudo, Takagi, Tsuyuki, Yano, & Nishida, 2008) is given as:

$$\mathbf{Drag} = \left(\frac{\mathbf{1}}{\mathbf{2}}\right) * \mathbf{A} * \mathbf{CD} * \rho * \boldsymbol{V}^{\mathbf{2}} \qquad \textbf{(3.6)}$$

The A is the wing area, CD is the coefficient of drag, ρ is the density of air flow, and V is the velocity of an air vehicle. There is a study done by (Uhlig, Sareen, Sukumar, Rao, & Selig, 2010) in which they related both the coefficients by saying that the drag fluctuates as the lift rapidly changes during stall delay. So the formula that was adapted from the study is:

$$\mathbf{CD} = \mathbf{0.044} + \mathbf{0.4\ CL}^2 \qquad \textbf{(3.7)}$$

The relation between CD and CL is shown in figure below. The blue line in the Figure 3.14 indicates the thin airfoil theory.

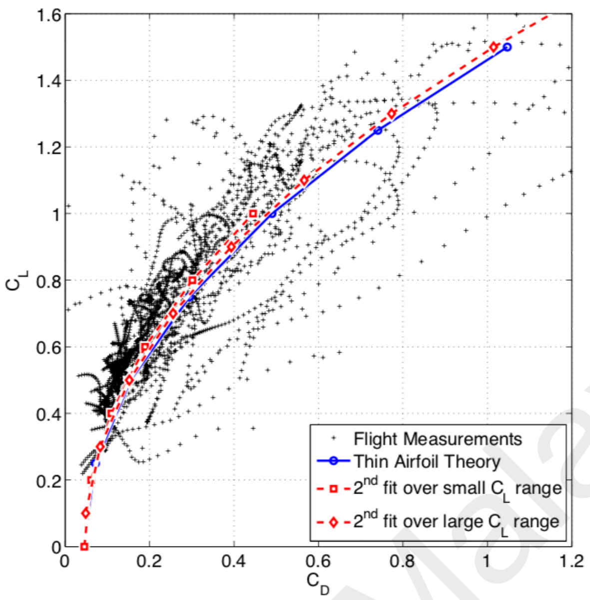


Figure 3.14: Experimental Lift Coefficient versus Drag Coefficient

3.6.5 Thrust formula

By taking the on-flexible properties of the wing flapping motion to be designed, the thrust can be seen as the opposite in direction to the drag force but same in magnitude, therefore the formula (Marek & Smreek) is:

$$\mathbf{Thrust} = \mathbf{Drag} = \left(\frac{1}{2}\right) * \mathbf{A} * \mathbf{CD} * \boldsymbol{\rho} * \boldsymbol{V}^2 \qquad \textbf{(3.8)}$$

Now taking the equation of coefficient of thrust equation (Svanberg, 2008), we have:

$$\mathbf{CT} = \mathbf{T}/(\boldsymbol{\rho}\mathbf{n}^2\mathbf{b}^4) \qquad \textbf{(3.9)}$$

The T is thrust force, ρ is local air density, n is the flapping speed (Hz), and b is the wing span. Therefore the coefficient of thrust can be calculated using this formula.

On the other hand, as an additional information, there is a formula given by (Weisstein, 2007) for a rotary wing air vehicle which is similar to equation (3.3). The formula is:

$$\mathbf{CT} = \mathbf{T}/(\left(\frac{\mathbf{1}}{\mathbf{2}}\right) * \mathbf{A} * \rho * (\Omega\mathbf{r})^{\mathbf{2}}) \qquad \textbf{(3.10)}$$

The Ω used here is the angular velocity and r is the radius of a propeller. It was mentioned that for a helicopter, C_t is 0.01 (Weisstein, 2007). However this formula is not used in this experiment.

3.7 Design Structure Analysis

Simple stress and strain analyses are conducted in this study on wings using Solid Works on three different shapes. Due to the different in shapes, it is expected to obtain different results on the wings. The purpose of this scope is to understand how different wing shapes affect the stress and strain of a flapping-wing.

CHAPTER 4: **RESULTS AND DISCUSSION**

The main purpose of this research is to design and investigate the mechanism of flapping wing which produces higher lift force and lower drag force. Numerical methods have been used to establish the lift force that is needed to lift the body from ground. There are two formulae used to determine the lift. In the first equation we assumed coefficient of drift to be 1. Then calculated for the force generated with the designed wing span for all two shapes.

This force is compared to the lift force equation to the other author's equation. The difference can be found below.

4.1 Flapping mechanism

The designed parts are assembled to make a half-complete flapping mechanism. The purpose of this project is to study the mechanism which gives bigger wing area. This is to investigate if a slight different in area might give a significant result in the lift force. That is what expected in this study mainly. Therefore, different shapes on wings were also studied. This flapping mechanism is used to verify the testing method. To achieve the main aim of the project we need to make sure that the flapping mechanism works as desired.

It was decided that the spar will be connected to the gear individually with the help of the connecting shafts. When the gear rotates with the help of the DC motor, the connecting shaft translates the rotary motion to translation motion. The distance between the center of the gear to the connecting shaft difference with the angle of flapping. We can also increase and reduce the length of the shaft to reduce or increase the angle of flapping of the wing respectively. The flapping model was made to rotate in different load in Solid works. The flapping model is as shown below in the Table 4.1, 4.2 and 4.3.

Table 4.1: Design 1 at up and down stroke

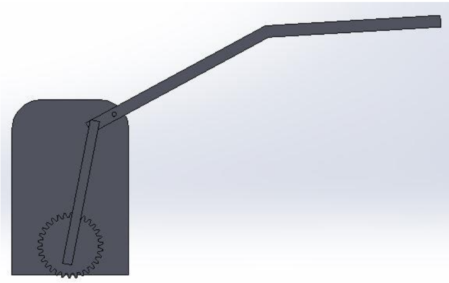
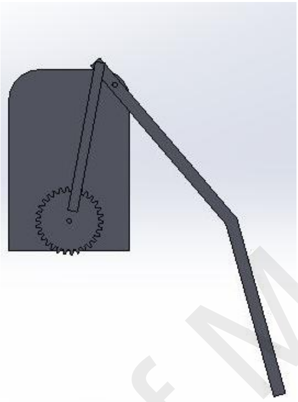
	Design A
Down stroke	
Upstroke	

