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Dissertation on

‘Biomimetic of a hummingbird: Design and analysis of wing and flapping mechanism’

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CERTIFICATE

This is to certify that the dissertation entitled

‘Biomimetic of a hummingbird: Design and analysis of wing and flapping mechanism’

is a bonafide work carried out by

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In partial fulfillment for the completion of 6th-semester course work in the Program of Study **B.Tech in Mechanical Engineering** under rules and regulations of PES University, Bengaluru during the period **Jun– Aug 2021**. It is certified that all corrections/suggestions indicated for internal assessment have been incorporated in the report. The dissertation has been approved as it satisfies the 6th-semester academic requirements in respect of project work.

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DECLARATION

We, **Rohit K Narang, Avva Sai Pranav, Sharan Manick, and Shaunak Anup Vaidya**, hereby declare that the dissertation entitled, '***Title,'*** is an original work done by us under the guidance of **Prof.Sachhidananda M H, Assistant Professor, Dept. of Mechanical Engineering** and is being submitted in partial fulfillment of the requirements for completion of 6^{th} Semester course work in the Program of Study **B.Tech in Mechanical Engineering**.

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ABSTRACT

The hummingbird has been an exciting point of research for decades together. New observations are being brought about every time new research is conducted on the bird. It has been a bird of great interest due to the different flapping modes, i.e., forward, backward, and hovering. Hummingbird being the smallest bird makes it a greater point of interest due to the incredible flapping speeds it can reach. Upon successfully replicating and studying such a bird, humans would be able to deploy it in various situations ranging from surveillance to rescue operations. Such is the potential of Hummingbirds. The hummingbirds have captivated the minds of researchers for not only their flight but also the amount of energy required, and the metabolic rate at which hummingbirds convert sugar into energy.

The objective of this report is to study the flight path and aerodynamic properties of a hummingbird. The research work is also aimed towards finding feasible flapping mechanisms and wing designs as it is believed that they are one of the key aspects to be highlighted upon. A handful of different mechanisms are explored along with their adjustable counterparts. These adjustments are explicitly made to ensure that the disadvantages from the former are minimized to an extent.

Multiple four-bar and five-bar mechanisms are observed and studied carefully and then worked upon to validate the existing research present. The respective models and simulations were carried out with CAD software and presented. Along with mechanisms, wing design is explored, and tests are run on them, respectively. The wing designs are carried out in CAD software, and then the appropriate tests are performed in a CFD-based software such as ANSYS Workbench.

Image processing techniques and photogrammetry were skillfully employed to judge the flight and encounter the wing path generation problem. The control engineering aspect is also implemented, and various equations related to the flight of the ornithopter are hence presented. These equations play a crucial role in the control and different flight scenarios present for the device. A holistic approach to the biomimetic design of a hummingbird is taken as a priority for the report

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LIST OF ABBREVIATIONS

Abbreviation	Caption
CAD	Computer-Aided Design
FWMAV	Flapping wing micro aerial vehicle
MEMS	Microelectromechanical systems
mAh	milliamps per hour
AOA	Angle of Attack
PET	Polyethylene terephthalate
CFD	Computational Fluid Dynamics
UDF	User Defined Functions

LIST OF EQUATIONS

CHAPTER 1: INTRODUCTION

One of the greatest minds of human history, Da Vinci to current scientists are fascinated by flight till the current generation. Da Vinci had a keen sense of curiosity coupled with observational skills that left no object in nature unanalyzed. Four hundred years before the first successful flight by the Wright brothers, Da Vinci had created a concept sketch of a variety of flying machines. His illustrations were highly detailed and contained notes on lift, thrust, equilibrium, and stability.

The first aerial voyage of any kind that man attempted successfully was using balloons. In 1738, Monsieur Rozier and Marquis d'Arlandes set sail in a balloon for a brief trip across Paris. In 1903, the Wright brothers managed to have the first controlled, sustained flight of a powered heavier than air aircraft flown. Their heavier-than-air aircraft research included works from many prominent figures such as Sir George Cayley, Otto Lilienthal, Octave Chanute, and Professor Samuel Langley.

In the years before their first flight, the Wright brother had sought out everything written about the subject. After coming across Ornithology, they believed there was nothing about a bird that humans could not scale up and replicate. Such is the effect on the birds throughout human history and the fascination with flight. It is undeniable that the idea of flight is highly inspired by humans' observation of birds in nature.

After years of a well-established aeronautical industry, we have discoveries on the bird's flight path and mechanics. Over the years, researchers have found that not all birds fly the same. Their classification is more diverse and distinct. We, as a team, have chosen a Hummingbird that has been a topic of research for a few decades and will be a topic of interest for decades to come as well.

Our present work focuses on analyzing flight path, required flapping rate, and kinematic study of a mechanism to achieve the flight path that a hummingbird generally exhibits. There is a portion of weight approximation and wing analysis; this is a part of the project works as it provides a range of input parameters for consideration during the kinematic design.

1.1 Biomimetics

Modern science developed over time; humans had an unquenchable curiosity about the world around us. The law of nature has always been "Survival of the fittest," which raised an even more significant question for researchers as sometimes counterintuitive design was still favourable and provided an advantage in many cases, leading to the thriving of a species. We followed the age-old expression " As monkeys see monkeys do." This ideology led to a new field of biomimetics, first coined by Otto Schmit in the year 1950. Humans began to take inspiration from such cases and further optimized existing designs, which revolutionized the design process and procedure. Biomimetics or biomimicry is taking inspiration from nature and biology to use to our advantage in engineering.

1.1.1 Design procedure for biomimetics

Scientists and engineers alike choose an organism of interest from nature and analyze it. The analysis comprises the working of the mechanism of a phenomenon, genealogy, and evolutionary study of an organism. The genealogy, evolutionary study, forms a basis for which a particular feature has survived throughout generations. It also provides a thorough understanding of why a specific trait has survived and its corresponding effects on the topic of interest.

The second step is replicating the mechanism, i.e., the design of the mechanism and a suitable control system. In this stage, we go through the standard mechanical design procedure, which comprises the following step:

1. Selection of possible mechanisms
2. Kinematic Design
3. Analysis of forces
4. Design of Elements
5. Prototyping
6. Optimization

The project's final step would be to optimize the design and replication of the phenomenon through various means, be it electrical, mechanical, or a combination of both. Innovative fabrication methods, design, and manufacturing are crucial in leading to future, plausible applications.

1.1.2 Applications of biomimetics

The aviation industry is one such industry that stands a testament to the application of biomimetics. It is a well-known fact that birds have heavily inspired the inspiration of flight. The first to achieve a successful flight, the Wright brothers had heavily studied ornithology during their research period.

The analysis of birds, fishes, and sharkskin has also given rise to a new section of swimwear that helps reduce water resistance. It has also helped inspire the streamlined design of many cars, race cars, and airplanes to reduce drag.

The sticky feet of geckos are known for their sticking ability. Further research found that the microstructure of hair-like projections of a gecko foot is the main factor in its sticking ability. Upon replicating this structure, they have been manufacturing human suits to help climb walls as geckos do.

Another day-to-day example of biomimetics is velcro. George de Mestral invented it in 1941. The burrs inspired it he found on himself and his dog when he had gone for walks. Their adhesive property fascinated him; being an engineer and entrepreneur got him to examine them under a microscope. Upon examination, he found that burrs have microscopic hooks that helped them adhere to fabric, which is now replicated and sold as velcro.

1.1.3 Drawbacks of Biomimetics

Drawbacks aren’t visible in plain sight; the faults lie in scenarios wherein the engineer cannot understand a particular phenomenon completely and choose replication blindly. Replication and mimicry have a fine line of separation, and it is a designer’s job to tread between that line and understand the difference. An example that illustrates this is as follows. In the 1960s, Mercedes-Benz sought to design an aerodynamic, safe, efficient, and maneuverable car. Using the concept of biomimetics, they chose boxfish, a fish near coral reefs. The boxfish’s carapace and shape were impressive hydrodynamic characteristics, low drag, and unique, inherent, and self-correcting stabilization properties. The box fish's body resembles a car which also helped design and made it an A-1 choice for their new vehicle.

Low and behold, in 2005, they unveiled the new car, the Bionic. The vehicle’s debut received substantial attention. Over time, Mercedes-Benz realized the problem with the vehicle Bionic. The self-stabilization feature that was a highlight of the vehicle proved to be its main drawback. Cars not only go straight but do have to take turns. The self-stabilization process greatly hindered the turning of the car. This is not true for a boxfish in nature which can zip away in the face of danger and navigate without collision in the complex environment of coral reefs. The difference in hydrodynamic analysis and reality led to a paradox named “The boxfish paradox.” The Royal Society later solved it, giving the following conclusions: drag reduction was lesser than average fish, and destabilizing moments present that helps maneuverability more than self-stabilization.

The problems faced by the bionic engineers could easily be avoided if the engineers completely understood the boxfish’s working principle and implemented it in a manner that would suffice their needs rather than complete replication. Understanding the consequences is an integral part of biomimetics.

1.2 Hummingbird

Hummingbirds are native to America and the family of Trochilidae. There are about 360 species, and a majority of these are present in the tropic. They range from 7.5-13 cm in length and weigh around 2- 24 grams. The smallest being ‘bee hummingbird’ and the largest being ‘giant hummingbird.’

1.2.1 Characteristic Features

Hold the record for the smallest bird and have a heartbeat of about 1000 beats per minute. They also are the only birds in the animal kingdom that can fly forward, hover in the state, and backward. They can remember every flower they have visited and calculate how long it will take for a particular flower to restock with nectar. When scaled to human size they consume about 155,000 calories a day.

CHAPTER 2: LITERATURE SURVEY

A literature survey is an examination of academic sources on a particular subject. It offers an overview of current knowledge, allowing for identifying approaches, applicable hypotheses, and research gaps. Journals containing previous attempts of ornithopters inspired by biomimicry were referred to understand the design procedure and the required techniques for kinematic analysis and design.

2.1 Literature survey

This paper by Paolo Dario et al.[1] gives the reader a thorough understanding of biomimicry and explains the various machines that have been bio-inspired. It served as a comprehensive guide to the big world of biomimicry. This paper spoke about the future scope of robotics.

This paper by Michael Rufo et al. [2] broke down biomimicry into multiple stages and gave the reader the approach required to approach biomimicry. It warned the reader about the danger of copying and mimicking, as copying without understanding the mechanism would lead to suboptimal design. The designer must implement only a particular bio mechanism to achieve the required function. This paper also spoke about the challenges of a surveillance robot and how the real world is more complex, no matter the harshness of the test environment. The robot should be capable of understanding and adapting to this ever-changing environment.

This paper done by Douglas et al. [3] spoke about the technical aspects of the hummingbird's flight. It brought about major/important characteristics of hummingbird flight that cannot be noticed with the naked eye. Unlike usual birds, hummingbird thrust is not entirely provided by its downstroke but rather a combination of both. It also gave other crucial details required for wing designing, such as Reynolds number.

The paper concluded that despite differences such as size, musculoskeletal, flight aerodynamics, and other nature-induced differences, hummingbirds resembled aerodynamic mechanisms similar to insects. The upstroke and downstroke wing movements of the bird are analyzed. It was found that hummingbirds provide 75% of their body weight in output during the downstroke and only 25% during the upstroke. This asymmetry was later explained by the fact that the cambered wing undergoes an inversion during the upstroke during flight. The leading-edge vortices produced during the downstroke also suggest that they may operate in significantly low Reynolds numbers to resemble that of insect hovering. This paper acted as a reference to the experimental test setup.

This paper by Yanghai Nan et al. [4] studies the hummingbirds from a morphology perspective to understand the biology of the hummingbird in-depth and understand how it is applicable to help create a Flapping wing MAV. For example, they have looked into the weight distribution of the components for each other, the path traced by the wings of the hummingbird in flight, and many other aspects. They have also compared some of the successful projects done by other researchers in the same field and their approaches in choosing a particular flapping mechanism. Then they studied specific scale laws to help develop the wing and once again compared the wings used by other researchers. Finally, they also looked into the design of the tail for the FWMAV and how it can be applied to improve stability.

This paper by Mostafa Hassanalian et al. [5] spoke about the various approaches taken in the wing design process. It provided the reader with the different manners to implement wings. Paper by Keith W.Moored et al. [6] spoke in detail about the tensegrity wing model and its calculations.

This paper by Bret W. Tobalske et al.[7] gave the actual values of the wing. This paper was a reference for the entire design process, and paper [8] acted as a proof of concept for the method implemented in the design phase. It also provided the team with a procedure and errors to avoid while carrying out photogrammetry.

The work done by Sridhar Kota et al. [9] and Steven M concerning compliant mechanisms introduced us to the bare basics of compliant mechanisms and found that compliant mechanism and Compliance in design leads to jointless, no-assembly, monolithic mechanical devices and is particularly suited for applications with a small range of motions. The fact emphasized here is that traditionally human-made designs are stiff, but the natural methods are 'compliant while also being strong at the same time. The compliant mechanisms and the first few steps were carried out to make a working model successfully. A topology synthesis was done to establish a possible topology concerning the input-output force-displacement relationship. The problem statement was tackled, and the size and shape optimization was done. It was also mentioned that a few key design criterions need to be met concerning the tests carried out. A few of the criteria are as follows:

(i) required stiffness to an external load,
(ii) required kinematic motion (both magnitude and direction)
(iii) Stress limitations and buckling instabilities,
(iv) design space and materials properties.
(v) dynamic considerations, and
(vi) weight limitations.

The paper concluded with the possible applications of Compliant mechanisms, and one of the critical areas mentioned was found out to be MEMS-Micro-electromechanical systems. The scope for future ideas with compliance in design is discussed.

The 2012 study by Yao-Wei Chin et al. [10] aimed to research a mechanism that would most likely use compliant mechanisms. The work showed that a clicking compliant mechanism produces more thrust per input power than a conventional non-clicking rigid-body mechanism for synthesis replication. A Dipteran insect model was used to simulate the flight of FWMAV's – known as Flapping Wing Micro Aerial Vehicles. The paper performed tests, did a kinematic analysis, and concluded that significant and fast wing strokes with a large pitching angle produced significantly higher thrust efficiency than a non-clicking mechanism with rotary joints.

The paper by Michael A.A.Fenelon et al. [11] looks into a flight mechanism known as the MSC mechanism, which stands for the "*Modified slider-crank*" mechanism. Here a rotary actuator was used, which provided active rotation and flapping of the wings. Before moving further, we would like to look into what a rotary actuator is. A rotary actuator is a simple actuator that produces a torque or a rotary motion. It is purely mechanical, where linear motion in one direction gives rise to rotary motion in another. The motion produced by an actuator may be either continuous rotation, as for an electric motor, or movement to a fixed angular position as for servo motors and stepper motors.

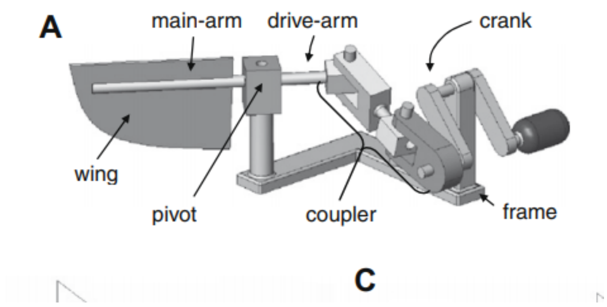


Fig. 2.1 Modified Slider Crank[11]

The kinematic design was explained and the flapping procedure was as follows –

As the crank rotates it pushes or pulls the drive-arm along an arc (since a pivot constrains the drive-arm), creating wing strokes. The crank's rotation also inclines the coupler concerning the stroke plane. This inclination of the coupler twists or rotates the drive-arm and the wing. Hence wing flapping with rotation is achieved through the rotation of a crank.

This paper by Michael et al. [12] focuses on developing a mechanism for an insect-sized FWMAV. They have used a simple four-bar mechanism to achieve the required flapping motion. The actuator used is a piezoelectric actuator, and the reason for this type of actuator is that the input crank's necessary input is minimal. After the design, forces applied to each link are also evaluated. Next, they propose a few manufacturing techniques and materials that can be used for the same. Finally, the mechanism was tested using a laser vibrometer, and the results obtained are per the design procedure.

This paper by David et al. [13] looks into the entire procedure of making an FWMAV based on a hummingbird. The prototypes made by them are around 62g which is slightly on the higher side. They have used a four-bar mechanism modified by adding a fifth linkage and a slider to amplify the output. The wing was of a flexible type that could undergo passive deformation and provide the required lift. An experimental approach was used for the wing design, and multiple iterations were made to find the optimal wing design, which gave the maximum lift. Plane tilting along with amplitude modulation of the wing was used to control and stabilize the system. An autopilot system was also developed to improve the same. Flight testing and Gimbal testing were performed, and results were found to be satisfactory, and some of these results were also presented.

This thesis by Matˇej et al. [14] mainly focuses on developing a control mechanism for an FWMAV. The main aim of this mechanism is to stabilize the vehicle during flight. They proposed two possible solutions for the same. They also developed a prototype of the robotic hummingbird in which they talk about the flapping mechanism and the wing design, which is of greater interest for us currently. They used a DC motor to power the flapping mechanism, which consisted of a slider-crank mechanism whose output was further amplified using a four-bar mechanism. They also compared different varieties of motors to find the one most suitable for the mechanism as mentioned above. For the initial wing design, inspiration was taken from other researchers in the same field. Further refinement was done by an experimental approach wherein multiple aspect ratios were compared to arrive at the most optimal aspect ratio that provides the highest lift. The materials used for the wing were also discussed.

The thesis by Matˇej et al. [14] proposed a formula for the lift of the wing undergoing flapping motion. The mean lift force calculations for flapping wings is found by approximating classical theory for a fixed-wing in steady flow while using cycle-averaged quantities. Here the concepts of center of pressure, mean velocity are put into use. Trends with regard to flapping flight are also observed.

In article [15], we learn that flapping-wing flight has been extensively studied in the field of entomology, resulting in observation on the methods of lift production, high manoeuvrability, and efficient flight for various natural flyers in differing flow regimes and leading to significant developments in biomimetic theories regarding flapping wing MAVs. In addition, advances in aerodynamic modelling methods have given insight into the unsteady 3-dimensional flow that characterizes typical flapping-wing flight. Therefore, before attempting to model a flapping wing MAV and analyze its stability, it is beneficial to consider previous studies carried out. The paper examines hover-capable flapping-wing flight as presented in earlier work. The kinematics and aerodynamics seen in nature and the resulting control methods are explored.

The research and development efforts presented in this paper by Roman Y. Krashanitsa et al. [16] address the flight dynamics of a flapping-wing air vehicle (ornithopter). The 74-cm-wing-span ornithopter was equipped with an automatic flight control system that provides stability augmentation and navigation of the vehicle and flight data acquisition. Wind tunnel tests were conducted with the control surfaces fixed in the trimmed position and the flapping motion of the wings activated by a motor at a constant throttle setting. Coefficients of vertical and horizontal force and pitching moment were determined at a free stream velocity of 7.25 m/sec, and the angle of the stroke plane varied from 0 to 40 degrees. A series of flight tests were conducted with fixed controls, demonstrating ornithopter stability in all axes. Proportional control laws were programmed into the autopilot for the closed-loop controls. Many flights of autonomous ornithopters were conducted with the telemetry acquisition. During the autonomous flights, the ornithopter performed waypoint and altitude navigation, demonstrating stable performance.

From the study done by Dean Ninian et al. [17], it is seen that the design and development of morphing (shapeshifting) aircraft wings—an innovative technology that can increase aerodynamic efficiency and reduce noise signatures of aircraft—was carried out. This research focused on reducing lift-induced drag at the airfoil flaps and improving the design to achieve optimum aerodynamic efficiency. The simulation revealed a 10.8% coefficient of lift increase for the initial morphing wing and 15.4% for the optimized morphing wing compared to conventional wing design. At angles of attack of 0, 5, 10, and 15 degrees, the optimized wing increases the lift-to-drag ratio of 18.3%, 10.5%, 10.6%, and 4%, respectively, compared with the conventional wing. Simulations also showed a significant improvement in pressure distribution over the lower surface of the morphing wing aerofoil. The increase in flow smoothness and reduction in vortex size reduced pressure drag along the wing’s trailing edge. A morphing wing reduced the size of the vortices, and therefore the noise levels measured were reduced by up to 50%.