Table 4.2: Design 2 at up and down stroke

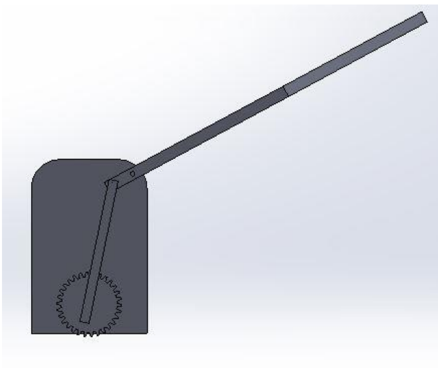
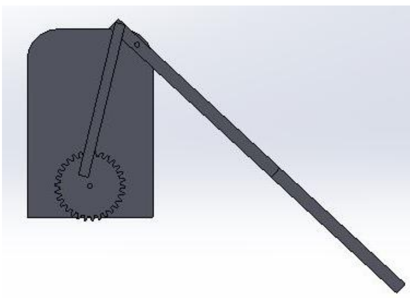
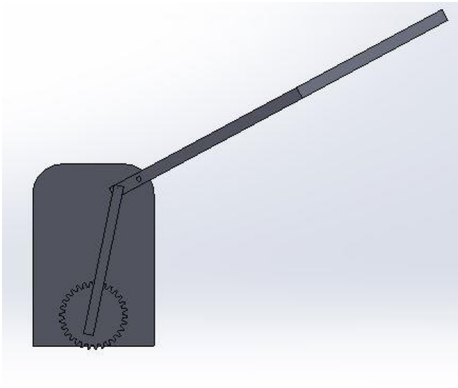
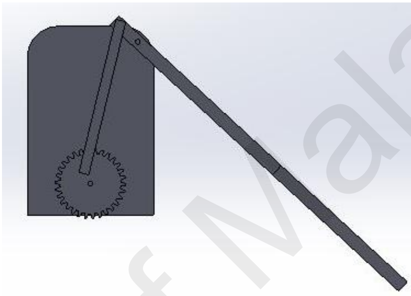
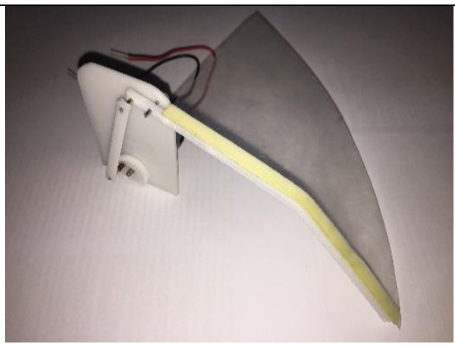
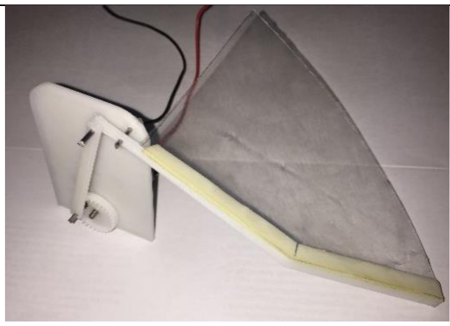
	Design B
Down stroke	
Upstroke	

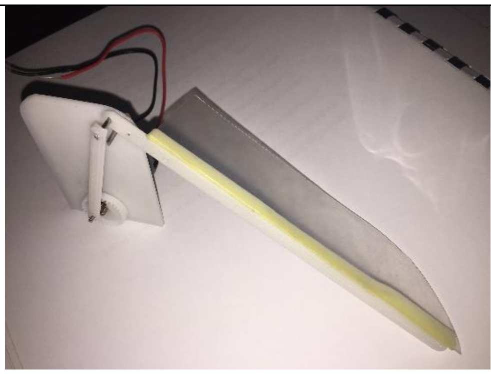
Table 4.3: Design 3 at up and down stroke

	Design C
Down stroke	
Upstroke	

The actual models of the three designs that were discussed in Table 3.2 are shown below in Table 4.4.

Table 4.4: Complete models

No	Name	Model
1.	Design 1	
2.	Design 2	

3.	Design 3	

4.2 Numerical calculation

Wings with different shapes shall have different aspect ratios. It is known that the formula is discussed in chapter one above. AR is dimensionless. Since there are three different wing shapes, the aspect ratio is calculated and tabulated as below. Table below shows the AR calculated for all three wings.

Table 4.5: Aspect Ratio of all wings

Shape	Calculation	Aspect Ratio (AR)
Wing 1	$AR=(0.115)^2 \div (0.0056)$	2.36
Wing 2	$AR=(0.115)^2 \div (0.0050)$	2.65
Wing 3	$AR=(0.115)^2 \div (0.0043)$	3.08

From table above, it is known that as the area reduces the AR increases. The difference of area of wing 1 and wing 2 is small compared to wing 3. This is due to the shape of wing 3 which has small chord. A long narrow wing gives a high aspect ratio, whereas low aspect ratio for short and wide wing. Since its wing tip has lesser area, the vortex induced downwards is less which give less induced drag. Aerodynamic efficiency of a wing is often predicted using aspect ratio because the lift-to-drag ratio is proportional to aspect ratio (Choi & Park, 2017).

Although a long and narrow wing has advantages, there are several reason why not all aircraft have high aspect ratio. A narrow wing has to be strong because of the air load is placed across the entire span. This creates high bending moment. Compared to broad wing, it has lesser bending moment.

4.2.1 Flapping Frequency Calculation

The frequency calculated by using equation (3.1) is shown in table below.

Table 4.6: Flapping Frequency

Name	Calculation	Frequency, f
Design 1	$f = 1.08(0.01986^{1/3} * 9.81^{1/2} * 0.115^{-1} * 0.0056^{-1/4} * 1.1839^{-1/3})$	27.53
Design 2	$f = 1.08(0.01986^{1/3} * 9.81^{1/2} * 0.115^{-1} * 0.0050^{-1/4} * 1.1839^{-1/3})$	28.32
Design 3	$f = 1.08(0.01986^{1/3} * 9.81^{1/2} * 0.115^{-1} * 0.0043^{-1/4} * 1.1839^{-1/3})$	29.40

Table above shows the frequency values for all three designs for the mass of 19.86g. All of those value are different because of varying wing areas. The smaller the area of wing, the higher the frequency is. This shows air vehicles with smaller wing area needs higher frequency.

4.2.2 Lift Force Calculation

The general equation for lift used to find out if the force is sufficient to lift the body. The equation (3.4) is used in Table 4.7 and the result is tabulated in Figure 4.1 below.

Table 4.7: Lift Force

Name	Calculation	Lift (N)
Design 1	L = 1.1839∗(0.0056∗2)∗20	0.2652
Design 2	L = 1.1839∗(0.0050∗2)∗20	0.2368
Design 3	L = 1.1839∗(0.0043∗2)∗20	0.2036

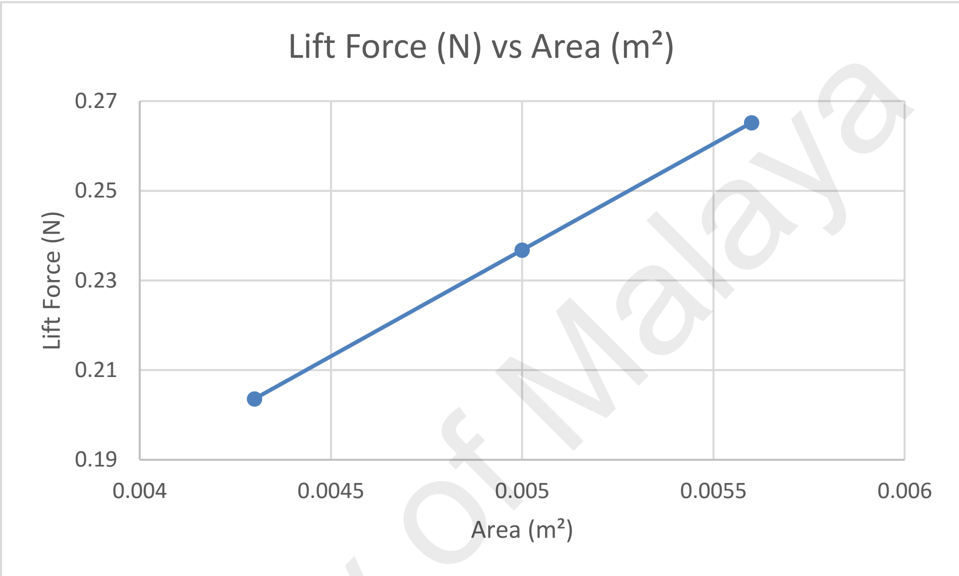


Figure 4.1: Graph of lift force versus area

Since the calculated weight of the complete mechanism is 19.86g, the converted value in Newtons earth shall be 0.195N. So, any force that is higher than 0.195N, it will produce lift on the object. But it also depends on the frequency of the flapping because lift increases when frequency increases. Figure above proves that area plays a big factor in generating force to lift the vehicle. The bigger the area, higher the lift force generated. In this case, the areas calculated are higher than masses of all three models, thus producing lift.