This paper by Che-Shu Lin et al. [18] employs the four-bar linkage to simulate the flapping motion of a bird. Wind tunnel tests are performed to understand and measure the lift and thrust of the flapping wing under different frequencies, speeds, and angles of attack. The varying trends with respect to each variable are observed and their corresponding effects on the flight are noted down. It was found that an angle of attack was necessary to have a lift force.

The study carried out by S Mahendran et al. [19] aims to understand the working principle of ornithopters and their ability to generate lift and thrust under various test conditions. The flapping wing mechanism employed here was the crank mechanism and is tested at two different speeds of 3m/s and 6m/s. The aerodynamic characteristics such as lift and drag are measured using the ANSYS software. The measurements are taken at different angles of attack and it is found out that the mechanism is the most efficient at an angle of 15 degrees with speed of 6m/s.

2.2 Summary of Literature

To summarize, the literature review is extensively done, considering some of the critical factors of an efficient FWMAV. The basics of biomimicry and the advantageous features of the hummingbird are studied. The aerodynamic characteristics of the hummingbird are also discussed, along with its style of flight. A wide range of research is already present to understand the biology of the hummingbird in-depth and its application as a flapping wing MAV. This research was essential in understanding MAVs and their category of devices. To generate a flapping motion similar to that of a bird, various mechanisms along with their work are studied and noted. One of the mechanisms included the four-bar mechanism and the slider-crank mechanism. The wingtip properties are also probed, and the difference concerning change in its orientation is noted down. Critical parameters such as the angle of attack and its influence are explored. Flapping lift properties and the methodologies to calculate flapping lift are explored. Flight dynamics and stability are key factors, and literature concerning these are thoroughly analyzed .

2.3 Gap in literature

After conducting an extensive literature review, most papers focused on traditional mechanisms. Attractive alternatives like the research round compliant mechanisms are short in number. The tools and materials required to synthesize the flapping mechanism also play a key role in influencing parameters like weight, dimensional limits, etc. The research solely around them is limited in number. Subsequently, the structural experimentations on these mechanisms are also low in number. Methods for unsteady-state CFD concerning the flapping motion of the wing are also challenging to find. The methodology for such simulations is bleak, and current research makes it harder to implement with the present work. The heart of a robotic hummingbird would be the control system, as this actuates the different motions the ornithopter can undergo. There is a clear gap in the literature about linking suitable control systems with electronic components and the flapping mechanism.

CHAPTER 3: METHODOLOGY

Following the design procedure of biomimicry the design procedure is split into the following stages:

- Photogrammetry and Kinematic Path of Flight
- Weight Approximation
- Wing Design and Analysis
- Mechanism Design and Analysis

Each stage was given a symbiotic treatment such that the results of one stage were used for the iterative design of the rest. In such a manner, it was true to the design procedure of biomimicry and allowed for the consideration of all the parameters that have arisen during the design process.

3.1 Photogrammetry and Kinematic Path

3.1.1 What is Photogrammetry?

Photogrammetry is the science and technology used to extract the dimension of an object using photos. The main aim of photogrammetry is to extract precise 3D dimensions from 2D images. The art of photogrammetry techniques has been present as long as the technique of taking photos. The process initially used mechanical and optical measurement tools. As technology improved, the techniques incorporated image processing techniques giving rise to sophisticated computer-aided solutions.

3.1.2 Why was photogrammetry used?

There was a need for photogrammetry as hummingbirds are native to the region of South America. In such scenarios studying the bird could be done through the means of various previously published papers or through the vast resource known as the internet. Hummingbirds have been a point of interest for decades as many researchers, zoologists, and enthusiasts have taken a great deal of effort to record videos of the flight path of hummingbirds. The videos in certain scenarios use state-of-the-art slow-motion cameras which capture about 3000 frames per second. This would be much greater than the rate of flapping of hummingbirds. Allowing the study of individual flaps and intermittent flaps. Paper [6] provided the dimensions of the hummingbird, it still was not enough to design the real-life wing structure as it is an organic structure, and the natural curves of it cannot be accounted for through the dimensions table. The paper[6] also acted as a validation method to see if the techniques of photogrammetry were used to provide valid results.

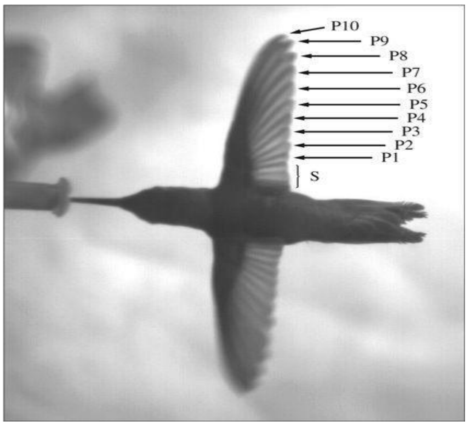


Fig. 3.1 Source Image Used for Photogrammetry[6]

3.1.3 Procedure

Step 1: Choosing a source image for the procedure.

There are primary considerations required for choosing the image:

1. The pixel density of the image
2. Clarity of the image
3. The orientation of the object in the image is to be measured

Step 2: Calibration.

The procedure would be using the tool from the internet

The user must input the density of pixels per inch (DPI) of the screen. This would provide a simple conversion from pixels to millimeters. The DPI calibration is done by measuring a red stripe on the screen using a physical ruler. Depending on the measurement value of the red stripe, the DPI of the screen is found.

Table 3.1 Millimetre-DPI table

Measurement (mm)	Screen DPI
76	100 DPI
82	92 DPI
89	85 DPI
95	80 DPI
101	75 DPI
108	70 DPI
115	66 DPI
120	63 DPI
127	60 DPI

Step 3: Measurement

The final step would be to measure pixels that are accomplished using the ruler option present in the tool roster of Adobe Photoshop—inputting the pixel value into the tool to obtain the corresponding millimeter value. The DPI value ensures the correct conversion from pixel to millimeter conversion.

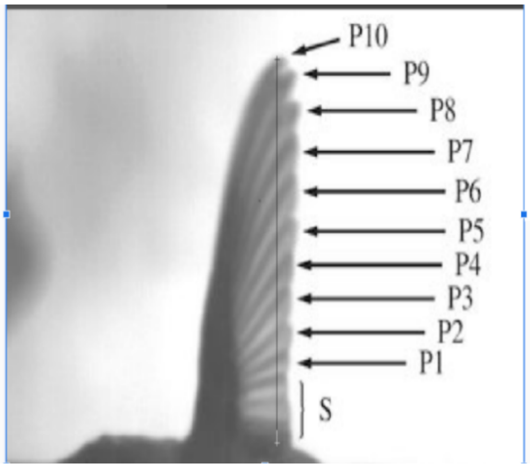


Fig. 3.2 Points on the wing [6]

Table 3.2 Morphological data for the hummingbird

Variable	Value
Body mass (g)	3.4 ± 0.1
Single wing length (mm)	47 ± 1
Wingspan, b (mm)	109 ± 2
Average wing chord, c (mm)	12 ± 1
Aspect ratio	9 ± 1
Single wing area (mm^2)	558 ± 18
The combined area of both wings and body (mm^2)	1346 ±108
Wing loading ($N\ m^{-2}$)	25 ± 3
Disc loading ($N\ m^{-2}$) Values are mean ± s.d. (N= 5)	3.6 ± 0.2

3.1.4 Modelling the Wing

After obtaining the angles and distances, it was a simple case of plotting the points in SolidWorks to create a 2D closed contour and extruding it.

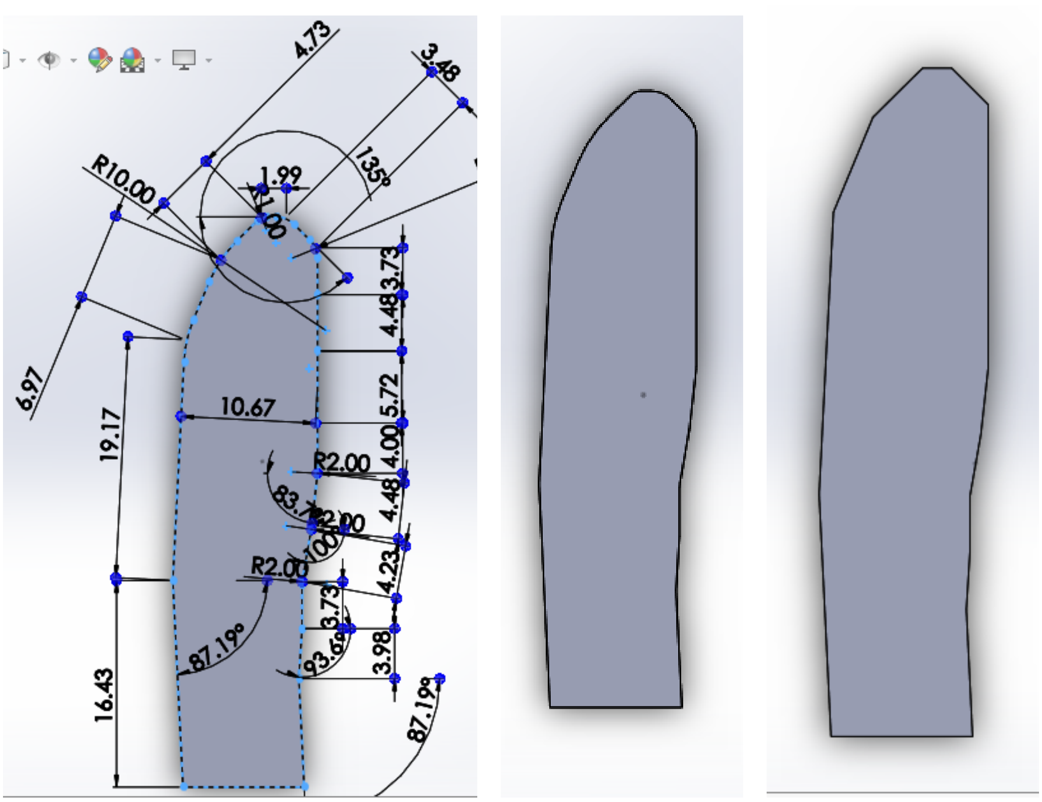


Fig. 3.3 Construction of the wing

The above design of the hummingbird in figure(3.3) also provided a validation of the process of photogrammetry and also allowed for the extension of this technique for the study of the kinematic path.

3.1.5 Kinematic Path of Flight

A drawback of photogrammetry is that when a 3D object is projected onto a 2D plane, there is a loss of information in one of the planes. This is compensated by the analysis of the object in two different views. In such a manner, the Kinematic path of flight analysis is dealt with in two stages. The procedure for the analysis of the Kinematic Path of Flight is the same as photogrammetry. It is extendable to a video due to the simple fact that videos are multiple images that are played back at a certain speed. Using this analogy, the image process technique of photogrammetry is extended onto a video. The software that is used for this procedure is Adobe Premiere Pro.

The first analysis is conducted from the side view of the bird; this would allow for the identification of the flight path by following the wingtip of the bird. In this study, the wing is considered rigid, neglecting the small amount of flex along the edge of the wing attached to the bird.

Fig. 3.4 Wingtip path on the source video

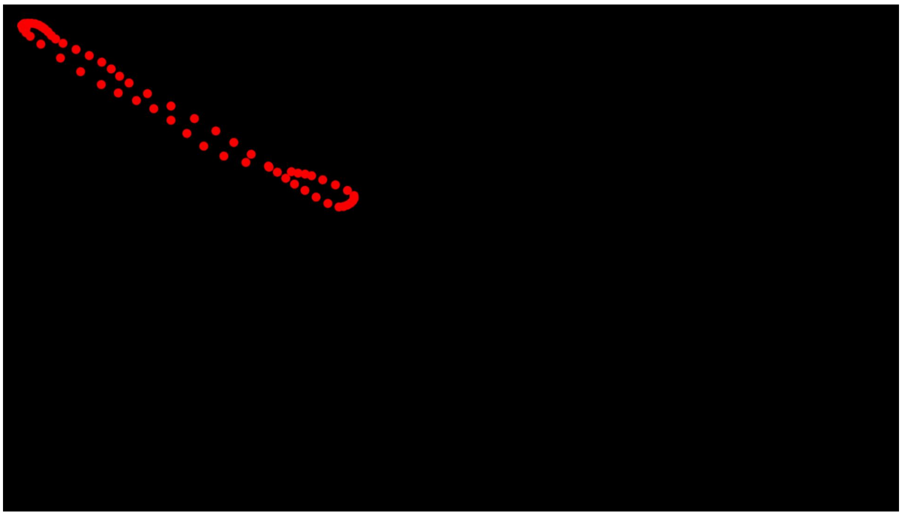


Fig. 3.5 Wingtip path on the transparent background

The following figures (3.4) and (3.5) show that hummingbirds follow a unique path of an 8, which is different from a majority that flaps in only one direction without any motion in another direction. Analyzing further and plotting multiple paths as shown in the image below, it can be inferred that the amplitude and direction of the eight shapes determine the flight characteristics and help maintain balance during its various flight modes: hover, forward and backward.

Fig. 3.6 Two strokes plotted side by side.

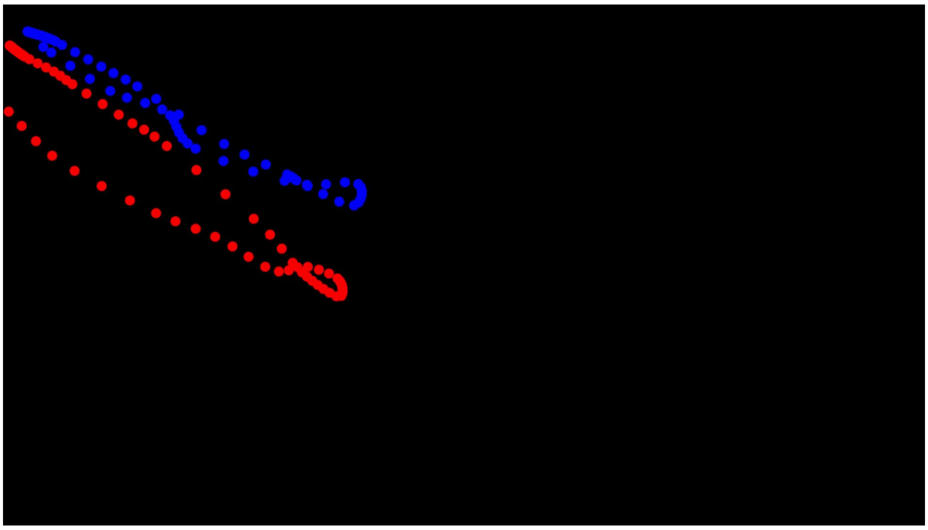


Fig. 3.7 Two strokes plotted side by side on black background

As mentioned earlier, the kinematic path, figure(3.7), shows two different wingtip paths. The variation in the eight shape orientation from the axis to the one in red helps in hover and maintaining flight.

The analysis of the wing in the front view is essential to understand the flight path of the hummingbird. In figure(3.8), the analysis was conducted using a reference point that does not change throughout the stroke.

Fig. 3.8 Front view of flapping

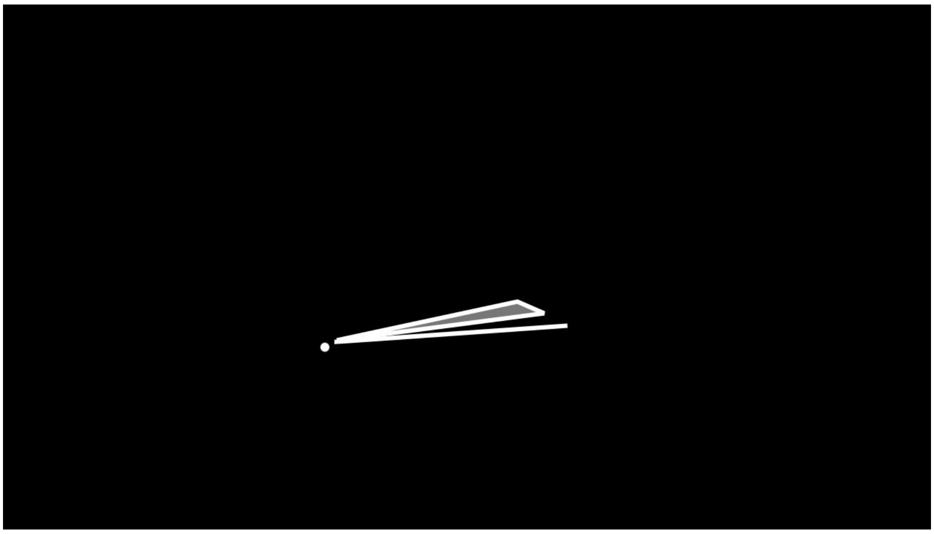


Fig. 3.9 Front view of flapping on black background

Figures (3.8) and (3.9) show that the wing moves perpendicularly to the reference point. The difference in line length is due to parallax error and the fact that any 3D object projected onto a 2D space will have a loss of data. This is one of the drawbacks of photogrammetry

From the above figures, we can infer that hummingbirds carry a 3D space motion of harmonic flapping and an eight shape motion at their wingtip. The report assumes only the harmonic flapping motion and designs a suitable mechanism. A spatial mechanism is essential for the complete emulation of the flapping of a hummingbird.

3.2 Weight Approximation

Approximate weight is calculated as it plays a crucial role in the design process. For a design of the wing, there must be a known value of weight. The weight of any robot is divided into the mechanical component and the electrical component.

The electronics design of any system is divided into four central sub-systems. The first is the system's brain; here, we have chosen the microprocessor as the brain of the system for being the upper weight limit and freedom to improve the design. Any aviation-based system's telemetry requires an inertial measurement unit, GPS, and a set of receivers and transmitters. The inertial measurement unit(IMU) contains a gyroscope sensor that allows for the bird's balance during flight. The GPS complements the IMU and helps in providing greater accuracy detail. The motor is the necessary component for the driving force, and all the above electronics require a power source. A lipo rechargeable battery is chosen for its lightweight, size, and reusability.

We have estimated two kinds of weight: the prototype and the weight required for a testbed.

3.2.1 Testbed

The testbed contains all the essential components ignoring the weight of the telemetry components and the power source. These are connected externally and then the weight is approximated.

Table 3.3 Electronics Weight Approximation for Test Bed

Sl.No	Name	Type	Voltage/Ampere per Hour	Weight(grams)
1	MPU-9520	Inertial Measurement Unit	3.3/60 mAh	4g
2	Neo-6M	Antenna	-	2g
3	Coreless Motor	Rotary Motor	3.3V	20g

In the testbed, we estimate the total electrical weight to be 26 g. The antenna of the GPS module is required on the bird; the main sensor board can be separated. If we consider the electrical weight to be 50 percent of the overall, the total weight the wing should be able to lift is 52 g.

3.2.2 Prototype

Table. 3.4 Electronics Weight Approximation for prototype

Sl.No	Name	Type	Voltage/Ampere per Hour	Total Weight of each component (grams)
1	Raspberry Pi Zero	Microprocessor	3.5V/72 mAh	9 g
2	MPU-9520	Inertial Measurement Unit	3.3/60 mAh	4g
3	Neo-6M	GPS	3.3V/2700 mAh	10g
4	HC-12	UART Receiver/Transmitter	3.3V/ 216 mAh	4g
5	Coreless Motor	Rotary Motor	3.3V	20g
6	3.7 V 3000 mAh	Lipo Rechargeable Battery	3.7	50g

The total weight of the prototype would be 193 grams with the mechanical components. The prototype's weight can further be reduced by redesigning the electrical system without the use of off-the-shelf components. In a scenario where off-the-shelf components are not used, the PCBs weight would be around 10 grams, as many of the repeated components of a circuit board, such as a 3.3 V circuit breaker, can be removed. Such components can further be simplified. Hence the total approximate weight of the prototype would be brought down to under 100 grams

3.3 WING DESIGN PROCEDURE

The 3d wing is designed in CAD software with a definite set of procedural steps. A 3D model of the wing is a necessity for any fluent-based analysis. The software used for this is DS Solidworks 2019. Solidworks is an efficient user-driven software. It has a wide range of support services in the form of forums, offline and online help. It easily allows for various other processes without the requirement of additional software for the same.

Solidworks allows for animations, forces due to motion, flow, part stress, deflection, vibration, and effects of temperature analyses.