Next, to find the lift coefficient by using force needed to lift the flapping unmanned air vehicle, the formula (3.5) is to be used. Before that, a consistent lift force is to be assumed for all designs so that it is simpler to compare the varying wing area to lift coefficient.

The lift force that was assumed here is 0.35N, which is higher than all three values. The different area of wing should produce different lift coefficient for same lift force. Table 4.8 below shows the computation and Figure 4.2 shows the results for lift coefficient.

Table 4.8: Lift Coefficient

Name	Calculation	Lift Coefficient, CL
Design 1	CL= (2∗0.35)÷1.1839∗20²∗(0.0056∗2)	0.1320
Design 2	CL= (2∗0.35)÷1.1839∗20²∗(0.0050∗2)	0.1478
Design 3	CL= (2∗0.35)÷1.1839∗20²∗(0.0043∗2)	0.1719

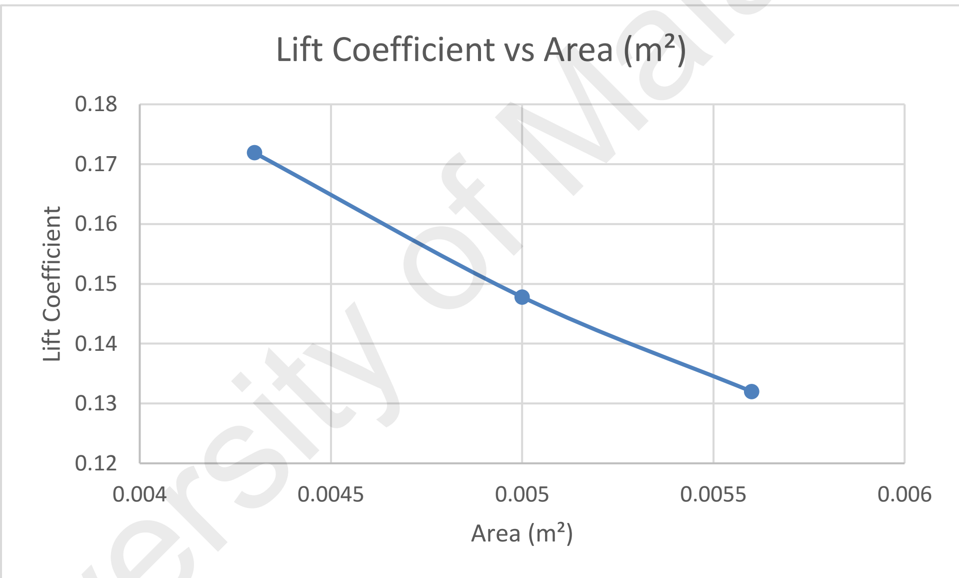


Figure 4.2: Graph of lift coefficient versus area

Figure above shows that area is inversely proportional to lift coefficient. For a given lift force and velocity, the coefficient of lift change with area of wings. Figure above shows that as area increase, the coefficient reduces. The flat plane is the planform area of the wing as viewed from above the air vehicle, it is possible, in theory, to utilize the total surface area as the reference area. The reference area is proportional to the wing planform area. It was mentioned that researchers are free to use any area which can be easily measured by performing the necessary math to produce the coefficient since the lift coefficient is determined experimentally (Djojodihardjo & Ramli, 2012). Sometimes when velocity is low, wing area can be increased to produce enough lift to avoid the ground.

4.2.3 Drag Force Calculation

Firstly, from the equation (3.8), the drag force for an ornithopters is assumed to be same the thrust. So that the air vehicle has lift. Using lift coefficients computed above, it is simpler to find the drag coefficient then the drag force. Table 4.9 shows the coefficient of drag for all designs.

Table 4.9: Drag Coefficient

Name	Calculation	Drag Coefficient, CD
Design 1	CD= 0.044 + 0.4(0.1320)	0.09680
Design 2	CD= 0.044 + 0.4(0.1478)	0.1031
Design 3	CD= 0.044 + 0.4(0.1719)	0.1128

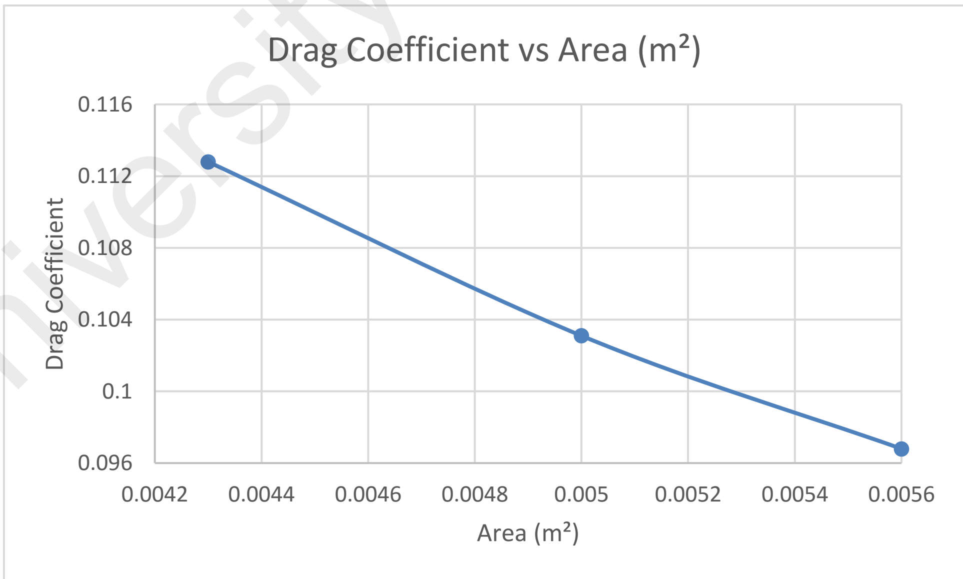


Figure 4.3: Graph of drag coefficient versus area

Noticing that the drag coefficient drop drastically when the area increases. It was said that bigger nominal wing area than frontal area, the resulting drag coefficient tend to be low (GegeZ, 2018). This statement matches the graph above. Engineers, in all cases take initiative to reduce drag by making or improving the designs or material used. Air vehicle is designed more streamlined which means it is more aerodynamic nowadays. The wings are also made narrower or by using new materials. Some materials used has smoother surface which eventually decreases the ability for the force of drag to effect it. Moreover, roughness and surface area deduction can decrease the friction drag of an air vehicle. Pressure drag also plays important role here. Air pushes against the front harder than the back when air is flowing past an object (Jahanmiri, 2013). The difference produced a backward force called pressure drag. Drag force should be smaller than thrust of an object so that the object will move forward similar to lift against gravitational force.

Next, with the obtained drag coefficient, the drag force can be calculated using equation (3.7). The further computation is shown in table below.