For optimal wing design within the design constraints, wing design is studied for its lift characteristics and corresponding flapping frequency. A standardized procedure is implemented for the uniformity and comparability of results in the design of wings.

A standard procedure is followed for the wing design. For each wing design trial, the wing length and the tip chord had a rate of inverse proportionality to each other. The root chord is kept constant. Further iterations of the wing design transformed the wing from a rectangular figure to a triangular outline in the later stages of the trials. A wing with a right-wing length in the range of a real hummingbird was considered. The effect of triangulation on each iteration was also taken into consideration. The geometry representations are given in the figure(3.10).

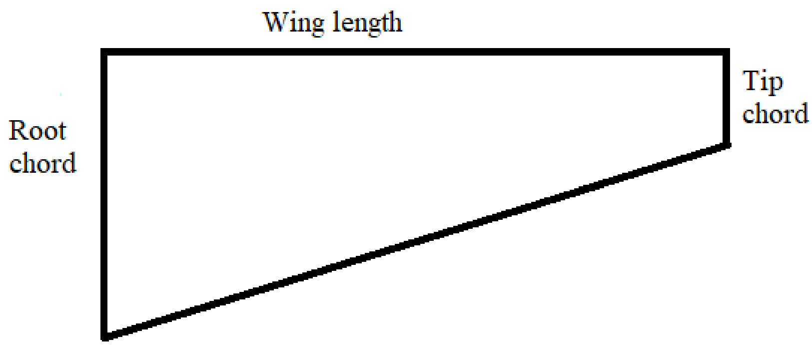


Fig. 3.10 Geometry specifications

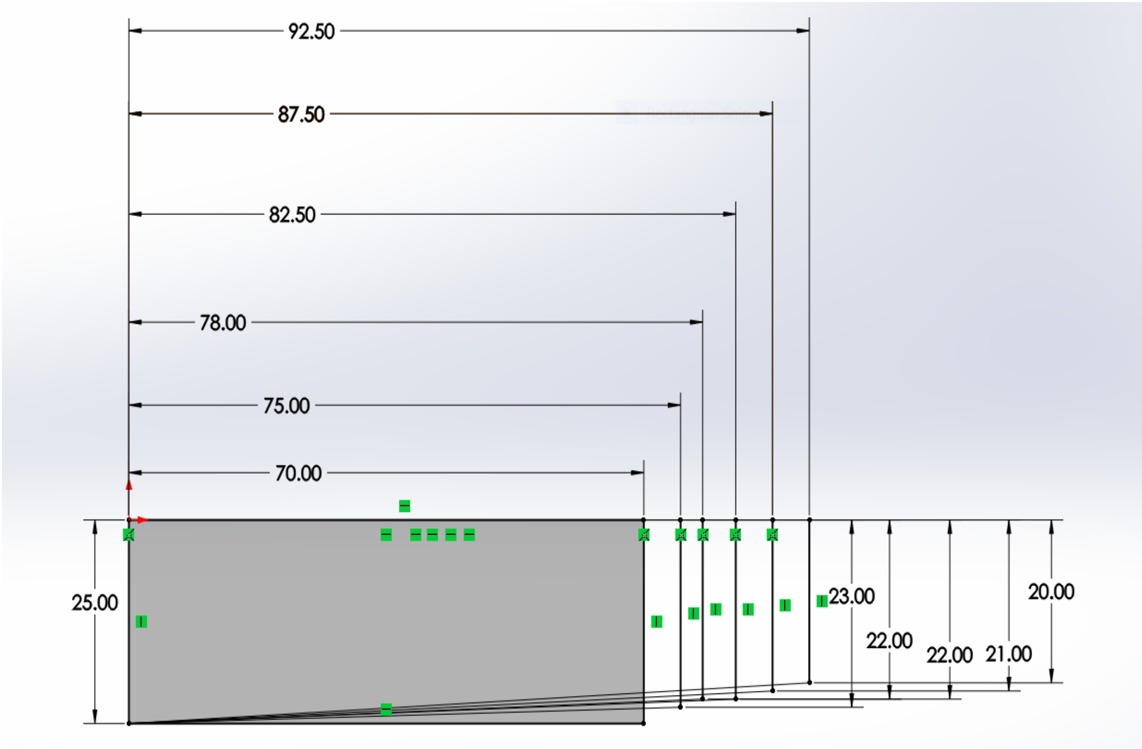


Fig. 3.11 Wing designs superimposed

An image of different wings superimposed on one another to show the dimensional increments is illustrated in figure(3.11).

3.3.1 Validation Work: Steady-state CFD Analysis

The procedure for the flapping wing motion of a hummingbird is broken down into steady state, unsteady-state flapping. The first step is to carry out a steady-state analysis to understand the aerodynamic properties. The previously designed wing models are utilized for steady-state analysis.

By steady state, it is meant that the wing moves through the air with a constant velocity. In the steady-state, there is no relative wing motion with respect to the viewer, i.e.; It is a fixed-wing.To reiterate, there is no flapping motion of the wing during steady-state analysis.

The first task was to obtain pressure contours of the wing and see how it behaves when it is not flapping. The result is used for validation purposes towards the project. These tests and simulations are used to understand the basic concepts of wing aerodynamics.

A brief flowchart procedure as shown in figure(3.12) to carry out the steady-state CFD simulation is given below:

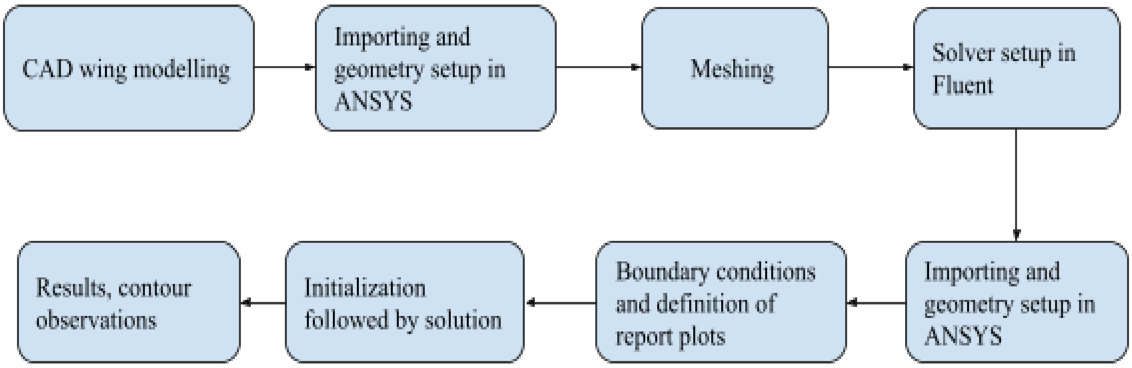


Figure 3.12 Procedure flowchart

The wing model is made with the help of CAD software. This wing geometry is then imported to ANSYS FLUENT in a ".STEP file" format. The imported wing is oriented at an angle of 15, and an enclosure is made around it. In the next step, the wing is subtracted using the boolean option. The surfaces' meshing and the naming of the surfaces are carried out before the solving process. In the fluent database, the Spalart-Allmaras is chosen, followed by providing the appropriate boundary conditions. The boundary conditions are kept at 5m/s inlet velocity and 0 pressure outlet, respectively. Standard initialization while computing from the inlet is done, and contours in the post-processing are recorded.

The resultant pressure contours are compared with a research paper [19].

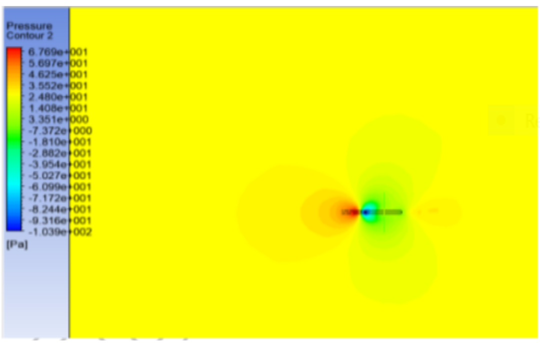


Fig. 3.13 Contours from research paper

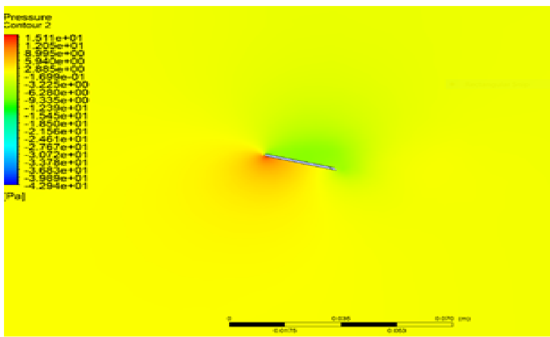


Fig. 3.14 Contours from present work

The figures(3.13) and (3.14) indicate that the concepts of steady-state aerodynamics hold true wherein the pressure differences on the upper and lower surfaces of the wing are distinctly visible.

From the results, it is visible that steady-state aerodynamics hold good verifying the analysis procedure. The picture on the right is the same analysis with a slight variation in the angle of attack. Hence, it is inferred that the simulation is validated as the respective pressure contours from both the pictures match.

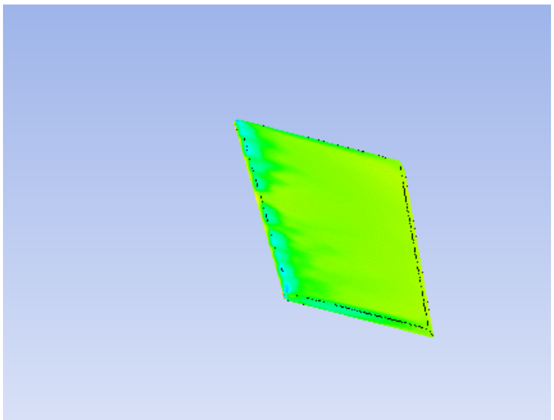


Fig. 3.15 Upper surface

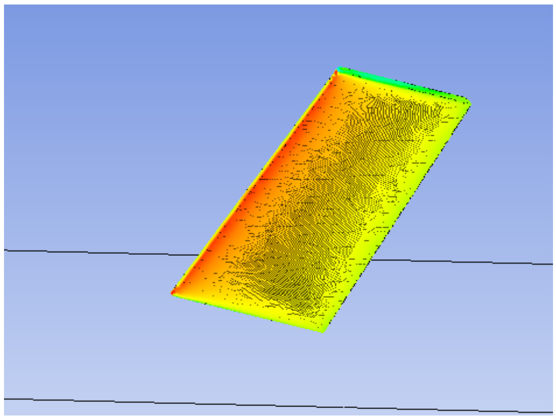


Fig. 3.16 Lower surface

Figure (3.15) represents the top surface of the aerofoil, while figure(3.16) on represents the bottom surface. As the intensity of the color (green - red) increases, the pressure value increases proportionally. A theoretical aerofoil has a higher pressure on the lower surface when compared to the upper surface. This trend is visible in figures (3.15) and (3.16), as mentioned earlier.

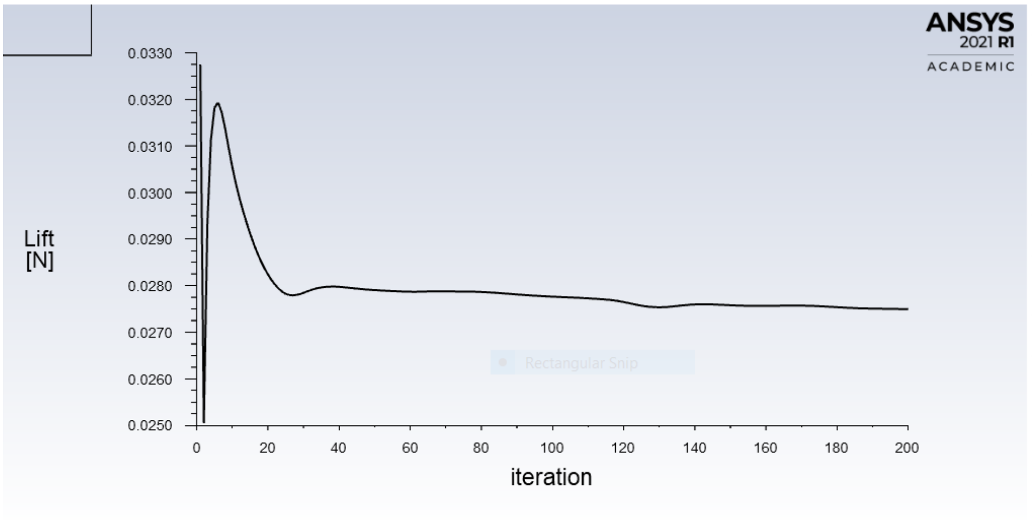


Fig. 3.17 Lift plot

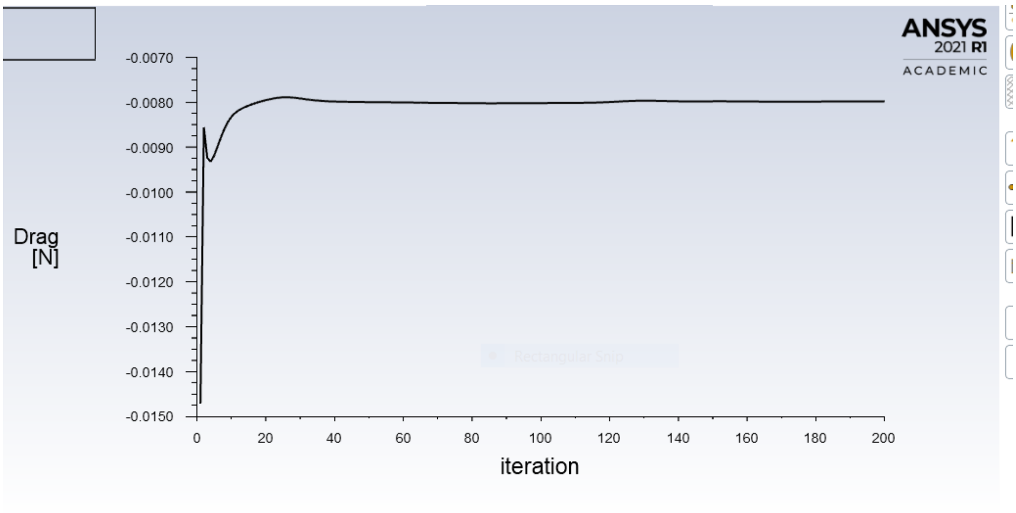


Fig. 3.18 Drag plot

Figures(3.17) and (3.18) indicate the lift and drag plots obtained respectively for the wing in the steady state tests.

3.3.2 The Angle of attack and its influence

In the following section, the influence of the angle of attack is observed, and variation of lift and drag properties. The angle of attack (AOA) is the angle between the chord of a wing and the relative wind. The straight line from the leading edge to the trailing edge is known as the wing's chord.

The procedure is started with an angle of inclination of 0 degrees, and it is then incremented by 2 degrees for every trial. The lift and drag values are recorded for each trial up to an angle of 30 degrees. This test is once again carried out in Ansys workbench with the help of the parametric analysis tool. Parametric analysis tools help the user obtain multiple results by varying a specified set of parameters. It is a fast and efficient way to find trends in results without the user having to make the changes for each calculation manually.

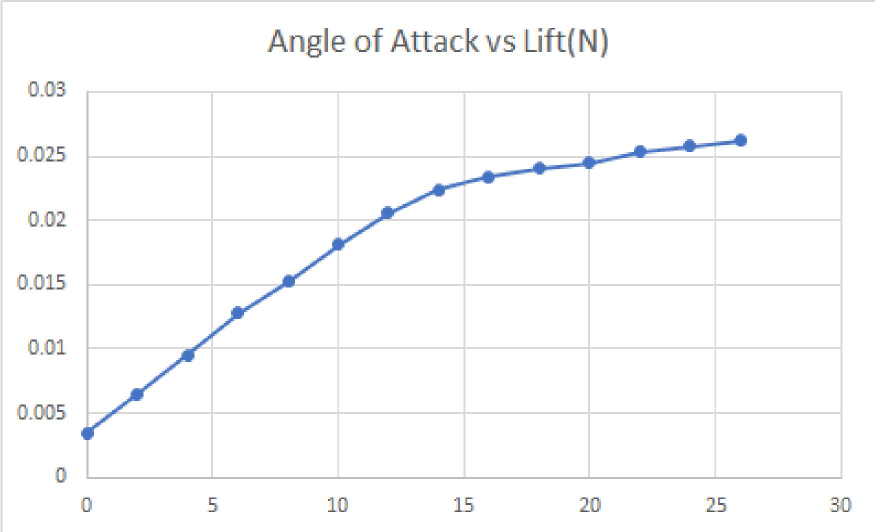


Fig. 3.19 Lift vs Angle of attack plot

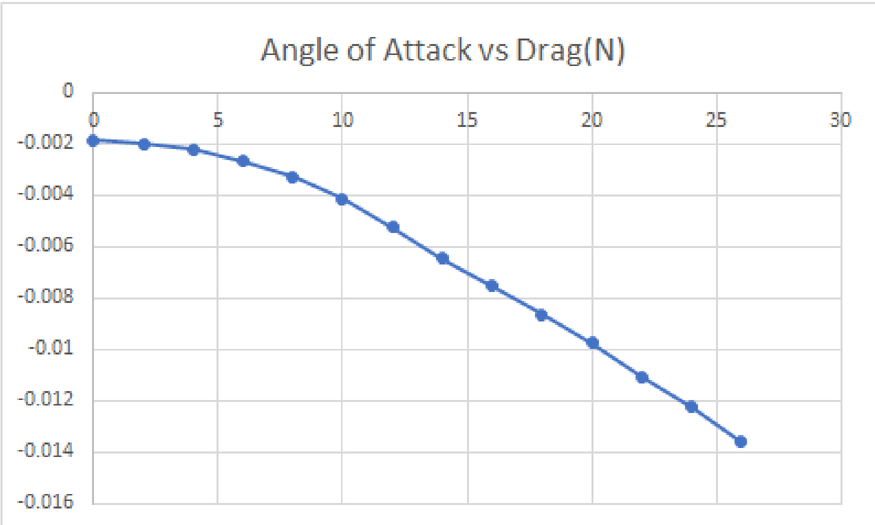


Fig. 3.20 Drag vs Angle of attack

From the above results observed in figure(3.19) and (3.20), two prominent trends are observed:

1) There is an increase in a steady-state lift with an increase in Angle of Attack

2) There is a subsequent increase in the magnitude of drag force with an increase in Angle of Attack

A trend of increasing lift is noticed with an increase in the angle of attack. At first glance, this would seem favorable, but it is also observed that with an increased angle of attack, the drag force experienced increases. This hints that there is only an optimal amount up to which the angle of attack can be increased. The data presented gives us valuable information on how the wing should be inclined and at what angle it should be oriented. In the application of a hummingbird, where there is a continuous change of angle of attack, the optimal range plays a vital role.

3.3.3 Mesh Independent Study

CFD solutions are highly dependent on the mesh(grid) size. The mesh size defines the accuracy of the analysis and the time taken for analysis.

The output result of a coarser mesh and finer mesh can neither be the same.

The mesh study is carried out to find how the result varies per mesh density and to reach the actual value of a CFD simulation, and it is required to do an independent mesh analysis.

Grid independence test is conducted until acceptable levels of tolerances in results are reached from the variation of mesh refinement. The test is also done to facilitate the reduction of computation time and memory requirements.

The Parametric analysis method of Ansys Workbench is used to perform this test. Parametric analysis is a fast and time-saving technique, as mentioned in the previous section. This tool of Ansys allows the user to vary the mesh with reference to specific inbuilt parameters utilized while meshing without having to run each calculation manually.

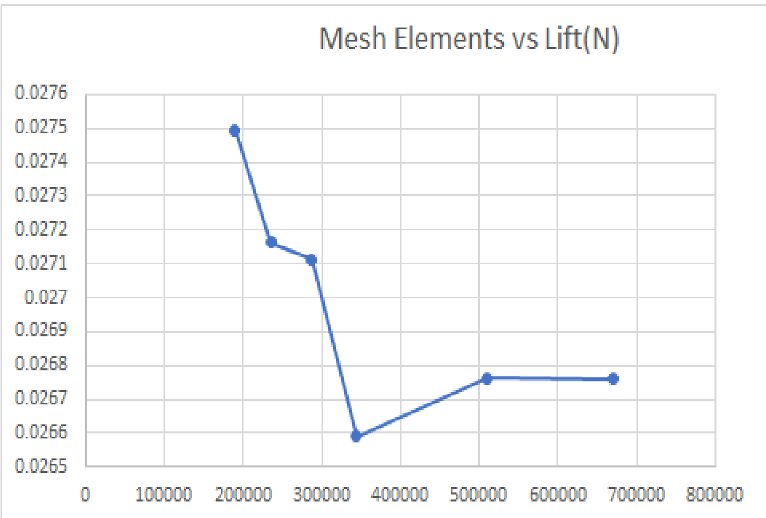


Fig. 3.21 Mesh elements vs Lift(N) plot

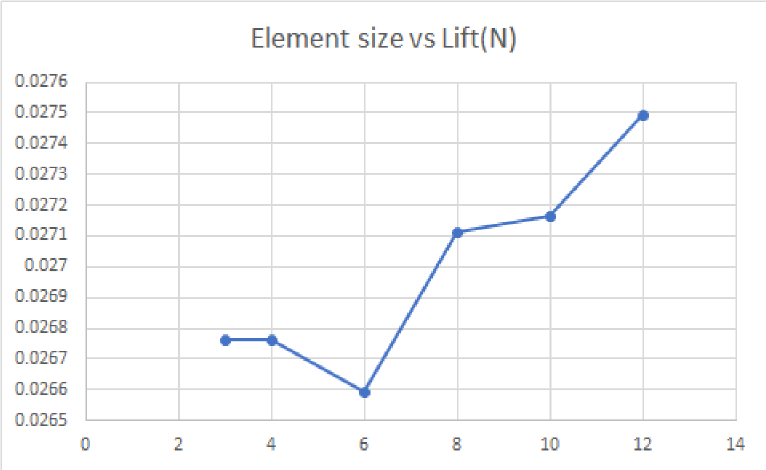


Fig. 3.22 Mesh Element size vs Lift(N) plot

Figures(3.21) and (3.22) lead to an observation that a mesh density with 520k elements gives results very close to the mesh with 630k elements. About the element size, it is also seen that an element size of 4 gives results very close to mesh with three as the element size.

With the above observation, it is concluded that the user can use a mesh with 520k elements, with each element having a size of 3 to achieve faster computation times.

3.3.4 Lift Calculations- Wing Lift Formula

The lift generated due to a flapping wing is significantly different from a fixed-wing, and hence the conventional formula cannot be applied to find the lift force calculations.

The flapping lift also takes into consideration a vital flight parameter which is the frequency of the wingbeat. This frequency is called " flapping frequency, "It is the number of wingbeats completed in one second.

The formula used here is derived from the reference[14].

The mean lift force for flapping wings is found by approximating classical theory for the fixed-wing in steady flow while using cycle-averaged quantities. A few assumptions are made:

1) The wing is flat and rigid.

2) The center of pressure is placed at mid-length(R_{CP})= R/2.

It is found that when a wing flaps at a certain frequency f with amplitude of $\Phi = 2\varphi m$, then its CP (Centre of pressure) moves at a mean velocity of

$Ucp = 2\Phi fRcp = \Phi fR$

The cycle average lift force for a pair of wings is written as

$F_L = 1/2\ \rho C_L(2S)U^2cp = \rho C_L S\ (\Phi fR)^2$

Here S is the area of a single wing and C_L is the mean lift coefficient

After including the wing aspect ratio definition as Aspect Ratio(AR) = R^2/S,

The final expression for lift force due to a *frequency induced flapping motion* can be given by

$\mathbf{F_L = 1/2\ \rho C_L\ x\ AR\ x\ (\Phi fS)^2}$

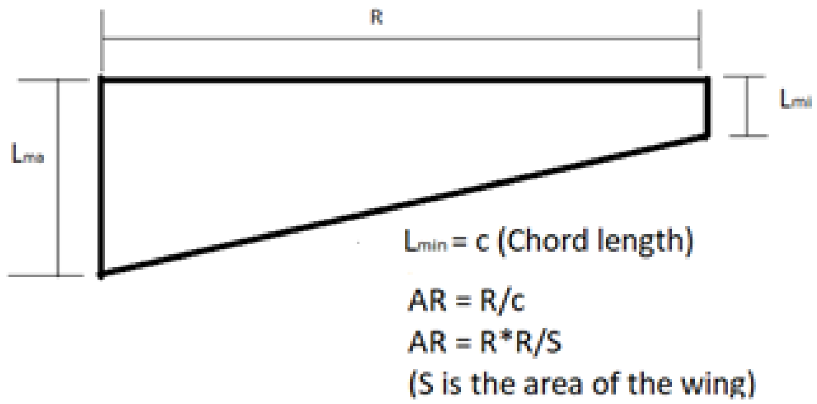


Fig. 3.23 Wing geometry terms and aspect ratio definition

The specific terminologies and the aspect ratio definition are provided in figure(3.23).

The above formula is further used to find the lift of different wings, each flapping with a range of frequencies. The calculations are tabulated and shown below.

Table 3.5 Lift values at different frequencies

	Aspect Ratio of the Wing	**Length (R)**	**Tip chord or Lmin**	**Area of wing S**	**Lift Values at different frequencies [gF]**				
S.R No		**(mm)**	**(mm)**	**(mm²)**	**f = 30 Hz**	**f = 35 Hz**	**f = 40 Hz**	**f = 50 Hz**	**f = 55 Hz**
1	5.6	70	25	1750	7.12	9.69	12.63	19.8	24
2	6.4	75	23	1800	8.42	11.47	14.91	23.4	28.3
3	7.0	78	22	1853	9.3	13.1	16.0	26.0	31.5
4	7.5	82.5	22	1939	10.9	14.9	19.5	30.5	36.9
5	8.5	87.5	21	2013	12.8	174.1	22.8	35.6	43.0
6	9.2	92.5	20	2081	14.8	20.1	26.0	41.1	49.7

The results obtained from the lift calculations are plotted in table(3.5). The frequencies are calculated from within the range of 30 - 80Hz keeping in mind the limits provided by the motor.

Table 3.6 Lift values at different frequencies

S.R No	Aspect Ratio of the Wing	Length (R) (mm)	Tip chord or Lmin (mm)	Area of wing S (mm^2)	Lift Values at different frequencies [gF]				
					f = 60 Hz	**f = 65 Hz**	**f = 70 Hz**	**f = 75 Hz**	**f = 80 Hz**
1	5.6	70	25	1750	28.5	33.4	38.8	44.5	50.7
2	6.4	75	23	1800	33.6	39.5	45.8	52.6	60.0
3	7.0	78	22	1853	37.5	44.3	51.6	58.6	66.6
4	7.5	82.5	22	1939	43.9	51.5	59.7	68.6	78.0
5	8.5	87.5	21	2013	51.2	60.9	69.8	80.1	91.1
6	9.2	92.5	20	2081	59.2	69.5	80.6	92.5	105.3

The above results drawn from tables(3.5) and (3.6) conclude two significant trends concerning flapping flight. It is found that that the corresponding flapping lift force:

1. Increases with increase in wing area and
2. Increases with an increase in flapping frequency

3.3.5 Wing Modelling

Once the appropriate dimensions for the wing are selected, the wing is then modeled in CAD software. The suitable materials are also decided upon based on their properties. The wing is conveniently made with an aperture so that it can be attached to the mechanism.

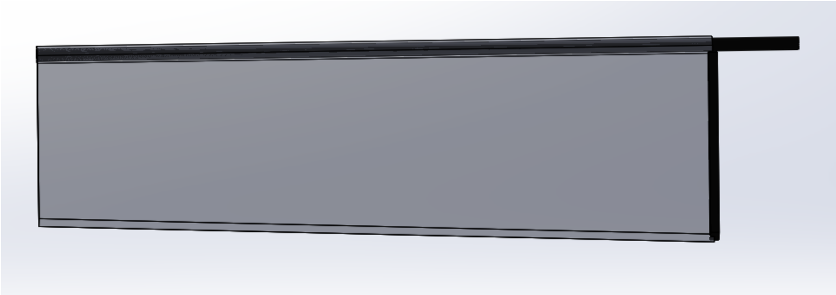


Fig. 3.24 Wing CAD modelling

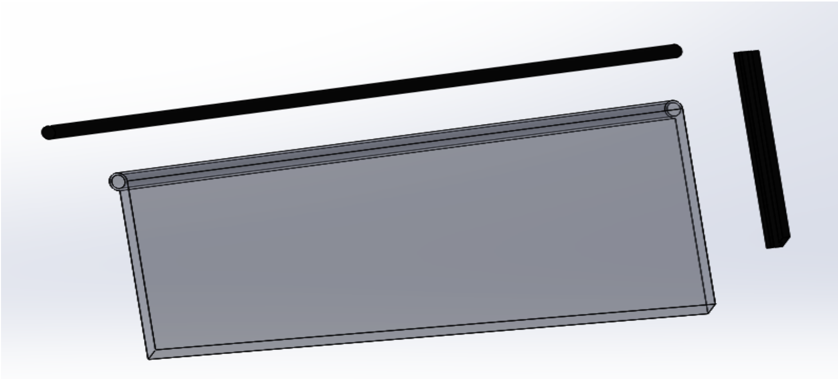


Fig. 3.25 Exploded view of CAD model

Figure(3.24) and figure(3.25) illustrate the wing's CAD model and its exploded view respectively.
The wing film is made with the substance PET, which stands for polyethylene terephthalate. PET is a standard commercial polymer having a wide range of applications ranging from packaging, fabrics, films to molded parts for automotive, electronics, and many more. The material was specifically chosen in this case due to a few stand-out properties:

1. PET has high strength and stiffness
2. It is very strong while being lightweight hence best suited for our application
3. It does not break or fracture, and its shatters resistant
4. Another critical property is the fact that it is an excellent material that is used in additive manufacturing processes

Rods of 1.5 mm thickness made from carbon fibre reinforce the wing films and act as a support structure for the PET film. One of the rods is made in such a way that it accommodates a fixture that is used to join it with the mechanism.

3.4 Mechanism Design and Analysis

3.4.1 Validation

The first choice for a flapping mechanism that employs a rocking motion would be a four-bar mechanism in which the output link generally takes a rotary motion at the input link from an actuator like a DC motor. However, there are certain limitations that we come across while going for a simple four-bar mechanism: the output angle generated is very low for our application. Therefore, a few modifications are necessary for the four-bar mechanism for implementation for the application.

It is still possible to use a simple four-bar mechanism without any modifications, but this has limitations. The mechanism used by Michael et al. [12] achieves this by using a piezoelectric actuator instead of a rotary one as the tip of the input link is to be varied between ±1mm, and this gives any output angle variation of ±60° as shown in figure(3.27) and figure(3.28), which is more than a traditional four-bar mechanism with a rotary actuator. The link lengths are taken from the paper, and the same is modeled in Solidworks as shown in figure(3.26).

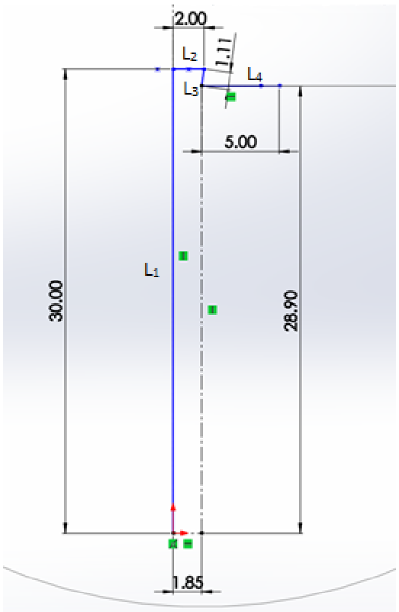


Fig. 3.26 Free body diagram of Mechanism 1 (all measurements are in mm and degrees)

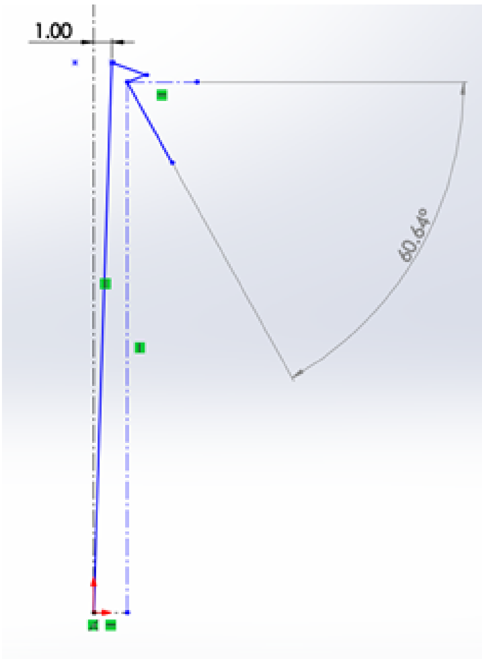


Fig. 3.27 Showing -60° (all measurements are in mm and degrees)

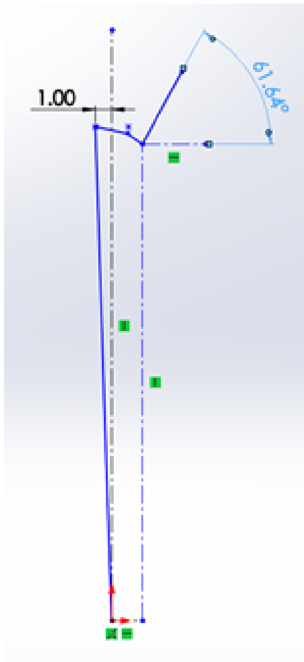


Fig. 3.28 Showing +60° (all measurements are in mm and degrees)

Controlling the input link for such a small displacement can be difficult. Instead, a rotary actuator like a DC motor would be preferred as they are widely used in similar applications.

To overcome the difficulties mentioned above, we will look into the mechanism used by David et al. [13], which is a 5-bar linkage but is essentially a simple four-bar mechanism with an added fifth linkage and a slider. The purpose of adding this additional link and a slider is to amplify the output of the four-bar mechanism to obtain the required results. The input to this mechanism is of the rotary type, and the output is a rocking motion with an amplitude of ±60°. The link lengths were taken from the paper. The same is modeled in Solidworks as shown in figure(3.29) and figure(3.30) and the positional, velocity, and acceleration graphs are also plotted.

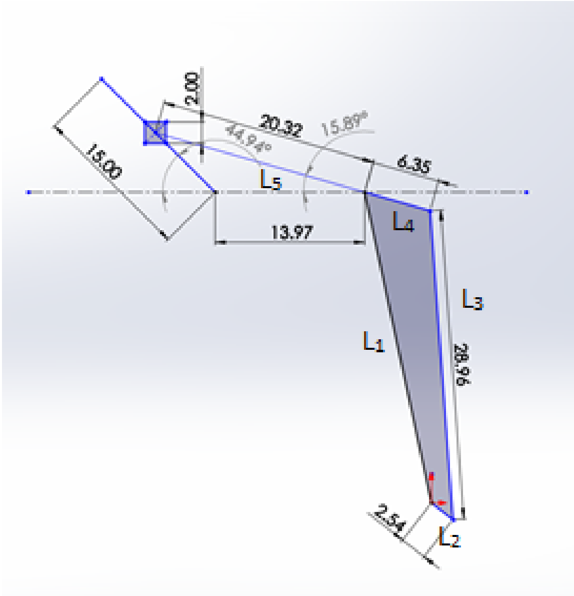
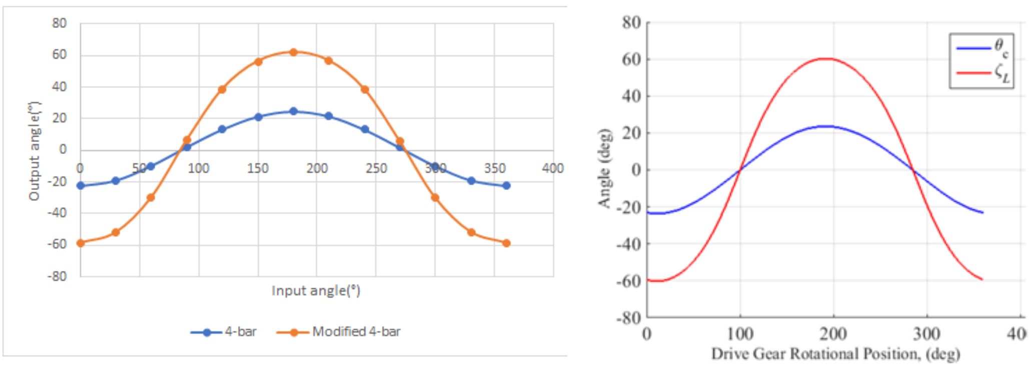


Fig. 3.29 Free Body Diagram of Mechanism 2 (all measurements are in mm and degrees)

Fig. 3.30 A still from the motion analysis of Mechanism 2

The results of the positional analysis were compared to the ones shown in the paper and were found to be similar as shown in figure(3.31). The following graphs show the results for the modified four-bar mechanism and the four-bar mechanism component. Observations show that only considering the four-bar mechanism, an output of ±20° is achieved, which is lesser than an output of ±60° produced after amplification.

The results align with our previous discussion about how low the output is when we use only a simple four-bar mechanism, which justifies the modifications introduced.



Results of mechanism 2 David et al

Fig. 3.31 Comparison with the research paper

The velocity and acceleration graphs shown in figure(3.32) will help us compare mechanisms which are modelled further.

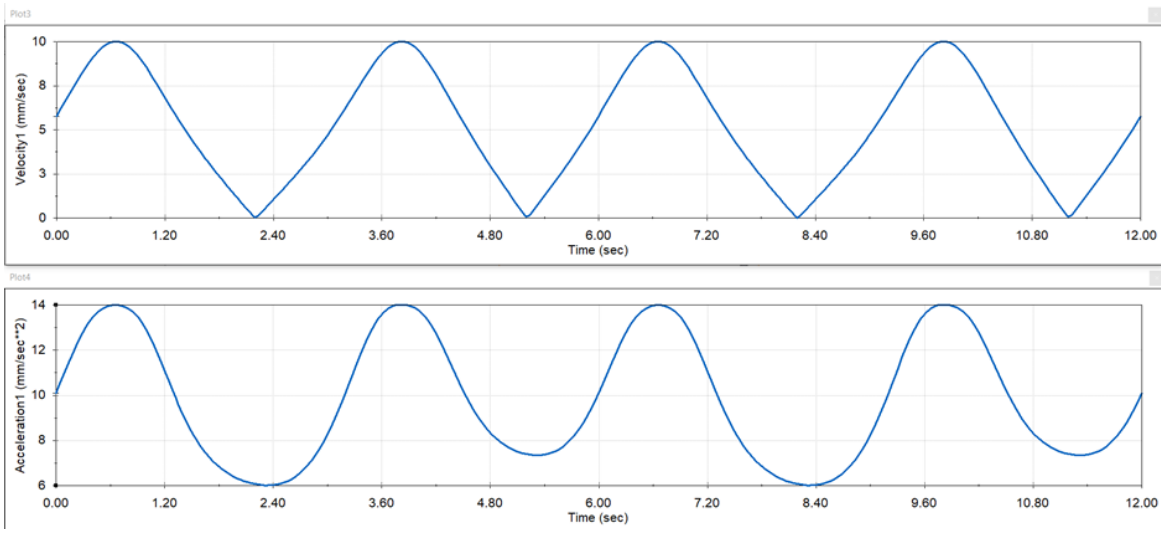


Fig. 3.32 Velocity and acceleration analysis of Mechanism 2 (both are done at 10rpm and the same follows for all other velocity and acceleration graphs)

The following mechanism by Matˇej et al. [14] has some similarities compared to the previous one. It is similar because it uses a modified four-bar mechanism, a rotary actuator at the input link, and an output of about ±60°. The difference in mechanisms is the introduction of a slider-crank at the input instead of at the output.

The slider-crank is further linked to a four-bar mechanism, successfully converting the sliding motion to a rocking motion.

The link lengths were taken from the paper and an image of the same is shown in figure(3.33), it was then modeled as shown in figure(3.34) and figure(3.35).