Table 4.10: Drag Force

Name	Calculation	Drag (N)
Design 1	$D = (½) * 0.0056 * 2 * 0.09680 * 1.1839 * 20^2$	0.2567
Design 2	$D = (½) * 0.0050 * 2 * 0.1031 * 1.1839 * 20^2$	0.2441
Design 3	$D = (½) * 0.0043 * 2 * 0.1128 * 1.1839 * 20^2$	0.2297

It is found that the drag force changes with area and drag coefficient. Here it can be seen that drag force is reducing with smaller area and smaller drag coefficient. This result may not be accurate since two parameters are varying, the area and coefficient. A proper computer aided simulation will produce the accurate coefficients. The lift and drag coefficients are related by the figure below.

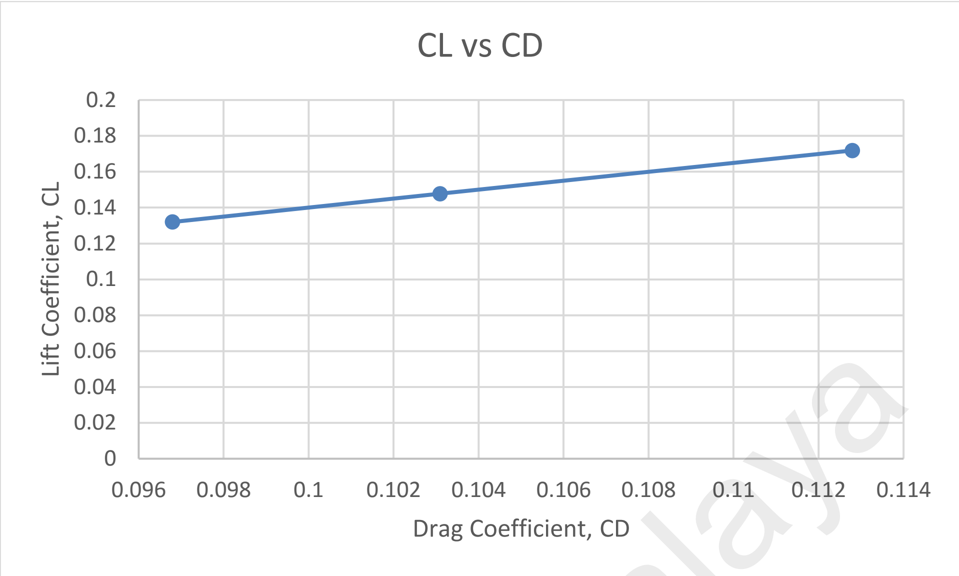


Figure 4.4: Computed Lift Coefficient versus Drag Coefficient

The above graph shows similarities to Figure 3.13 whereby the lift coefficient increase with drag coefficient.

4.2.4 Thrust Force Calculation

Now from equation (3.8) it is said that thrust is same magnitude as drag. Keeping that in mind, the calculation below has been done. Thus, value of thrust was used in equation (3.9) to obtain thrust coefficient. Table 4.11 below shows the computation for 20 Hz.

Table 4.11: Thrust Coefficient

Name	Calculation	Thrust Coefficient
Design 1	$CT = 0.2567/(1.1839*20^2*0.115^4)$	3.099
Design 2	$CT = 0.2441/(1.1839*20^2*0.115^4)$	2.947
Design 3	$CT = 0.2297/(1.1839*20^2*0.115^4)$	2.773

Table above shows the coefficient of thrust for all three design with frequency of 20Hz. Now taking the values for different coefficient of thrust with 2 Hz intervals for those designs are shown in the Table 4.12.