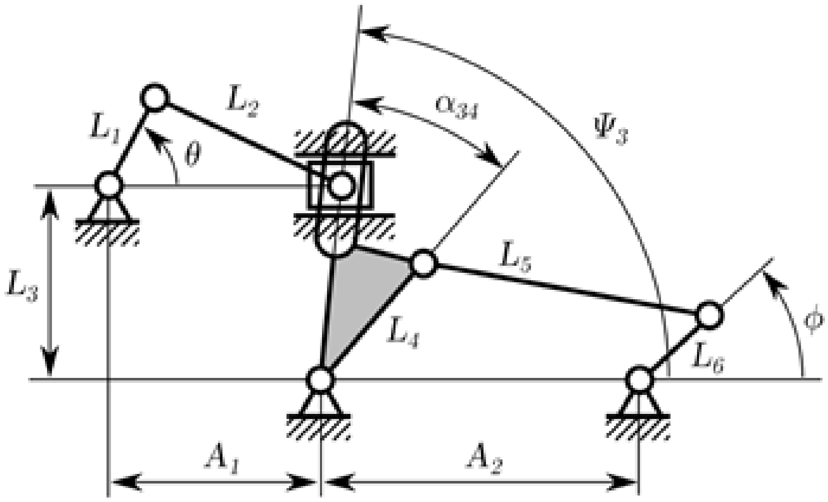


Fig. 3.33 Image of mechanism given in the paper[14]

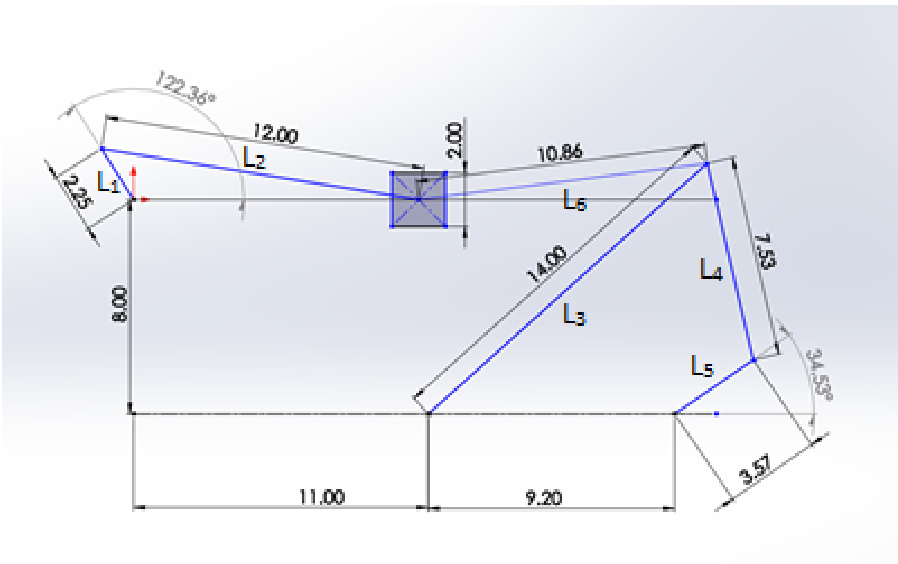


Fig. 3.34 Free Body Diagram of Mechanism 3 (all measurements are in mm and degrees)

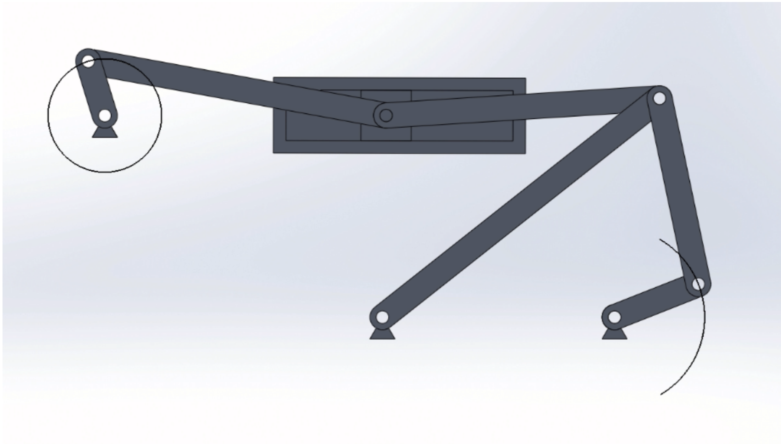
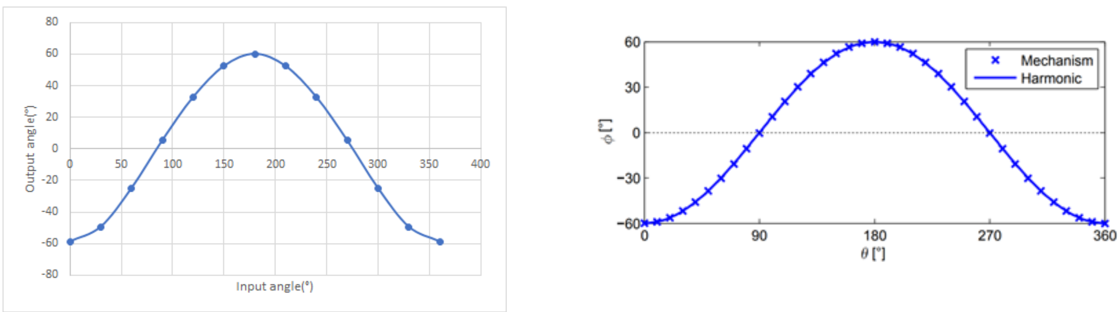


Fig. 3.35 A still from the motion analysis of Mechanism 3

Observation of the positional analysis was found to be the same as in the referred paper. Furthermore, the results were also compared to a harmonic function as seen in figure(3.36).



Results of mechanism 3 Matˇej et al

Fig. 3.36 Comparison with the research paper

Velocity and acceleration graphs are also plotted as shown in figure(3.37) and they will help us compare mechanisms which are modelled further.

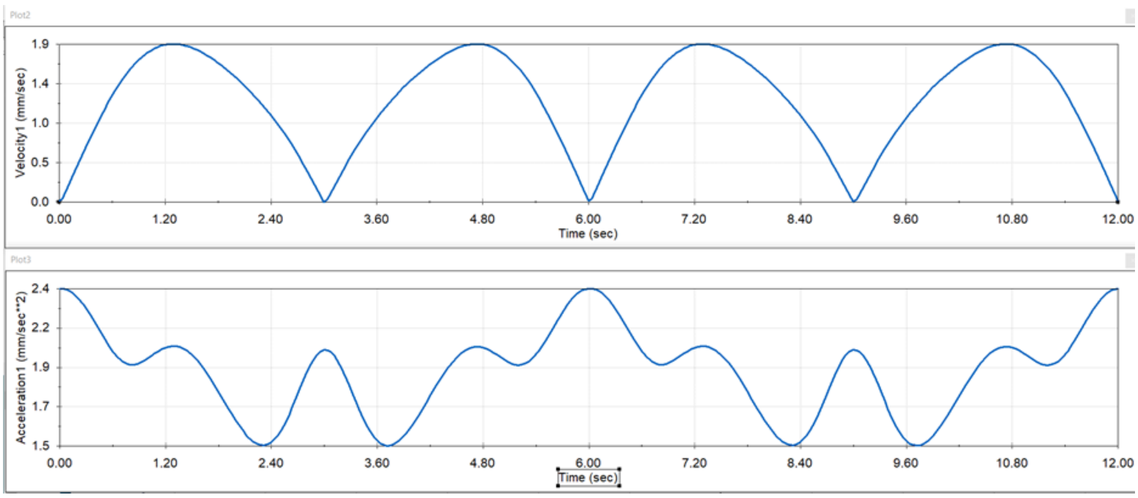


Fig. 3.37 Velocity and acceleration analysis of Mechanism 3

Another iteration of the same mechanism is performed, the free body diagram is as shown in figure(3.38) and reasons being –

1. In the first Iteration, L3 was considered as the distance between the mounting points. The link between the cam and L4 was ignored.
2. In the second iteration, L3 was considered the distance between the mounting points and the length of the link between the cam and L4 mounting point.

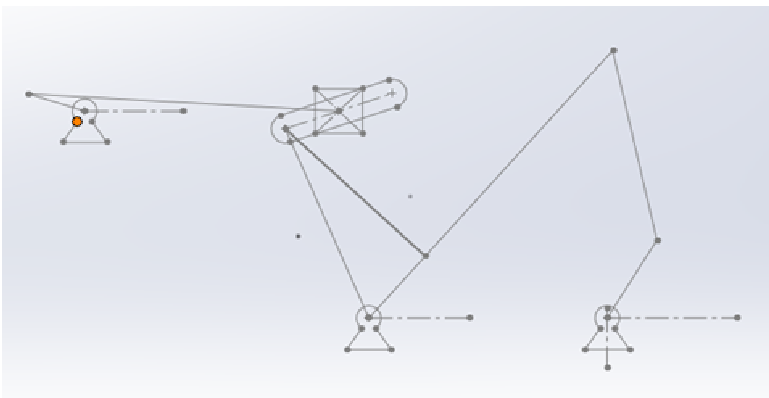


Fig. 3.38 Free Body Diagram of Mechanism 3 (iteration 2)

The results of the second iteration were compared to the first iteration and the results are in figure(3.39) -

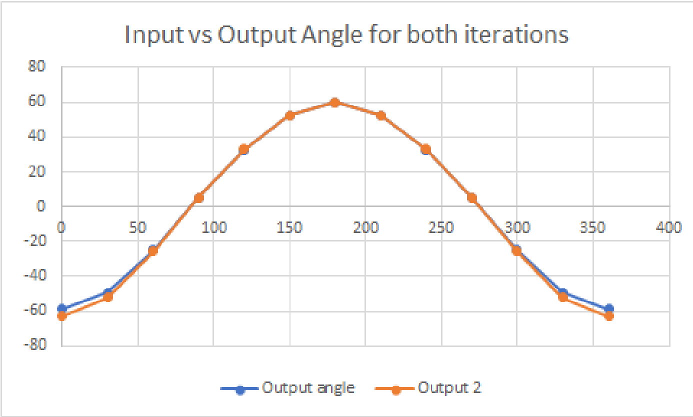


Fig. 3.39 Comparing results of iteration 1 and 2

3.4.2 Design of a four-bar mechanism

The previous designs were taken from papers, as mentioned. A new iteration of a four-bar mechanism is designed to achieve a total flapping amplitude of 120° and a time ratio of 1.

The design procedure is the graphical method for synthesizing crank rocker linkages for specified rocker amplitude as mentioned in the book "Kinematics, Dynamics, and Design of Machinery by Kenneth, Gary, and Sunil."[20]

The initial parameters are the time ratio, input angle, output angle, and one assumed link length.

The input angle is 360° as the input of the mechanism is actuated through a rotary actuator, which is assumed to be a coreless DC motor.

The time ratio is the time taken between the forward and backward stroke. In a mechanism where the flapping simulation of the wing is being considered, we assume the motion to be symmetric, i.e., the time taken for both strokes to be equal. Hence the considered time ratio is 1.

The output angle is considered as 120° to maintain symmetry. A real-life hummingbird motion ranges from +60 to -80 degrees.

These values of time ratio and output angle are inferred through a literature survey and the various resources surveyed on flapping mechanisms used for the hummingbird.

Through the graphical method and the known input parameters, we can extract the lengths of the remaining links and the free body diagram is as drawn as shown in figure(3.40). A similar design procedure has been followed throughout the paper.

A graph of output angle vs input angle is shown in figure(3.41) which is asymmetric unlike previous mechanisms and the velocity and acceleration graphs are shown in figure(3.42).

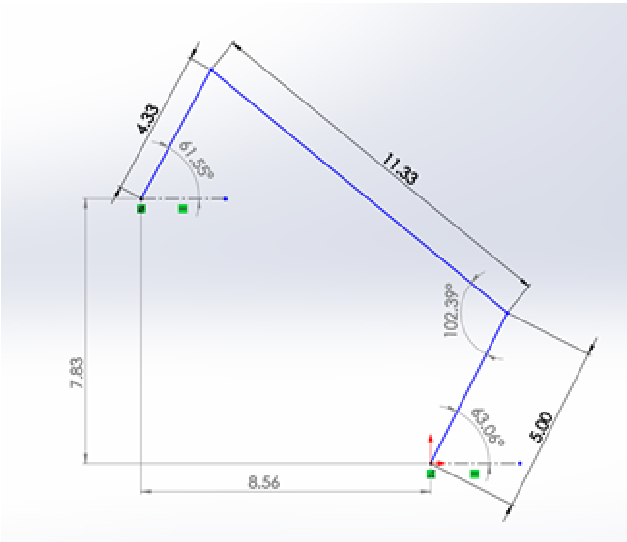


Fig. 3.40 Free Body Diagram of Mechanism 4 (all measurements are in mm and degrees)

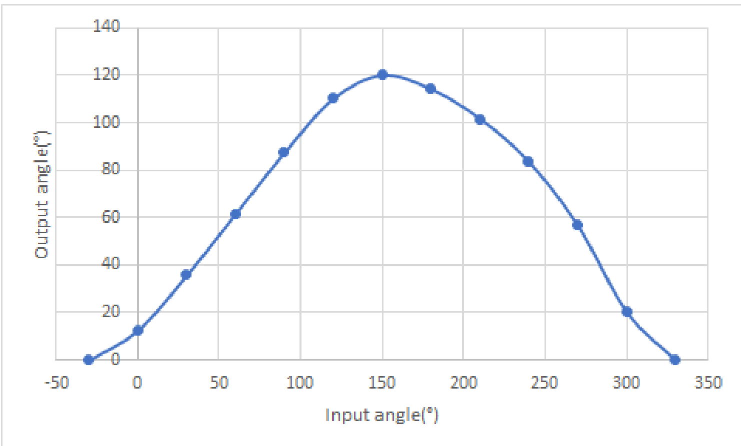


Fig. 3.41 Position analysis of Mechanism 4

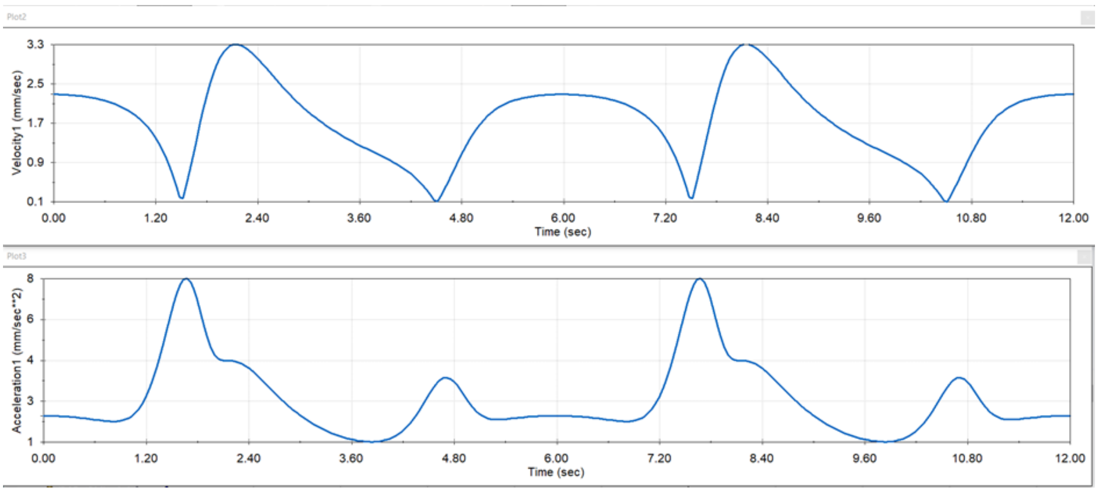


Fig. 3.42 Velocity and acceleration analysis of Mechanism 4

This mechanism's maximum and minimum transmission angles (η_{max} and η_{min} respectively) are not feasible as they are very far from the optimal value of 90°; they need to be as close as possible to 90°. Hence this design is not feasible.

$$\eta_{max} \approx 152°$$

$$\eta_{min} \approx 27°$$

The velocity graph of this mechanism is also very different from the velocity graphs of mechanisms 2 & 3 (Figure 3.32 and figure 3.37 respectively).

A four-bar mechanism with a total flapping amplitude of 40° is designed to address the above-stated shortcomings. The reduction in flapping amplitude ensures that the transmission angle is in a feasible range. In subsequent iterations, an addition of an amplifier helps in reaching the required design amplitude. The results are compared with the second and third mechanisms discussed above.

The mechanism is modelled as shown in figure(3.43) and figure(3.44) with the position analysis in figure(3.45) which shows that it is much more symmetric than the position analysis of mechanism 4.

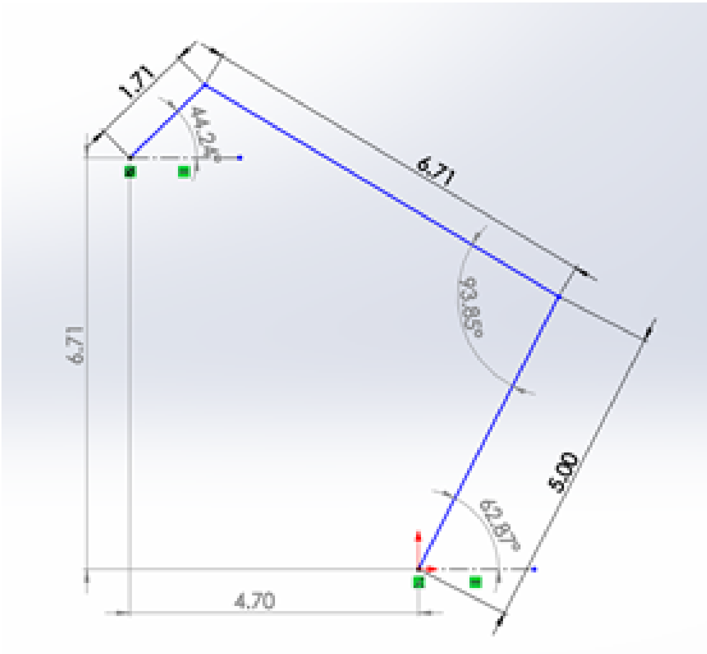


Fig. 3.43 Free Body Diagram of Mechanism 5 (all measurements are in mm and degrees)

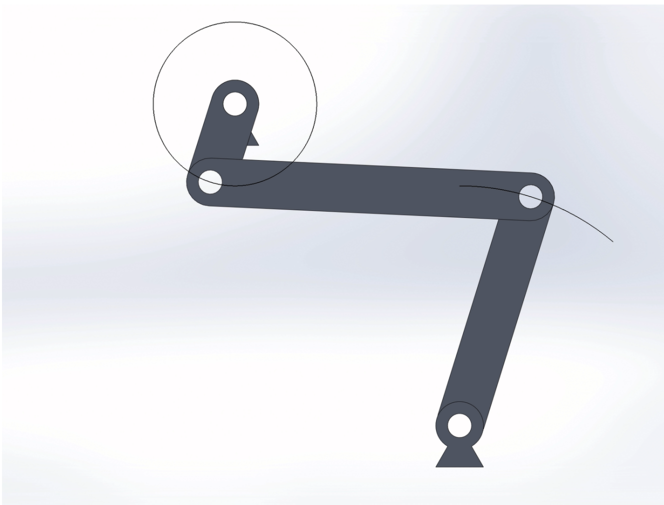


Fig. 3.44 A still from the motion analysis of Mechanism 5

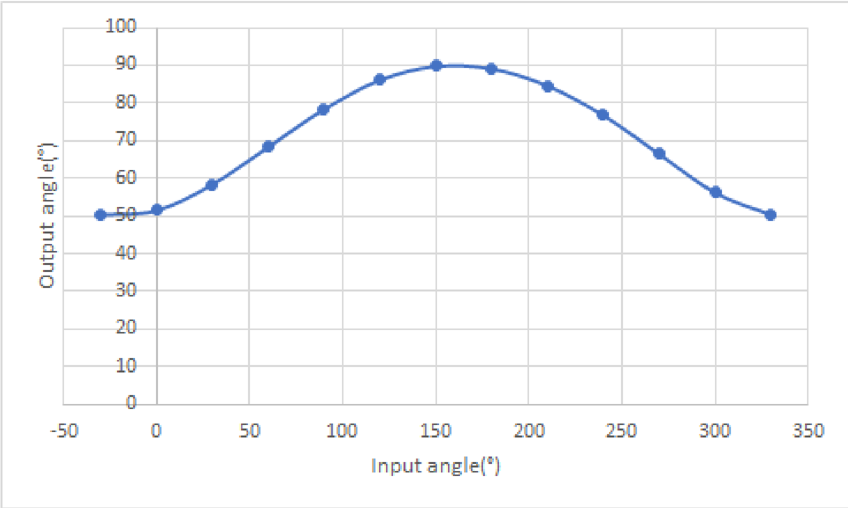


Fig. 3.45 Position analysis of Mechanism 5

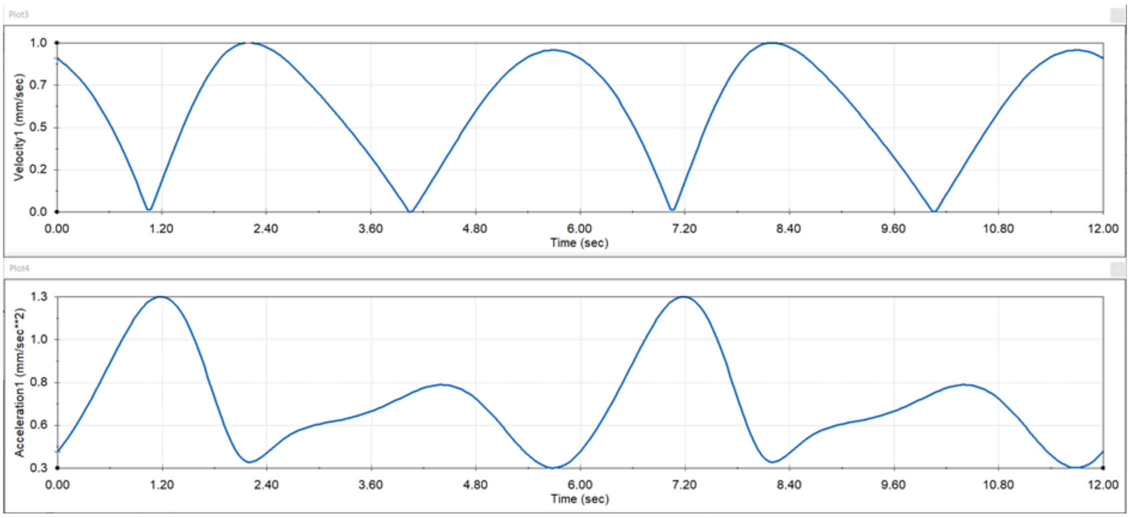


Fig. 3.46 Velocity and acceleration analysis of Mechanism 5

The velocity graph as shown in figure(3.46) is similar to the velocity graphs of mechanisms 2 & 3 (Figure 3.32 and figure 3.37 respectively), and the transmission angles are feasible and much better than the previous four-bar mechanism.

$$\eta_{max} \approx 114°$$

$$\eta_{min} \approx 65°$$

3.4.3 Design of modified four-bar mechanism

We have the four-bar mechanism, which gives us a flapping amplitude of ±20°. The next step would be to modify this mechanism to give us a flapping amplitude of ±60°.

The method to go about this is inspired by one of the mechanisms reviewed earlier in this project (Mechanism 2 - Figure 3.29).
The modification is done by adding an extra linkage with a slider as shown in figure(3.47) and figure(3.50), and the velocity and acceleration analysis for the output linkage is done as shown in figure(3.49).

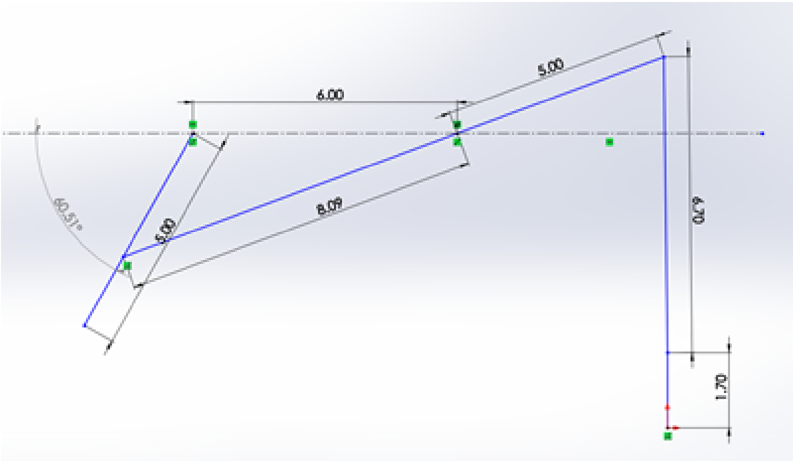


Fig. 3.47 Free Body Diagram of Mechanism 6 (all measurements are in mm and degrees)

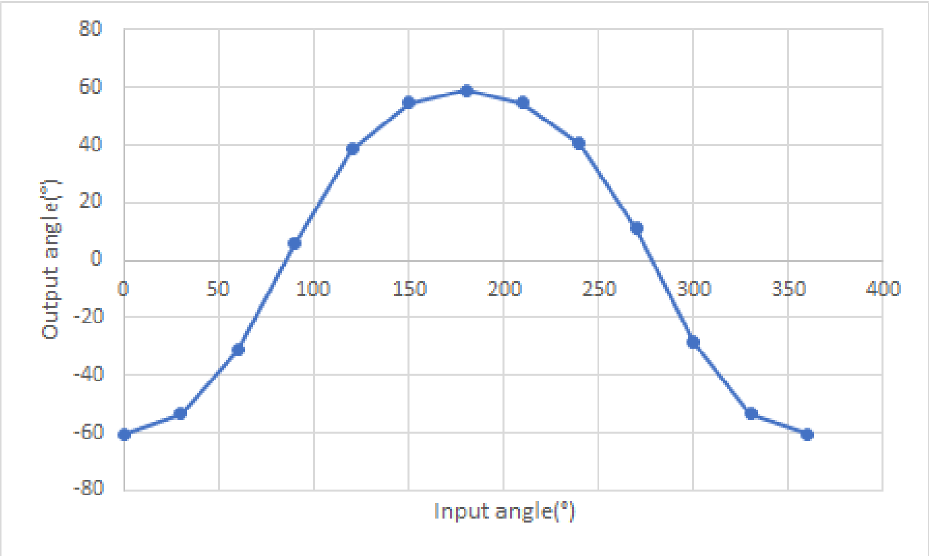


Fig. 3.48 Position analysis of Mechanism 6

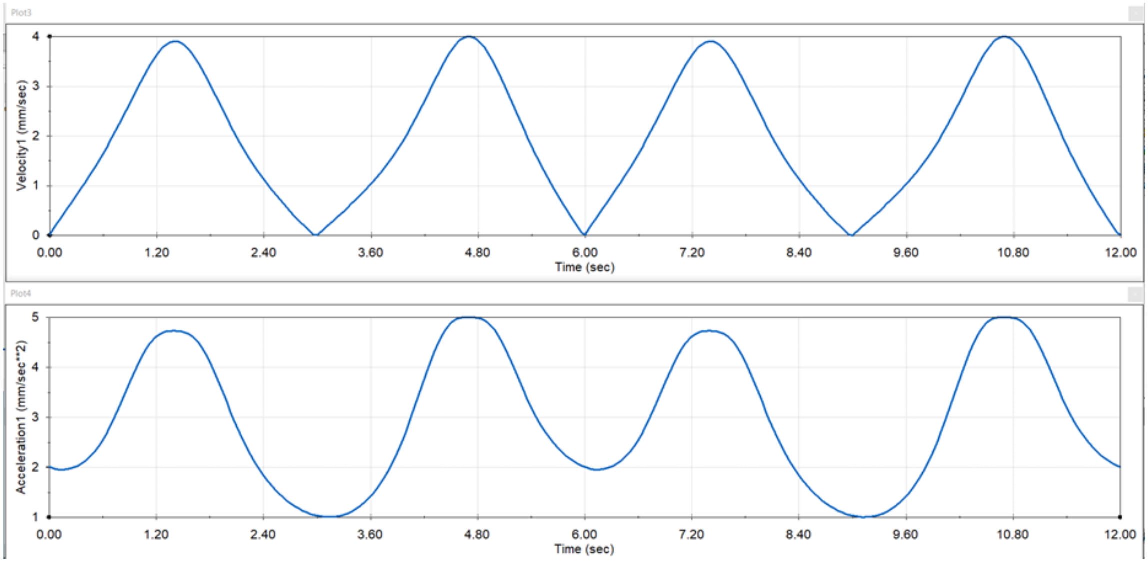


Fig. 3.49 Velocity and acceleration analysis of Mechanism 6

The position, velocity and acceleration graphs are all very similar to mechanism 2 which was reviewed earlier.

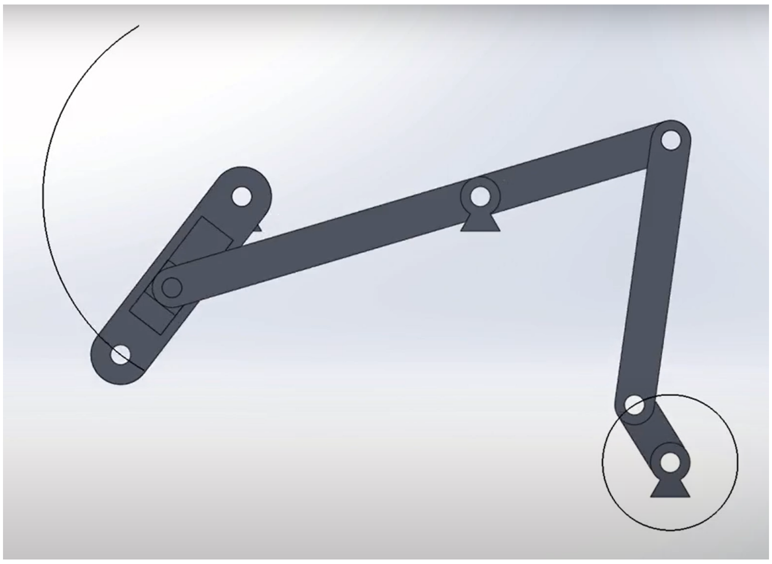


Fig. 3.50 A still from the motion analysis of Mechanism 6

The slider mechanism in mechanism 6 can be replaced by a pin and slot as a possible iteration of the same as shown in figure(3.51). A pin and slot help reduce frictional forces and allow for precise manufacturing in the scenario of smaller components.

The position, velocity, and acceleration plots remain the same.

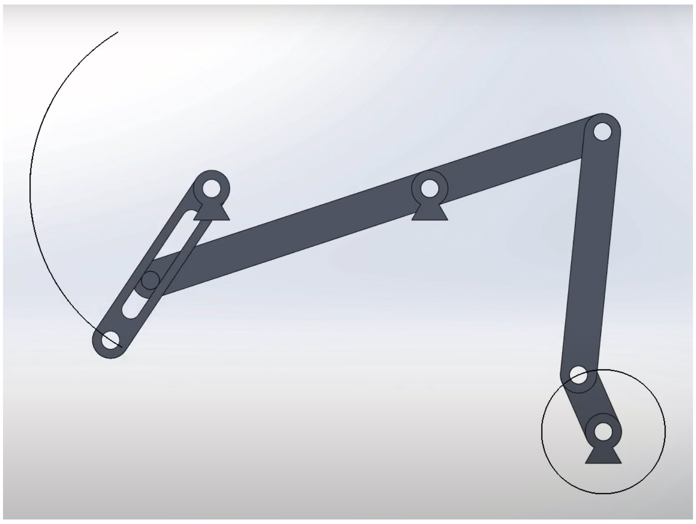


Fig. 3.51 A still from the motion analysis of Mechanism 6 (Pin and slot variation)

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Photogrammetry and Kinematic Path

The kinematic path analysis through image processing technique shows that the hummingbird flight contains two specific strokes, the eight shape followed by the wingtip and the harmonic flapping in the front view. The report contains the mechanism for the flapping shown in the front view, which is essential for hovering.

4.2 Weight Approximation

Upon estimating the mechanical and electrical components, it is approximated that the total testbed weight to be 52 grams, and the prototype weight with the telemetry devices weight to be 80 grams.

4.3 Wing Design and Analysis

4.3.1 Angle of attack

From the parametric tests concluded it is found that the lift forces increase with an increase in the angle of attack while the optimum angle of attack at which the wing is oriented lies in the range of 10-15 degrees.

4.3.2 Lift calculations

From the wing lift formula derived and the values calculated for each wing model corresponding to a specific frequency, two important features are noticed.
The trends observed from figure(3.52) and figure(3.53) indicate that -

1. Increases with increase in wing area and
2. Increases with an increase in flapping frequency

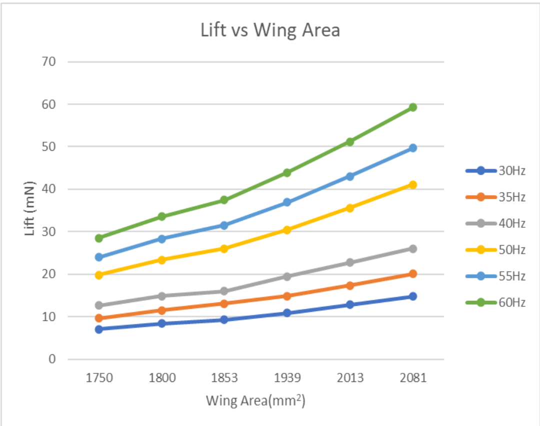


Fig 3.52 Lift vs Wing area plot for different frequencies

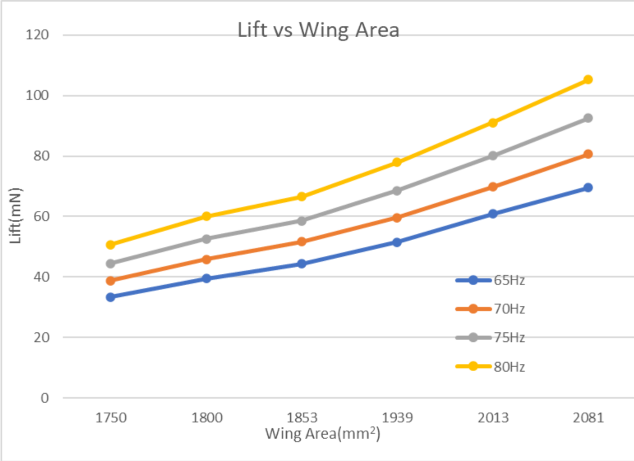


Fig 3.53 Lift vs Wing area plot for different frequencies

4.3.3 Wing dimensions and flapping frequency

Based on the weight approximations calculated, the required lift force needed for the ornithopter liftoff is chosen from tables (3.5) and (3.6). For the current work, a wing of length 82.5 mm and 22mm tip chord is chosen. The wing is found to have an aspect ratio of 7.5. The required flapping frequency is 70Hz. The coreless motor chosen for this task is rated at 60000 rpm, which exceeds the required flapping frequency.

4.4 Mechanism Design and Analysis

After reviewing multiple flapping mechanisms, the kinematic design of a mechanism has been obtained, giving us the required flapping amplitude of ±60° with the input angle being 360°. The maximum transmission angle is 114°, and the minimum transmission angle is 65°(of the four-bar component). Another point to note is that the link lengths mentioned in the free body diagram are not the final dimensions and can be scaled depending on the requirements and on any further analysis which would be done.

The output link's position, velocity, and acceleration graphs have been plotted as shown in figure(3.54) and figure(3.55) respectively which are similar to the mechanism 2 from which it is inspired.

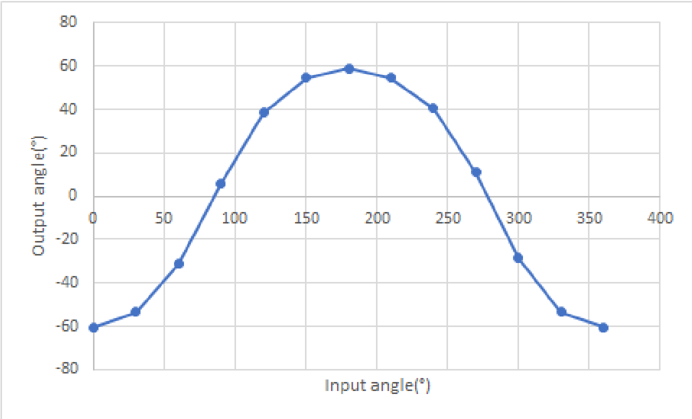


Fig 3.54 Position analysis of Mechanism 6

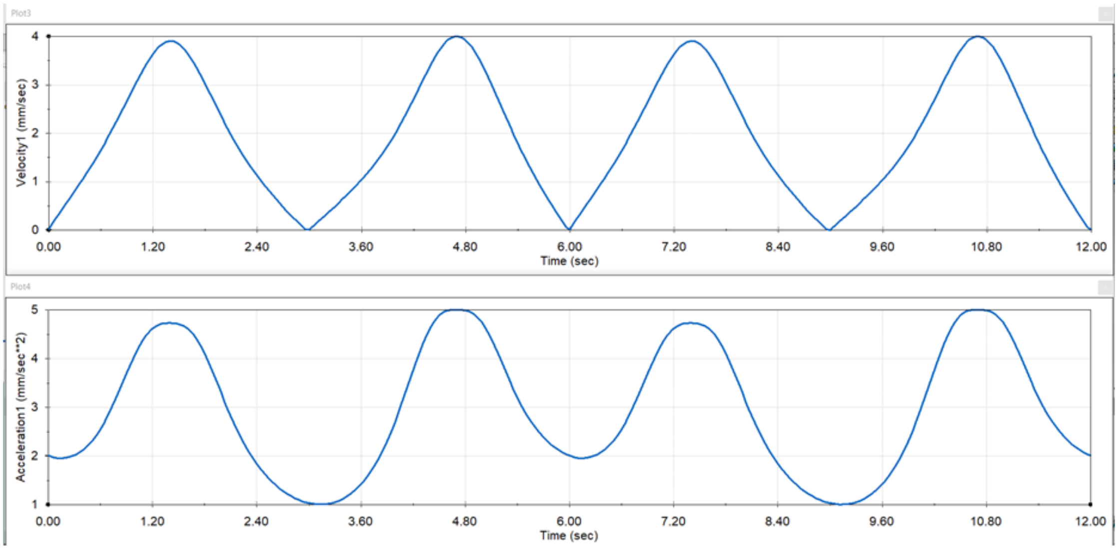


Fig 3.55 Velocity and acceleration analysis of Mechanism 6

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

The kinematic study gives the designer an understanding of which motion of the hummingbird plays a significant role. This is important as the considerable pitfall of biomimicry is the lack of understanding of a process being simulated. A weight approximation study is conducted to ensure that the designer has an approximate weight to perform any form of aerodynamic research. The aerodynamic research is undertaken with weight approximation being a crucial input parameter. The mechanism design uses the required flapping frequency found by the aerodynamic study to design a suitable mechanism.

In each design stage, a few essential characteristics were observed for the successful design of the hummingbird. In the stage of path analysis, the various motions involved and the contributing factors were found for the three modes of flight of a hummingbird; hover, backward, and forward.

In the aerodynamic study, the effect of various factors plays a major role. The hummingbird wing flaps in an eight-shape motion, except standard wing parameters; all other parameters vary with time. Hence, a wing designer must understand every parameter's trend and effect that varies with respect to time. One such example would be the angle of attack, where there is an optimal range after which an increase of angle of attack leads to detrimental effects.

In the mechanism design, a designer can design a mechanism that achieves a particular flapping motion but must ensure that the design mechanism's transmission angle lies in the feasible range. This ensures the feasibility of the mechanism, which is an essential factor for realizing a mechanism. The complete replication of the various movements of a hummingbird, a spatial mechanism, is more suitable when compared to a linkage mechanism. A designer can make various improvements at each stage of the design process.

One such improvement would be a spatial mechanism or the design of a linkage mechanism that can follow an eight shape. One such mechanism is illustrated in figure(3.56). Here the first set of links draw an oval shape while the slider link creates motion in the x-direction simulating an eight motion. The major drawback of this type of mechanism is that an additional mechanism requires another mechanism to cause the flapping motion. The second drawback is that such a mechanism cannot generate the eight motions from all locations, i.e., highly dependent on the initial and final position.