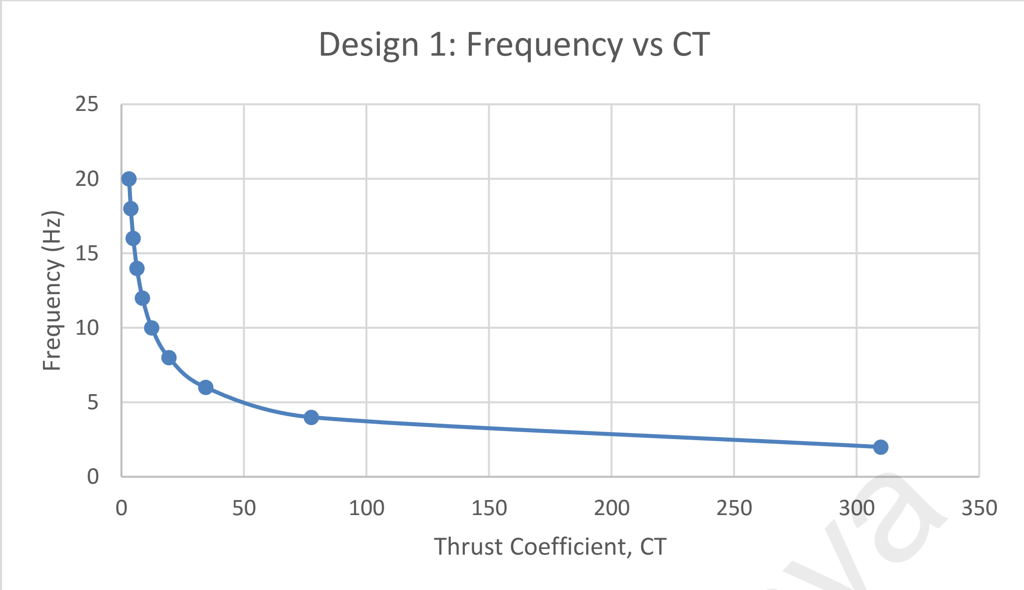


Figure 4.5: Graph for Design 1

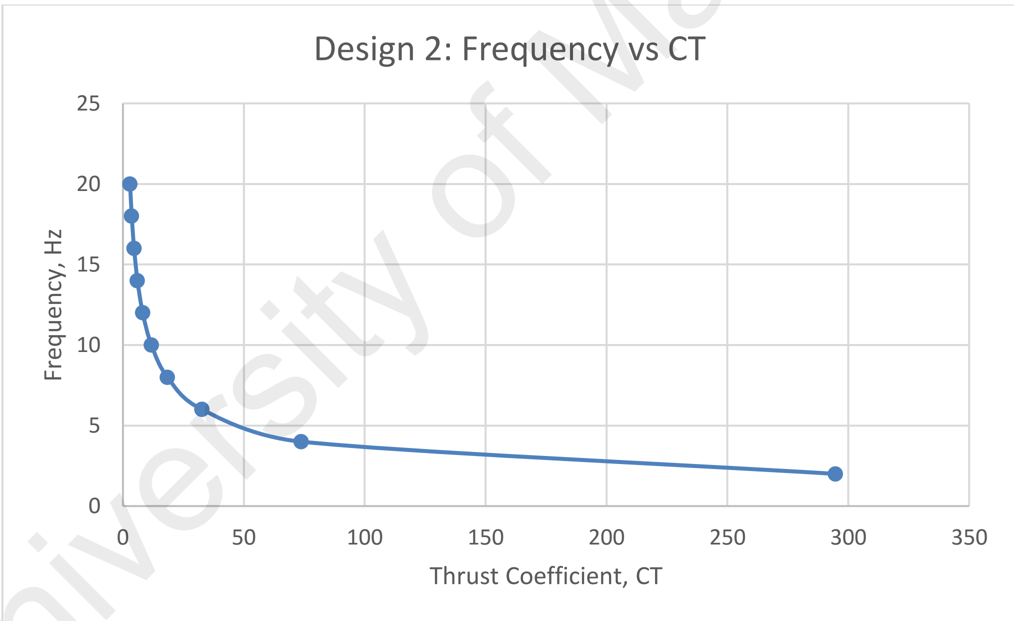


Figure 4.6: Graph for Design 2

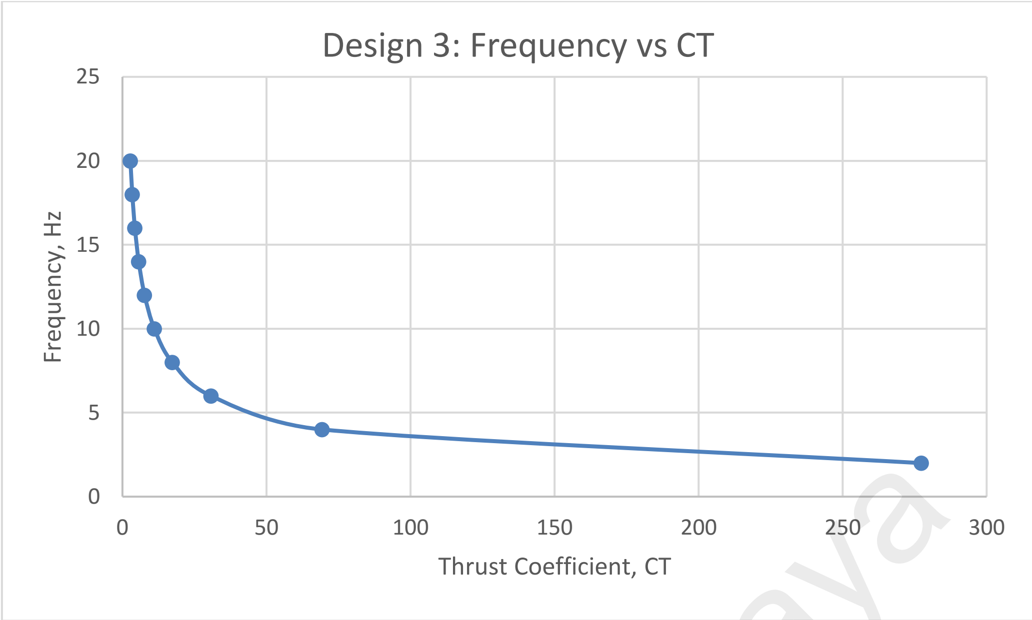


Figure 4.7: Graph for Design 3

It is known and proved that thrust coefficient is inversely proportional to frequency which indicates that the force is high when the coefficient of thrust is small.

High frequency will produce stress on certain parts of the design. Therefore it is necessary to study on the stress and strain of the designs as well.

4.3 Stress and Strain Simulation

Based on the simulation that was done the three designs it was found that the results were almost similar one to one another. The results of the simulation is as below.

4.3.1 Design 1

The stress and strain on the wing for design 1 is at the hinge of the spar which is attached to the body. There is slight stress encountered at the beginning of wing sheet which is near the hinge joint. The total min and max stress and strain for this design is shown in figures below.

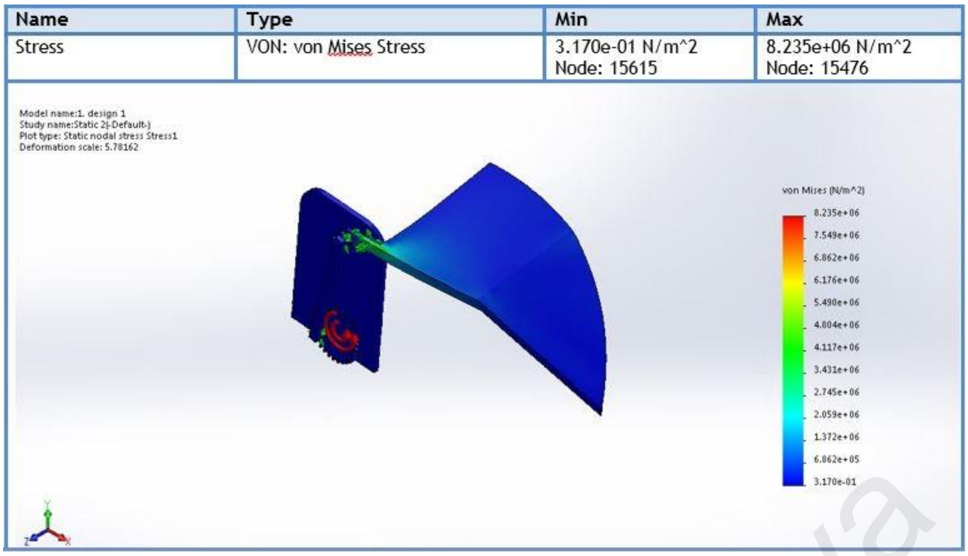


Figure 4.8: Stress on Design 1

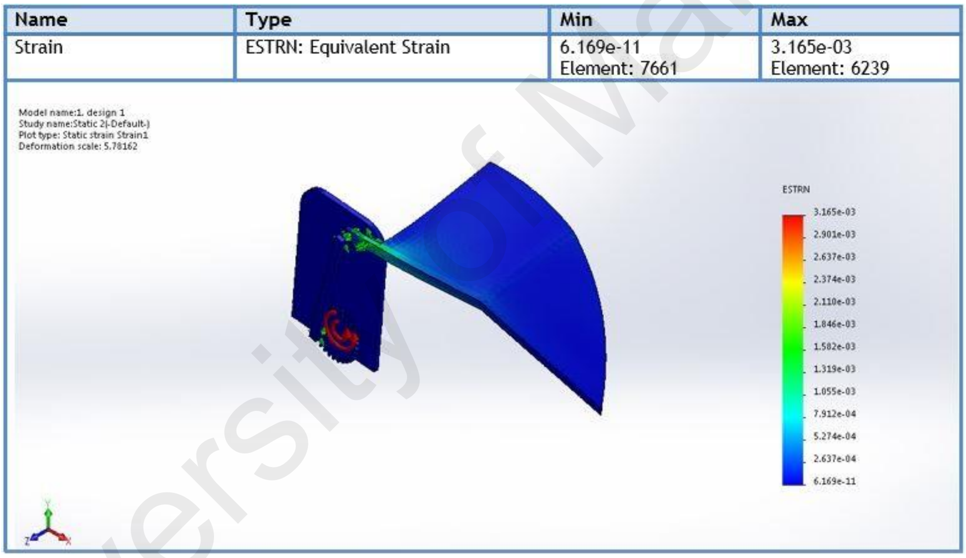


Figure 4.9: Strain on Design 1

4.3.2 Design 2

The stress and strain on the wing for design 2 is same as design 1 but in this design it is noticed that at the hinge the stress area is slightly bigger. There is slight stress encountered at the beginning of wing sheet which is near the hinge joint. The total min and max stress and strain for this design is shown in figure below.