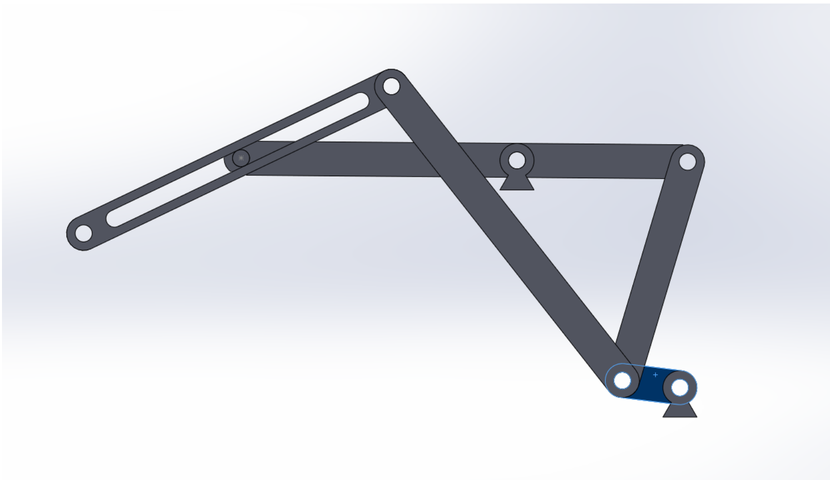


Fig 3.56 Mechanism to simulate eight motion

The second scope of improvement would be in the aerodynamic study, i.e., to better understand wing flapping and its associated aerodynamic properties. It is crucial to perform Dynamic CFD simulations, as shown in figure(3.57). Dynamic meshing tool in Ansys helps the user achieve such tasks by enabling the object's movement and mesh while computing. These features are obtained by implementing a UDF (user-defined function) that acts as the mesh movement's command mode.

Simulations are carried out on a 2D scale to understand and grasp the concept of dynamic meshing and UDF. A flat rectangular 2d plate is made to oscillate harmonically with the help of a user-defined function.

The corresponding aerodynamic properties, contours are noted and observed. A similar procedure is carried onto a 3d wing model designed from CAD software.

Another improvement for the flight path analysis would be to use better image processing techniques and libraries where the wing boundaries can be recognized through contour detection but would initially require the grayscaling of the picture for computational reasons. The next step would be to obtain the individual points of the contour and plot them in 3D space to analyze each flap and arrive at a generalized function. The generalized process can then be implemented into UDF in simulation software such as Ansys to understand the flight and aerodynamic properties further. Figure(3.57) illustrates the wing model undergoing trial flapping motion in the Ansys dynamic mesh environment

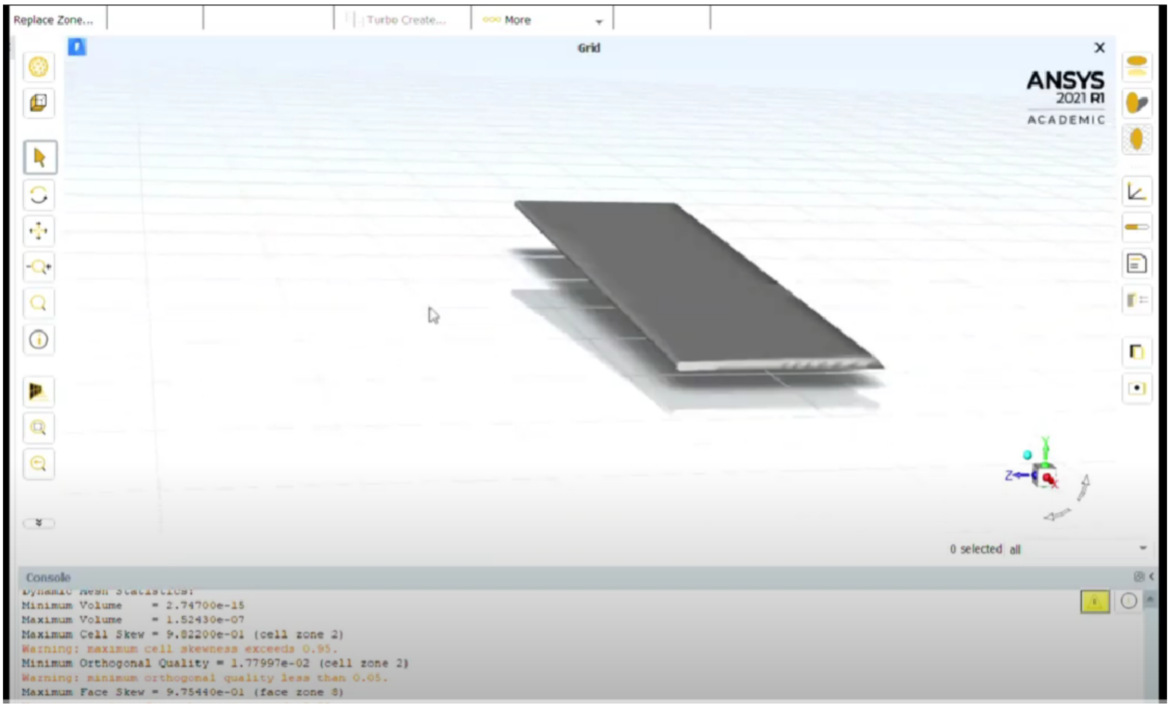


Fig 3.57 Dynamic Mesh Layout

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***Abstract*—The hummingbird has been an exciting point of research for decades together. New observations are being brought about every time new research is conducted on the bird. It has been a bird of great interest due to the different flapping modes, i.e., forward, backward, and hovering. Hummingbird being the smallest bird makes it a greater point of interest due to the incredible flapping speeds it can reach. Upon successfully replicating and studying such a bird, humans would be able to deploy it in various situations ranging from surveillance to rescue operations. Such is the potential of Hummingbirds. The hummingbirds have captivated the minds of researchers for not only their flight but also the amount of energy required, and the metabolic rate at which hummingbirds convert sugar into energy. The objective of this report is to study the flight path and aerodynamic properties of a hummingbird. The research work is also aimed towards finding feasible flapping mechanisms and wing designs as it is believed that they are one of the key aspects to be highlighted upon. A handful of different mechanisms are explored along with their adjustable counterparts. These adjustments are explicitly made to ensure that the disadvantages from the former are minimized to an extent. Multiple four-bar and five-bar mechanisms are observed and studied carefully and then worked upon to validate the existing research present. The respective models and simulations were carried out with CAD software and presented. Along with mechanisms, wing design is explored, and tests are run on them, respectively. The wing designs are carried out in CAD software, and then the appropriate tests are performed in a CFD-based software such as ANSYS Workbench. Image processing techniques and photogrammetry were skillfully employed to judge the flight and encounter the wing path generation problem. The control engineering aspect is also implemented, and various equations related to the flight of the ornithopter are hence presented. These equations play a crucial role in the control and different flight scenarios present for the device. A holistic approach to the biomimetic design of a hummingbird is taken as a priority for the report.**

I. INTRODUCTION

One of the greatest minds of human history, Da Vinci to current scientists are fascinated by flight till the current generation. Da Vinci had a keen sense of curiosity coupled with observational skills that left no object in nature unanalyzed. Four hundred years before the first successful flight by the Wright brothers, Da Vinci had created a concept sketch of a variety of flying machines. His illustrations were highly detailed and contained notes on lift, thrust, equilibrium, and stability.

The first aerial voyage of any kind that man attempted successfully was using balloons. In 1738, Monsieur Rozier and Marquis d’Arlandes set sail in a balloon for a brief trip across Paris. In 1903, the Wright brothers managed to have the first controlled, sustained flight of a powered heavier than air aircraft flown. Their heavier-than-air aircraft research included works from many prominent figures such as Sir George Cayley, Otto Lilienthal, Octave Chanute, and Professor Samuel Langley.

In the years before their first flight, the Wright brother had sought out everything written about the subject. After coming across Ornithology, they believed there was nothing about a bird that humans could not scale up and replicate. Such is the effect on the birds throughout human history and the fascination with flight. It is undeniable that the idea of flight is highly inspired by humans’ observation of birds in nature.

After years of a well-established aeronautical industry, we have discoveries on the bird’s flight path and mechanics. Over the years, researchers have found that not all birds fly the same. Their classification is more diverse and distinct. We, as a team, have chosen a Hummingbird that has been a topic of research for a few decades and will be a topic of interest for decades to come as well.

Our present work focuses on analyzing flight path, required flapping rate, and kinematic study of a mechanism to achieve the flight path that a hummingbird generally exhibits. There is a portion of weight approximation and wing analysis; this is a part of the project works as it provides a range of input parameters for consideration during the kinematic design.

A. Biomimetics

Modern science developed over time; humans had an unquenchable curiosity about the world around us. The law of nature has always been ”Survival of the fittest,” which raised an even more significant question for researchers as sometimes counterintuitive design was still favourable and provided an advantage in many cases, leading to the thriving of a species. We followed the age-old expression " As monkeys see monkeys do." This ideology led to a new field of biomimetics, first coined by Otto Schmit in the year 1950. Humans began to take inspiration from such cases and further optimized existing designs, which revolutionized the design process and procedure. Biomimetics or biomimicry is taking inspiration from nature and biology to use to our advantage in engineering

1) Design procedure for biomimetics:
Scientists and engineers alike choose an organism of interest from nature and analyze it. The analysis comprises the working of the mechanism of a phenomenon, genealogy, and evolutionary study of an organism. The genealogy, evolutionary study, forms a basis for which a particular feature has survived throughout generations. It also provides a thorough understanding of why a specific trait has survived and its corresponding effects on the topic of interest.

The second step is replicating the mechanism, i.e., the design of the mechanism and a suitable control system. In this stage, we go through the standard mechanical design procedure, which comprises the following step:

1) Selection of possible mechanisms
2) Kinematic Design
3) Analysis of forces
4) Design of Elements
5) Prototyping
6) Optimization

The project's final step would be to optimize the design and replication of the phenomenon through various means, be it electrical, mechanical, or a combination of both. Innovative fabrication methods, design, and manufacturing are crucial in leading to future, plausible applications.

2) Applications of biomimetics:
The aviation industry is one such industry that stands a testament to the application of biomimetics. It is a well-known fact that birds have heavily inspired the inspiration of flight. The first to achieve a successful flight, the Wright brothers had heavily studied ornithology during their research period.

The analysis of birds, fishes, and sharkskin has also given rise to a new section of swimwear that helps reduce water resistance. It has also helped inspire the streamlined design of many cars, race cars, and airplanes to reduce drag.

The sticky feet of geckos are known for their sticking ability. Further research found that the microstructure of hair-like projections of a gecko foot is the main factor in its sticking ability. Upon replicating this structure, they have been manufacturing human suits to help climb walls as geckos do.

Another day-to-day example of biomimetics is velcro. George de Mestral invented it in 1941. The burrs inspired it he found on himself and his dog when he had gone for walks. Their adhesive property fascinated him; being an engineer and entrepreneur got him to examine them under a microscope. Upon examination, he found that burrs have microscopic hooks that helped them adhere to fabric, which is now replicated and sold as velcro.

3) Drawbacks of Biomimetics:
Drawbacks aren't visible in plain sight; the faults lie in scenarios wherein the engineer cannot understand a particular phenomenon completely and choose replication blindly. Replication and mimicry have a fine line of separation, and it is a designer's job to tread between that line and understand the difference. An example that illustrates this is as follows. In the 1960s, Mercedes-Benz sought to design an aerodynamic, safe, efficient, and maneuverable car. Using the concept of biomimetics, they chose boxfish, a fish near coral reefs. The boxfish's carapace and shape were impressive hydrodynamic characteristics, low drag, and unique, inherent, and self-correcting stabilization properties. The box fish's body resembles a car which also helped design and made it an A-1 choice for their new vehicle.

Low and behold, in 2005, they unveiled the new car, the Bionic. The vehicle's debut received substantial attention. Over time, Mercedes-Benz realized the problem with the vehicle Bionic. The self-stabilization feature that was a highlight of the vehicle proved to be its main drawback. Cars not only go straight but do have to take turns. The self-stabilization process greatly hindered the turning of the car. This is not true for a boxfish in nature which can zip away in the face of danger and navigate without collision in the complex environment of coral reefs. The difference in hydrodynamic analysis and reality led to a paradox named "The boxfish paradox." The Royal Society later solved it, giving the following conclusions: drag reduction was lesser than average fish, and destabilizing moments present that helps maneuverability more than self-stabilization.

The problems faced by the bionic engineers could easily be avoided if the engineers completely understood the boxfish's working principle and implemented it in a manner that would suffice their needs rather than complete replication. Understanding the consequences is an integral part of biomimetics.

B. Hummingbird

Hummingbirds are native to America and the family of Trochilidae. There are about 360 species, and a majority of these are present in the tropic. They range from 7.5-13 cm in length and weigh around 2- 24 grams. The smallest being 'bee hummingbird' and the largest being 'giant hummingbird.'

1) Characteristic Features:
Hold the record for the smallest bird and have a heartbeat of about 1000 beats per minute. They also are the only birds in the animal kingdom that can fly forward, hover in the state, and backward. They can remember every flower they have visited and calculate how long it will take for a particular flower to restock with nectar. When scaled to human size they consume about 155,000 calories a day.

II. Literature Survey

A literature survey is an examination of academic sources on a particular subject. It offers an overview of current knowledge, allowing for identifying approaches, applicable hypotheses, and research gaps. Journals containing previous attempts of ornithopters inspired by biomimicry were referred to understand the design procedure and the required techniques for kinematic analysis and design.

A. Literature survey

This paper by Paolo Dario et al.[1] gives the reader a thorough understanding of biomimicry and explains the various machines that have been bio-inspired. It served as a comprehensive guide to the big world of biomimicry. This paper spoke about the future scope of robotics.

This paper by Michael Rufo et al. [2] broke down biomimicry into multiple stages and gave the reader the approach required to approach biomimicry. It warned the reader about the danger of copying and mimicking, as copying without understanding the mechanism would lead to suboptimal design. The designer must implement only a particular bio mechanism to achieve the required function. This paper also spoke about the challenges of a surveillance robot and how the real world is more complex, no matter the harshness of the test environment. The robot should be capable of understanding and adapting to this ever-changing environment.

This paper done by Douglas et al. [3] spoke about the technical aspects of the hummingbird's flight. It brought about major/important characteristics of hummingbird flight that cannot be noticed with the naked eye. Unlike usual birds, hummingbird thrust is not entirely provided by its downstroke but rather a combination of both. It also gave other crucial details required for wing designing, such as Reynolds number.

The paper concluded that despite differences such as size, musculoskeletal, flight aerodynamics, and other nature-induced differences, hummingbirds resembled aerodynamic mechanisms similar to insects. The upstroke and downstroke wing movements of the bird are analyzed. It was found that hummingbirds provide 75% of their body weight in output during the downstroke and only 25% during the upstroke. This asymmetry was later explained by the fact that the cambered wing undergoes an inversion during the upstroke during flight. The leading-edge vortices produced during the downstroke also suggest that they may operate in significantly low Reynolds numbers to resemble that of insect hovering. This paper acted as a reference to the experimental test setup.

This paper by Yanghai Nan et al. [4] studies the hummingbirds from a morphology perspective to understand the biology of the hummingbird in-depth and understand how it is applicable to help create a Flapping wing MAV. For example, they have looked into the weight distribution of the components for each other, the path traced by the wings of the hummingbird in flight, and many other aspects. They have also compared some of the successful projects done by other researchers in the same field and their approaches in choosing a particular flapping mechanism. Then they studied specific scale laws to help develop the wing and once again compared the wings used by other researchers. Finally, they also looked into the design of the tail for the FWMAV and how it can be applied to improve stability.

This paper by Mostafa Hassanalian et al. [5] spoke about the various approaches taken in the wing design process. It provided the reader with the different manners to implement wings. Paper by Keith W.Moored et al. [6] spoke in detail about the tensegrity wing model and its calculations.

This paper by Bret W. Tobalske et al.[7] gave the actual values of the wing. This paper was a reference for the entire design process, and paper [8] acted as a proof of concept for the method implemented in the design phase. It also provided the team with a procedure and errors to avoid while carrying out photogrammetry.

The work done by Sridhar Kota et al. [9] and Steven M concerning compliant mechanisms introduced us to the bare basics of compliant mechanisms and found that compliant mechanism and Compliance in design leads to jointless, no-assembly, monolithic mechanical devices and is particularly suited for applications with a small range of motions. The fact emphasized here is that traditionally human-made designs are stiff, but the natural methods are 'compliant while also being strong at the same time. The compliant mechanisms and the first few steps were carried out to make a working model successfully. A topology synthesis was done to establish a possible topology concerning the input-output force-displacement relationship. The problem statement was tackled, and the size and shape optimization was done. It was also mentioned that a few key design criterions need to be met concerning the tests carried out. A few of the criteria are as follows:

- Required stiffness to an external load,
- Required kinematic motion (both magnitude and direction)
- Stress limitations and buckling instabilities,
- Design space and materials properties.
- Dynamic considerations, and
- Weight limitations.

The paper concluded with the possible applications of Compliant mechanisms, and one of the critical areas mentioned was found out to be MEMS-Micro-electromechanical systems. The scope for future ideas with compliance in design is discussed.

The 2012 study by Yao-Wei Chin et al. [10] aimed to research a mechanism that would most likely use compliant mechanisms. The work showed that a clicking compliant mechanism produces more thrust per input power than a conventional non-clicking rigid-body mechanism for synthesis replication. A Dipteran insect model was used to simulate the flight of FWMAV's – known as Flapping Wing Micro Aerial Vehicles. The paper performed tests, did a kinematic analysis, and concluded that significant and fast wing strokes with a large pitching angle produced significantly higher thrust efficiency than a non-clicking mechanism with rotary joints.

The paper by Michael A.A.Fenelon et al. [11] looks into a flight mechanism known as the MSC mechanism, which stands for the "Modified slider-crank" mechanism. Here a rotary actuator was used, which provided active rotation and flapping of the wings. Before moving further, we would like to look into what a rotary actuator is. A rotary actuator is a simple actuator that produces a torque or a rotary motion. It is purely mechanical, where linear motion in one direction gives rise to rotary motion in another. The motion produced by an actuator may be either continuous rotation, as for an electric motor, or movement to a fixed angular position as for servo motors and stepper motors.

The kinematic design was explained and the flapping procedure was as follows – As the crank rotates it pushes or pulls the drive-arm along an arc (since a pivot constrains the drive-arm), creating wing strokes. The crank's rotation also inclines the coupler concerning the stroke plane. This inclination of the coupler twists or rotates the drive-arm and the wing. Hence wing flapping with rotation is achieved through the rotation of a crank.

This paper by Michael et al. [12] focuses on developing a mechanism for an insect-sized FWMAV. They have used a simple four-bar mechanism to achieve the required flapping motion. The actuator used is a piezoelectric actuator, and the reason for this type of actuator is that the input crank's necessary input is minimal. After the design, forces applied to each link are also evaluated. Next, they propose a few manufacturing techniques and materials that can be used for the same. Finally, the mechanism was tested using a laser vibrometer, and the results obtained are per the design procedure.

This paper by David et al. [13] looks into the entire procedure of making an FWMAV based on a hummingbird. The prototypes made by them are around 62g which is slightly on the higher side. They have used a four-bar mechanism modified by adding a fifth linkage and a slider to amplify the output. The wing was of a flexible type that could undergo passive deformation and provide the required lift. An experimental approach was used for the wing design, and multiple iterations were made to find the optimal wing design, which gave the maximum lift. Plane tilting along with amplitude modulation of the wing was used to control and stabilize the system. An autopilot system was also developed to improve the same. Flight testing and Gimbal testing were performed, and results were found to be satisfactory, and some of these results were also presented.

This thesis by Mat˘ej et al. [14] mainly focuses on developing a control mechanism for an FWMAV. The main aim of this mechanism is to stabilize the vehicle during flight. They proposed two possible solutions for the same. They also developed a prototype of the robotic hummingbird in which they talk about the flapping mechanism and the wing design, which is of greater interest for us currently. They used a DC motor to power the flapping mechanism, which consisted of a slider-crank mechanism whose output was further amplified using a four-bar mechanism. They also compared different varieties of motors to find the one most suitable for the mechanism as mentioned above. For the initial wing design, inspiration was taken from other researchers in the same field. Further refinement was done by an experimental approach wherein multiple aspect ratios were compared to arrive at the most optimal aspect ratio that provides the highest lift. The materials used for the wing were also discussed.