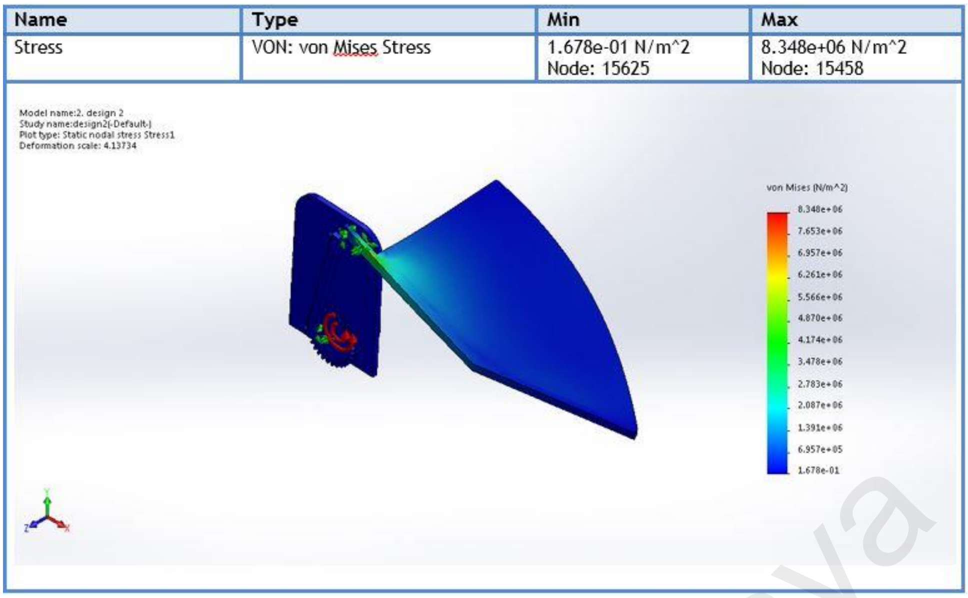


Figure 4.10: Stress on Design 2

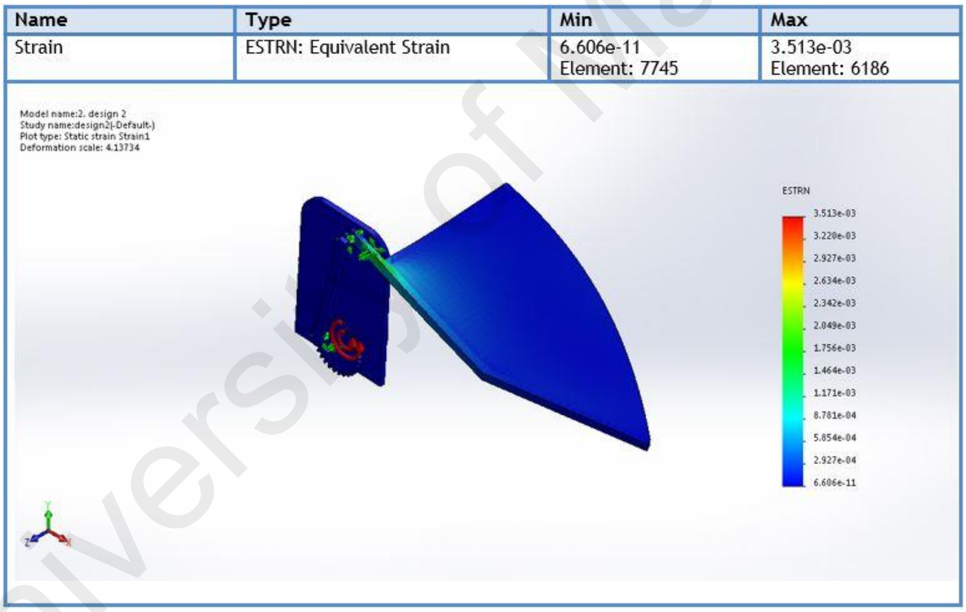


Figure 4.11: Strain on Design 2

4.3.3 Design 3

The stress and strain on the wing for design 3 is same as design 1 but in this design the wing chord is smaller. It is found that smaller chord does not affect hinge connection. The total min and max stress and strain for this design is shown in figure below.

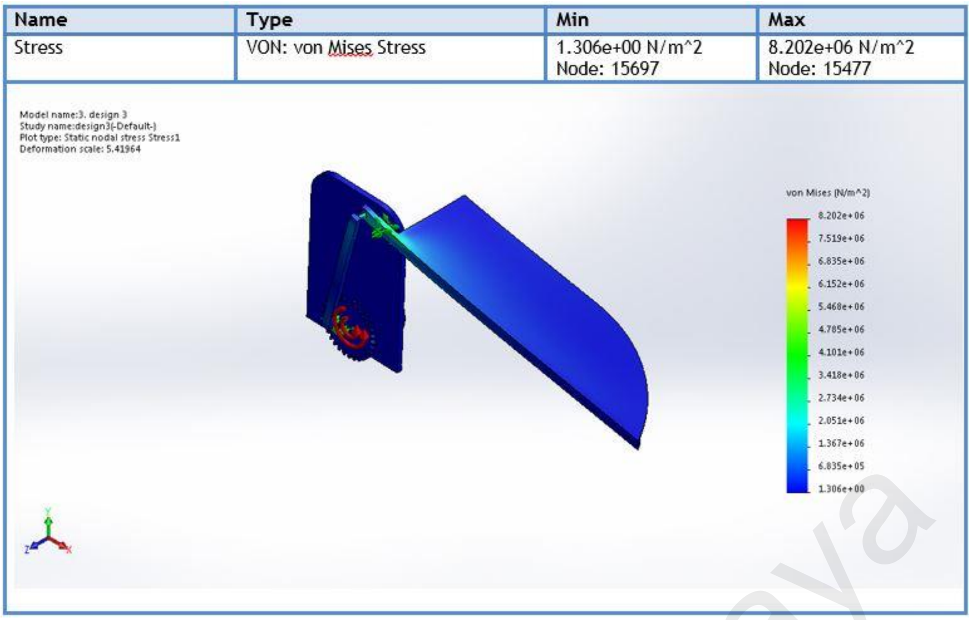


Figure 4.12: Stress on Design 3

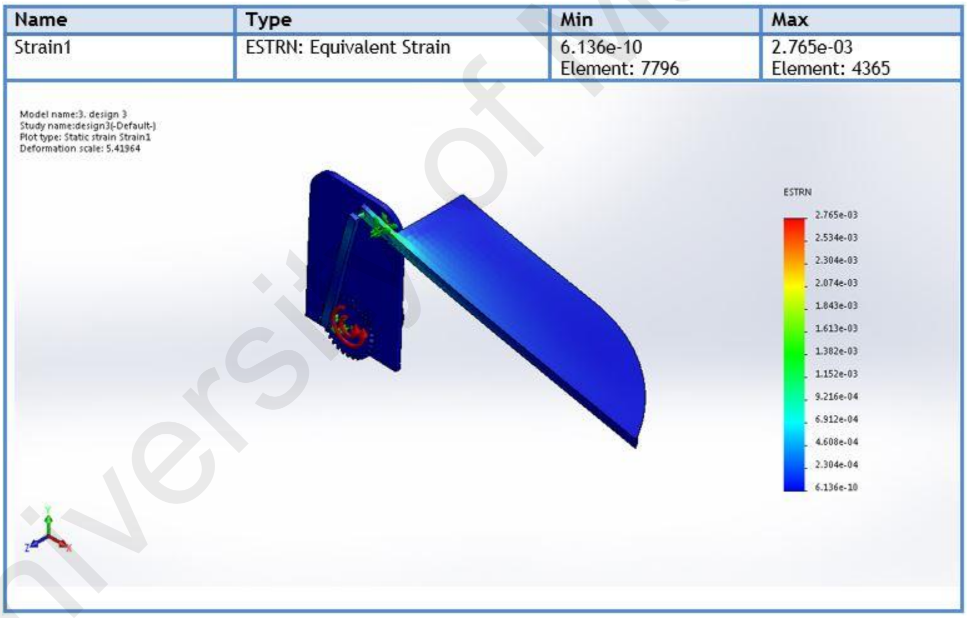


Figure 4.13: Strain on Design 3

Is t is known that stress and strain for different wing shapes do not affect the wing connection. All types of wings can be used in flapping unmanned air vehicle. If noticed carefully wing 3 is has slightly higher stress on whole wing compare to wings 1 and 2. The blue on wing 1 and 2 are darker than wing 3. This shows that bigger area of wing the stress is distributed over the whole wing. Obviously the hinge joint will have highest stress due to its connection to the body.

CHAPTER 5: **CONCLUSION**

The ultimate goal of this research was reached by designing a model of a medium sized flapping air vehicle with three different wing shapes with different areas. Solid Works was used to design, create a model and to assemble each part. To see the motion of the assembled components, motion analysis in Solid Works was used to judge the functional capability of the mechanism. The mechanism is printed using a 3D printer, assembled, and made successfully in flapping condition.

Overall weight of the body is found to be around 19.86 grams which is almost 0.195 N. This meant that the lift force should be more that 0.195 N to lift the body up in the air. It is computed that the force obtained for all three designs were sufficient to lift the air vehicles. Ultimately, Design 1 showed higher force compared to others mainly because of its wing area is bigger than other wings.

Design 1 shows highest drag force computed with lowest drag coefficient, CD. Coefficient of lift, CL increase with reducing area. The graph plotted to find the relation of drag coefficient and lift coefficient was satisfying with an experimental curve which proves that as CL increases, CD reduces. The coefficient of thrust has also been calculated for different frequencies which shows that as frequency decreases, the thrust increases. This has been done to all three designs and three showed similar curves.

From the structure analysis done, it is determined that the hinge joint exerts stress on the spars. Anyhow Design 1 shows higher stress (min) than Design 2 and 3 whereas strain did not show any difference. Design 3 has the lowest minimum stress. Comparing all three wings, they are possible to be utilized as air vehicle because all the results of computation and analyses are within the limitation and constraints. However Design 1 is an optimized design to be utilized.

5.1 Recommendation

The following are the recommendations for future work:

- → Universal joints can be used to attach wing with the vehicle body. This will make the wings to maneuver as desired.
- → A suitable and simple software such as ANSYS, should be used to do simulation or flow simulations to get accurate readings without any errors. The software should be user-friendly.
- → A more complex mechanical model can be designed to reduce the links. Reduction of links reduces the friction and connection which in turn helps in smooth movement.

REFERENCES

Abas, M. F., Rafie, A. S., Yusoff, H. B., & Ahmad, K. A. (2015). *Flapping wing micro-aerial-vehicle: Kinematics, membranes, and flapping mechanism of ornithopter and insect flight.* Chinese Journal of Aeronautics.

Azuma, A., Azuma, S., Watanabe, I., & Furuta, T. (1984). *Flight Mechanics Of A Dragonfly.* Great Britain: The Company of Biologists Limited.

Bachmann, R. J., Frank J. Boria, R. V., Ifju, P. G., & Quinn, R. D. (2007). *A Biologically Inspired Micro-Vehicle Capable of Aerial and Terrestrial Locomotion.*

Bates-Green, & Howie. (2017). *Materials for 3D Printing by Fused Deposition.* Edmonds Community College.

Billingsley, D., Slipher, G., Grauer, J., & Hubbard, J. (2009). *Testing of a Passively Morphing Ornithopter Wing.*

C., G., & R., Z. (2007). Some problems of micro air vehicles development. *Bulletin of the Polish Academy of Science, Technical Sciences*, 91-98.

Chen, B.-H., Chen, L.-S., Lu, Y., Wang, Z.-J., & Lin, P.-C. (2016). *Design of a Butterfly Ornithopter.* Journal of Applied Science and Engineering.

Choi, J.-S., & Park, G.-J. (2017). Multidisciplinary design optimization of the flapping wing system for forward flight. *International Journal of Micro Air Vehicles*, 93-110.

Cutler, C. (2015, December 17). *How Does Aspect Ratio Affect Your Wing?* Retrieved from www.boldmethod.com: www.boldmethod.com/learn-to-fly/aircraft-systems/how-does-aspect-ratio-affect-a-wing/

DeLaurier, J. D. (1999). The Development and testing of a Full-Scale Piloted Ornithopter. *Canadian Aeronautics and Space Journal*.

Djojodihardjo, H., & Ramli, A. S. (2012). *Kinematic and Aerodynamic Modeling of Flapping Wing Ornithopter.* Researchgate.

Fenelon, M., & Furukawa, T. (2010). *Design of an active flapping wing mechanism and a micro aerial vehicle using a rotary actuator.* Elsevier.

GegeZ. (2018, November 26). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Drag_coefficient

George, R. B. (2011). *Design and Analysis of a Flapping Wing Mechanism for Optimization.* Brinham Young University.

George, R. B., & Thomson, D. S. (2011). *Design of a Flapping Wing Mechanism for Force Analysis and Optimization.*

Gerdes, J. (2010). *Design, Analysis, and Testing of a Flapping Wing Miniature Air Vehicle.*

Gerdes, J. W., Gupta, S. K., & Wilkerson, S. A. (2012). *A REVIEW OF BIRD-INSPIRED FLAPPING WING MINIATURE AIR VEHICLE DESIGNS.*

Grand, C., Mouret, J.-B., Martimelli, P., & Doncieux, S. (2008). *Flapping-Wing Mechanism for a Bird-Sized UAVs: Design, Modeling and Control.* Researchgate.

Grauer, J. A., & Jr., J. E. (2009). *A Multibody Model of an Ornithopter.* Florida.

Hall, N. (2015, May 5). Retrieved from www.grc.nasa.gov: https://www.grc.nasa.gov/www/k-12/airplane/momntm.html

Han, J.-H., Lee, J.-S., & Kim, D.-K. (2008). Ornithopter modeling for flight simulation. *International Conference on Control, Automation and Systems.* Seoul, Korea: IEEE.

Hedenstrom, A., & Liechti, F. (2001). *Field Estimates of Body Drag Coefficient on the Basis of Dives in Passerine Birds.* The Company of Biologists Limited.

Hodanbosi, C. (1996, August). *Lift Formula*. Retrieved from NASA: https://www.grc.nasa.goc/www/k-12/WindTunnel/Activities/lift_formula.html

Hu, H., Kumar, A. G., Abate, G., & Albertani, R. (2010). An experimental investigation on the aerodynamic performance of flexible membrane wings in flapping flight. *Researchgate*, 575-586.

Islam, S., Hasan, M. M., Tamal, M. M., Mian, J., & Evan, T. R. (2013). Detail Solidworks Design and Simulation of an Unmanned Air Vehicle. *Journal of Mechanical and Civil Engineering*, 95-100.

Jahanmiri, M. (2013). *Aircraft Drag Reduction: An Overview.*

Jasveer, S., & Jianbin, X. (2018). Comparison of Different Types of 3D Printing Technologies. *International Journal of Scientific and Research Publications*, 7602.

Kermode, A. C. (2006). *MECHANICS OF FLIGHT.* PEARSON.

Kinkaid, T. (2006). *Study of Micro Sized Technology, Micro Air Vehicles, and Design of a Payload Carrying Flapping Wing Micro Air Vehicle.* California: Dudley Knox Library.

Liang, B., Cui, J., & Zhang, L. (2011). *Research on Birds Flapping-Wing Bionic Mechanism.*

Malik, A., & Ahmad, F. (2010). *Effect of Different Design Parameter On Lift, Thrust and Drag of an Ornithopter.*

Marek, P., & Smreek, L. (n.d.). *DEVELOPMENT OF DART MAV - FIXED WING HOVER - CAPABLE MICRO AERIAL VEHICLE.*

Margerie, E. d., Mouret, J.-B., Ravasi, T., Martinelli, P., & Grand, C. (2007). *Flapping-wing flight in bird-sized UAVs for the ROBUR project: from an evolutionary optimization a real flapping-wing mechanism.*

Mawere, C. (2014). The Impact and Application of 3D Printing Technology. *International Journal of Science and Research (IJSR).*

Michelson, R. C. (2010). *Overview of Micro Air Vehicle System Design and Integration Issues.* John Wiley & Sons Ltd.

Miller, L. A., & Peskin, C. S. (2009). *Flexible clap and fling in tiny insect flight.* The Company of Biologists.

Muir, R. E., & Viola, I. M. (2017). *The Leading-Edge Vortex of Swift Wings.*

Muller, T. J. (2001). *Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications.* American Institute of Aeronautics and Astronautics.

Nabawy, M., & Crowther, W. (2017). *The role of the leading edge vortex in lift augmentation of steadily revolving wings: a change in perspective.* Royal Society Publishing.

Orlowski, C. (2011). Flapping wing micro air vehicles.

Orlowski, C. T. (2011). *Flapping Wing Micro Air Vehicles: An Analysis of the Importance of the Mass of the Wings to flight Dynamics, Stability, and Control.*

Orlowski, C. T. (2011). *Flapping Wing Micro Air Vehicles: An Analysis of the Importance of the Mass of the Wings to Flight Dynamics, Stability, and Control.*

Parker, G., & Borbone, J. (2010). *Wing and Gliding Dynamics of a Flapping Winged Ornithopter.*

Pfeiffer, A. T., Lee, J.-S., Han, J.-H., & Baier, H. (2010). Ornithopter flight simulation based on flexible multibody dynamics. *Journal of Bionic Engineering*, 102-111.

Phan, H. V., Au, T. K., & Park, H. C. (2018). *Clap-and-fing mechanism in a hovering insect-like two-winged flapping-wing micro air vehicle.* Royal Society Publishing.

Phan, H. V., Nguyen, Q. V., Truong, Q. T., Truong, T. V., Park, H. C., Goo, N. S., . . . Kim, M. J. (2012). Stable Vertical Takeoff of an Insect-Mimicking Flapping-Wing System Without Guide Implementing Inherent Pitching Stability. *Journal of Bionic Engineering*, 391-401.

Reid, L. D., & Etkin, B. (1996). *Dynamics of Flight: Stability and Control, 3rd Edition.* New York.

Ryan, M. (2012). *Design Optimization and Classification of Compliant Mechanisms for Flapping Wing Micro Air Vehicles.*

Sai, P. M., Bharadwaj, K., Teja, K. R., Dagamoori, K., Tarun, K. V., & Vijayan, V. (2016). *Design, Fabrication and Testing of Flapping Wing Micro Air Vehicle.* International Journal of Engineering Research and Application.

Sandeep, & Chhabra, D. (2008). COMPARISON AND ANALYSIS OF DIFFERENT 3D PRINTING TECHNIQUES. *International Journal of Latest Trends in Engineering and Technology*, 264-272.

Saxena, A. (2016). *A Comprehensive Study on 3D Printing Technology*. Researchgate.

Schouveiler, L., Hover, F. S., & Triantafyllou, M. (2005). Performance of flapping foil propulsion. *Journal of Fluids and Structures*, 949-959.

Shin, J.-U., Kim, D., Kim, J.-H., & Myung, H. (2013). Micro aerial vehicle type wall-climbing robot mechanism. 26-29.

Shin, J.-U., Kim, D., Kim, J.-H., & Myung, H. (2013). Micro aerial vehicle type wall-climbing robot mechanism. *Robot and Human Interactive Communication*, (pp. 26-29).

Shyy, W., Lian, Y., Tang, J., Viieru, D., & Liu, H. (2008). *Aerodynamics of Low Reynolds Number Flyers.* New York: Cambridge University Press.

Singh, S. M. (2014). *FLAPPING WINGS, A THEORETICAL APPROACH.* International Journal of Engineering Science & Advanced Technology.

Subramanian, K. K. (2016, March 6). Retrieved from www.quora.com: https://www.quora.com/What-is-Cl-max-for-an-aircraft

Sudo, S., Takagi, K., Tsuyuki, K., Yano, T., & Nishida, K. (2008). *THE DRAGONFLY FLIGHT BY A PAIR OF WINGS AND FREQUENCY CHARACTERISTICS OF WINGS.*

Sun, M., & Xiong, Y. (2005). Dynamic flight stability of a hovering bumblebee. *Journal of Experimental Biology*, 447-459.

Sunderland, R. (2017, May 8). Retrieved from Thisismoney: https://www/thisismoney.co.uk/money/news/article-4486224/How-birds-helping-Airbus-build-quieter-planes.html

Svanberg, C. E. (2008). *Biomimetic Micro Air Vehicle Testing Development and Small Scale Flapping Wing Analysis.*

Taylor, G. K., Nudds, R. L., & Thomas, A. L. (2003). Flying and swimming animals cruise at a Strouhal number tuned for high power efficiency. *International Journal of Science*, 707-711.

Thipyopas, C., & Intaratep, N. (2011). *Aerodynamics Study of Fixed-Wing MAV; Wind Tunnel and Flight Test.*

Tsai, B.-J., & Fu, Y.-C. (2009). Design and Aerodynamics Analysis of a Flapping-wing Micro Aerial Vehicle. *Aerospace Science and Technology*, 383-392.

Uhlig, D., Sareen, A., Sukumar, P., Rao, A. H., & Selig, M. S. (2010). *Determining Aerodynamic Charateristics of a Micro Air Vehicle Using Motion Tracking.* American Institute of Aeronautics and Astronautics, Inc.

Wang, Q. (2017). *Modeling, design and optimization of flapping wings for efficient hovering flight.*

Wang, Z. J. (2000). Vortex shedding and frequency selection in flapping flight. *Courant Institute of Mathematical Sciences*, 323-341.

Weisstein, E. W. (2007). Retrieved from www.scienceworld.wolfram.com: http://scienceworld.wolfram.com/physics/ThrustCoefficient.html

Whitney, J. P., & Wood, R. J. (2010). *Aeromechanics of passive rotation in flapping flight.* Cambridge university Press.

Wissa, A. A., Tummala, Y., & J. E. Hubbard, M. I. (2012). *Passively morphing ornithopter wings constructed using a novel compliant spine: design and testing.* IOP Publishing Limited.

Yu, C., Kim, D., & Zhao, Y. (2014). *Lift and Thrust Characteristics of Flapping Wing Aerial Vehicle with Pitching and Flapping Motion.* Scientific Research.