The thesis by Mat˘ej et al. [14] proposed a formula for the lift of the wing undergoing flapping motion. The mean lift force calculations for flapping wings is found by approximating classical theory for a fixed-wing in steady flow while using cycle-averaged quantities. Here the concepts of center of pressure, mean velocity are put into use. Trends with regard to flapping flight are also observed.

In article [15], we learn that flapping-wing flight has been extensively studied in the field of entomology, resulting in observation on the methods of lift production, high manoeuvrability, and efficient flight for various natural flyers in differing flow regimes and leading to significant developments in biomimetic theories regarding flapping wing MAVs. In addition, advances in aerodynamic modelling methods have given insight into the unsteady 3-dimensional flow that characterizes typical flapping-wing flight. Therefore, before attempting to model a flapping wing MAV and analyze its stability, it is beneficial to consider previous studies carried out. The paper examines hover-capable flapping-wing flight as presented in earlier work. The kinematics and aerodynamics seen in nature and the resulting control methods are explored.

The research and development efforts presented in this paper by Roman Y. Krashanitsa et al. [16] address the flight dynamics of a flapping-wing air vehicle (ornithopter). The 74-cm-wing-span ornithopter was equipped with an automatic flight control system that provides stability augmentation and navigation of the vehicle and flight data acquisition. Wind tunnel tests were conducted with the control surfaces fixed in the trimmed position and the flapping motion of the wings activated by a motor at a constant throttle setting. Coefficients of vertical and horizontal force and pitching moment were determined at a free stream velocity of 7.25 m/sec, and the angle of the stroke plane varied from 0 to 40 degrees. A series of flight tests were conducted with fixed controls, demonstrating ornithopter stability in all axes. Proportional control laws were programmed into the autopilot for the closed-loop controls. Many flights of autonomous ornithopters were conducted with the telemetry acquisition. During the autonomous flights, the ornithopter performed waypoint and altitude navigation, demonstrating stable performance.

From the study done by Dean Ninian et al. [17], it is seen that the design and development of morphing (shapeshifting) aircraft wings—an innovative technology that can increase aerodynamic efficiency and reduce noise signatures of aircraft—was carried out. This research focused on reducing lift-induced drag at the airfoil flaps and improving the design to achieve optimum aerodynamic efficiency. The simulation revealed a 10.8% coefficient of lift increase for the initial morphing wing and 15.4% for the optimized morphing wing compared to conventional wing design. At angles of attack of 0, 5, 10, and 15 degrees, the optimized wing increases the lift-to-drag ratio of 18.3%, 10.5%, 10.6%, and 4%, respectively, compared with the conventional wing. Simulations also showed a significant improvement in pressure distribution over the lower surface of the morphing wing aerofoil. The increase in flow smoothness and reduction in vortex size reduced pressure drag along the wing's trailing edge. A morphing wing reduced the size of the vortices, and therefore the noise levels measured were reduced by up to 50%.

This paper by Che-Shu Lin et al. [18] employs the four-bar linkage to simulate the flapping motion of a bird. Wind tunnel tests are performed to understand and measure the lift and thrust of the flapping wing under different frequencies, speeds, and angles of attack. The varying trends with respect to each variable are observed and their corresponding effects on the flight are noted down. It was found that an angle of attack was necessary to have a lift force.

The study carried out by S Mahendran et al. [19] aims to understand the working principle of ornithopters and their ability to generate lift and thrust under various test conditions. The flapping wing mechanism employed here was the crank mechanism and is tested at two different speeds of 3m/s and 6m/s. The aerodynamic characteristics such as lift and drag are measured using the ANSYS software. The measurements are taken at different angles of attack and it is found out that the mechanism is the most efficient at an angle of 15 degrees with speed of 6m/s.

B. *Summary of Literature*

To summarize, the literature review is extensively done, considering some of the critical factors of an efficient FWMAV. The basics of biomimicry and the advantageous features of the hummingbird are studied. The aerodynamic characteristics of the hummingbird are also discussed, along with its style of flight. A wide range of research is already present to understand the biology of the hummingbird in-depth and its application as a flapping wing MAV. This research was essential in understanding MAVs and their category of devices. To generate a flapping motion similar to that of a bird, various mechanisms along with their work are studied and noted. One of the mechanisms included the four-bar mechanism and the slider-crank mechanism. The wingtip properties are also probed, and the difference concerning change in its orientation is noted down. Critical parameters such as the angle of attack and its influence are explored. Flapping lift properties and the methodologies to calculate flapping lift are explored. Flight dynamics and stability are key factors, and literature concerning these are thoroughly analyzed .

C. *Gap in literature*

After conducting an extensive literature review, most papers focused on traditional mechanisms. Attractive alternatives like the research round compliant mechanisms are short in number. The tools and materials required to synthesize the flapping mechanism also play a key role in influencing parameters like weight, dimensional limits, etc. The research solely around them is limited in number. Subsequently, the structural experimentations on these mechanisms are also low in number. Methods for unsteady-state CFD concerning the flapping motion of the wing are also challenging to find. The methodology for such simulations is bleak, and current research makes it harder to implement with the present work. The heart of a robotic hummingbird would be the control system, as this actuates the different motions the ornithopter can undergo. There is a clear gap in the literature about linking suitable control systems with electronic components and the flapping mechanism.

III. METHODOLOGY

- Photogrammetry and Kinematic Path of Flight
- Weight Approximation
- Wing Design and Analysis
- Mechanism Design and Analysis

Each stage was given a symbiotic treatment such that the results of one stage were used for the iterative design of the rest. In such a manner, it was true to the design procedure of biomimicry and allowed for the consideration of all the parameters that have arisen during the design process.

A. *Photogrammetry and Kinematic Path*

1) *What is Photogrammetry?:*

Photogrammetry is the science and technology used to extract the dimension of an object using photos. The main aim of photogrammetry is to extract precise 3D dimensions from 2D images. The art of photogrammetry techniques has been present as long as the technique of taking photos. The process initially used mechanical and optical measurement tools. As technology improved, the techniques incorporated image processing techniques giving rise to sophisticated computer-aided solutions.

2) *Why was photogrammetry used?:*

There was a need for photogrammetry as hummingbirds are native to the region of South America. In such scenarios studying the bird could be done through the means of various previously published papers or through the vast resource known as the internet. Hummingbirds have been a point of interest for decades as many researchers, zoologists, and enthusiasts have taken a great deal of effort to record videos of the flight path of hummingbirds. The videos in certain scenarios use state-of-the-art slow-motion cameras which capture about 3000 frames per second. This would be much greater than the rate of flapping of hummingbirds. Allowing the study of individual flaps and intermittent flaps. Paper [6] provided the dimensions of the hummingbird, it still was not enough to design the real-life wing structure as it is an organic structure, and the natural curves of it cannot be accounted for through the dimensions table. The paper[6] also acted as a validation method to see if the techniques of photogrammetry were used to provide valid results.

3) *Procedure:*

1) Choosing a source image for the procedure
   There are primary considerations required for choosing the image:
   - The pixel density of the image
   - Clarity of the image

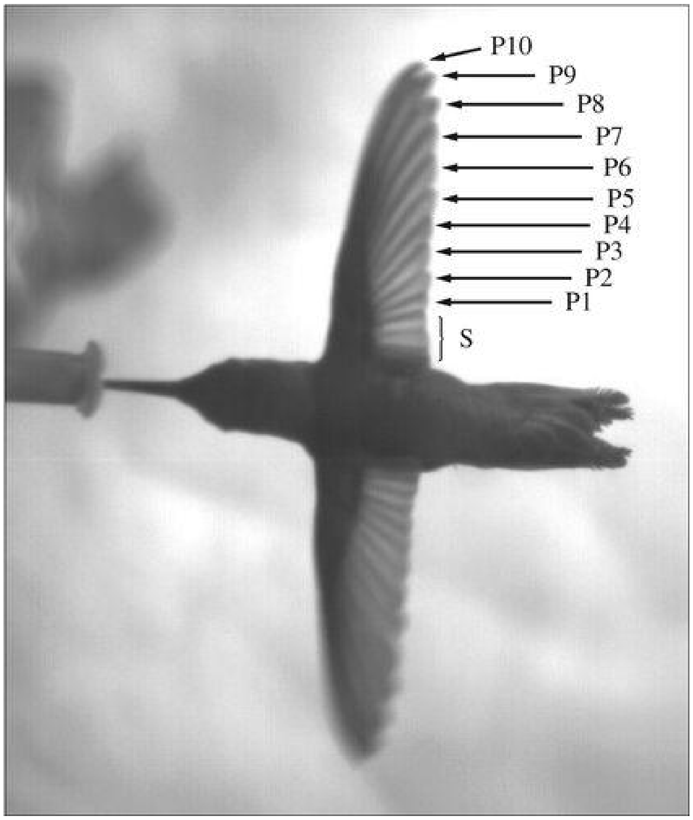


Fig. 1. Source Image Used for Photogrammetry. P1-10 denotes the points on the wing.

- The orientation of the object in the image is to be measured

2) Calibration.
The procedure would be using the tool from the internet The user must input the density of pixels per inch (DPI) of the screen. This would provide a simple conversion from pixels to millimeters. The DPI calibration is done by measuring a red stripe on the screen using a physical ruler. Depending on the measurement value of the red stripe, the DPI of the screen is found.

Measurement (mm)	Screen DPI
76	100 DPI
82	92 DPI
89	85 DPI
95	80 DPI
101	75 DPI
108	70 DPI
115	66 DPI
120	63 DPI
127	60 DPI

TABLE I
MILLIMETRE-DPI TABLE

3) Measurement
The final step would be to measure pixels that are accomplished using the ruler option present in the tool roster of Adobe Photoshop—inputting the pixel value into the tool to obtain the corresponding millimeter value. The DPI value ensures the correct conversion from pixel to millimeter conversion.

Variable	Value
Body mass (g)	3.4 ± 0.1
Single wing length	109 ± 2
Average wing chord, c (mm)	12 ± 1
Aspect ratio	9 ± 1
Single wing area (mm2)	558 ± 18
The combined area of both wings and body (m m2)	1346 ±108
Wing loading (N m-2)	25 ± 3
Disc loading (N m-2) Values are mean ± s.d. (N= 5)	3.6 ± 0.2

TABLE II
MORPHOLOGICAL DATA FOR THE HUMMINGBIRD

4) Modelling the Wing:
After obtaining the angles and distances, it was a simple case of plotting the points in SolidWorks to create a 2D closed contour and extruding it. The above design of the

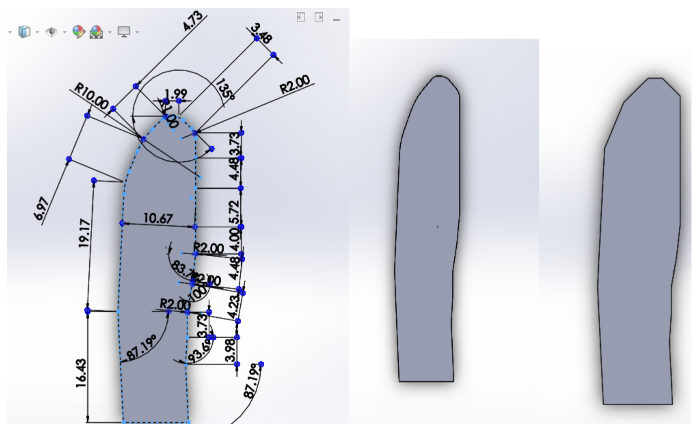


Fig. 2. Construction of the wing

hummingbird in figure(2) also provided a validation of the process of photogrammetry and also allowed for the extension of this technique for the study of the kinematic path.

5) Kinematic Path of Flight:
A drawback of photogrammetry is that when a 3D object is projected onto a 2D plane, there is a loss of information in one of the planes. This is compensated by the analysis of the object in two different views. In such a manner, the Kinematic path of flight analysis is dealt with in two stages. The procedure for the analysis of the Kinematic Path of Flight is the same as photogrammetry. It is extendable to a video due to the simple fact that videos are multiple images that are played back at a certain speed. Using this analogy, the image process technique of photogrammetry is extended onto a video. The software that is used for this procedure is Adobe Premiere Pro.

The first analysis is conducted from the side view of the bird; this would allow for the identification of the flight path by following the wingtip of the bird. In this study, the wing is considered rigid, neglecting the small amount of flex along the edge of the wing attached to the bird.

The following figure(3) and figure(4) show that hummingbirds follow a unique path of an 8, which is different from a majority that flaps in only one direction without any motion in another direction. Analyzing further and plotting multiple paths as shown in the image below, it can be inferred that the amplitude and direction of the eight shapes determine the flight characteristics and help maintain balance during its various flight modes: hover, forward and backward.

Fig. 3. Wingtip path on the source video

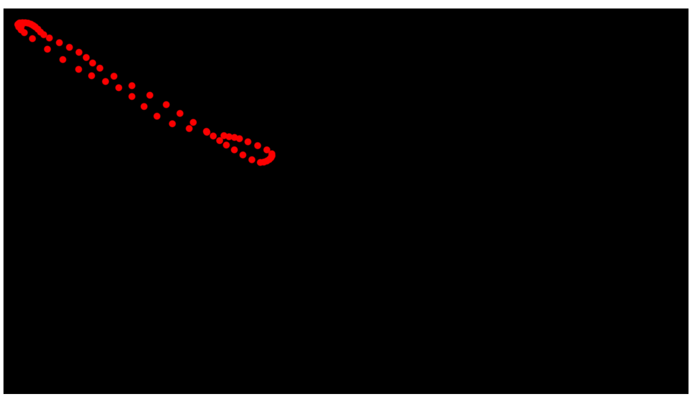


Fig. 4. Wingtip path on the transparent background

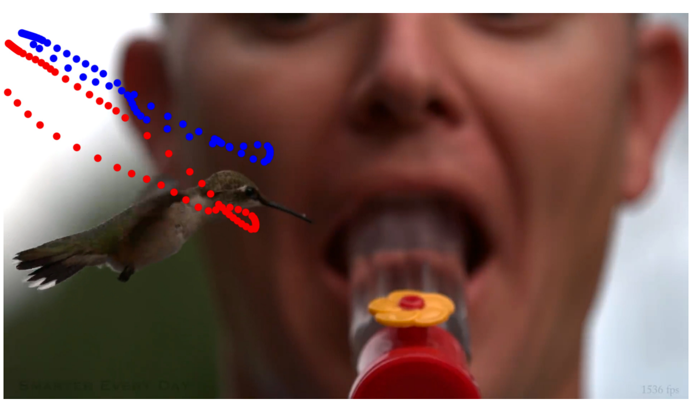


Fig. 5. Two strokes plotted side by side

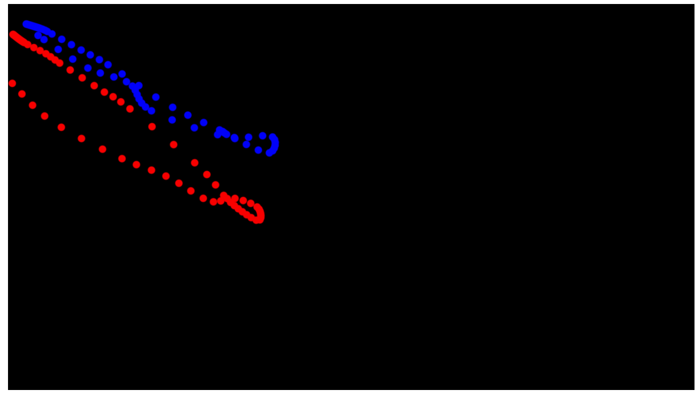


Fig. 6. Two strokes plotted side by side on black background

As mentioned earlier, the kinematic path, figure(6), shows two different wingtip paths. The variation in the eight shape orientation from the axis to the one in red helps in hover and maintaining flight.

The analysis of the wing in the front view is essential to understand the flight path of the hummingbird. In figure(7), the analysis was conducted using a reference point that does not change throughout the stroke.

Figures (7) and (8) show that the wing moves perpendicularly to the reference point. The difference in line length is due to parallax error and the fact that any 3D object projected onto a 2D space will have a loss of data. This is one of the drawbacks of photogrammetry.

From the above figures, we can infer that hummingbirds carry a 3D space motion of harmonic flapping and an eight shape motion at their wingtip. The report assumes only the harmonic flapping motion and designs a suitable mechanism. A spatial mechanism is essential for the complete emulation of the flapping of a hummingbird.

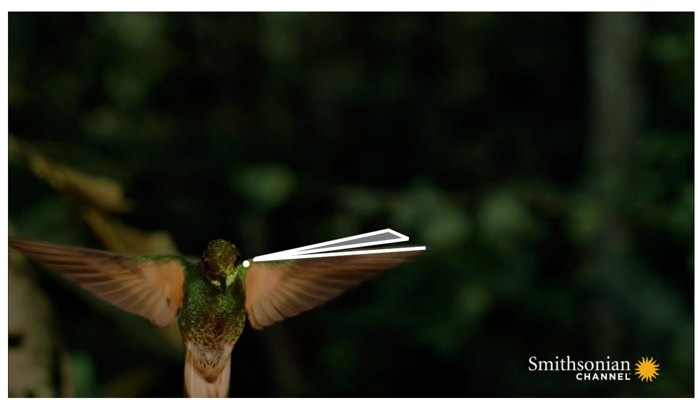


Fig. 7. Front view of flapping

B. *Weight Approximation*

Approximate weight is calculated as it plays a crucial role in the design process. For a design of the wing, there must be a known value of weight. The weight of any robot is divided into the mechanical component and the electrical component.

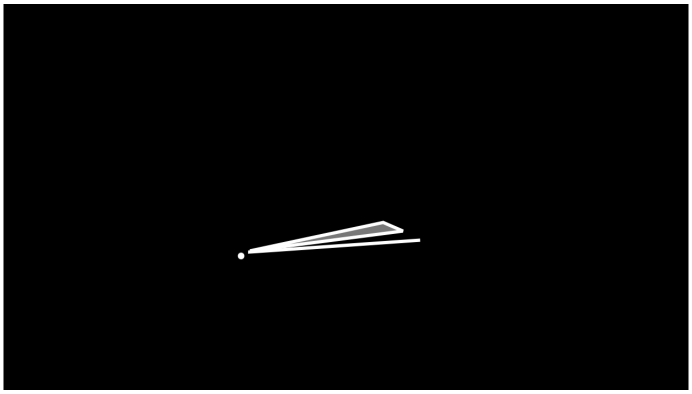


Fig. 8. Front view of flapping on black background

Sl.No	Name	Type	Voltage/Ampere Per hour	Total Weight of each component
1	Rasperry Pi Zero	Microprocessor	3.5V/72 mAh	9 g
2	MPU-9520	Inertial Measurement Unit	3.3/60 mAh	4g
3	Neo-6M	GPS	3.3V 2700mAh h	10g
4	HC-12	UART Receiver/ Transmitter	3.3V/ 216mAh	4g
5	Coreless Motor	Rotary Motor	3.3V	20g
6	3.7V 3000mAh	Lipo Rechargeable Battery	3.7	50g

TABLE IV
ELECTRONICS WEIGHT APPROXIMATION FOR PROTOTYPE

The electronics design of any system is divided into four central sub-systems. The first is the system's brain; here, we have chosen the microprocessor as the brain of the system for being the upper weight limit and freedom to improve the design. Any aviation-based system's telemetry requires an inertial measurement unit, GPS, and a set of receivers and transmitters. The inertial measurement unit(IMU) contains a gyroscope sensor that allows for the bird's balance during flight. The GPS complements the IMU and helps in providing greater accuracy detail. The motor is the necessary component for the driving force, and all the above electronics require a power source. A lipo rechargeable battery is chosen for its lightweight, size, and reusability.

We have estimated two kinds of weight: the prototype and the weight required for a testbed.

1) Testbed:
The testbed contains all the essential components ignoring the weight of the telemetry components and the power source. These are connected externally and then the weight is approximated. In the testbed, we estimate the total electrical weight to be 26 g. The antenna of the GPS module is required on the bird; the main sensor board can be separated. If we consider the electrical weight to be 50 percent of the overall, the total weight the wing should be able to lift is 52 g (table IV).

Sl.No	Name	Type	Voltage/ Ampere per Hour	Weight (grams)
1	MPU-9520	Inertial Measurement Unit	3.3/60 mAh	4g
2	Neo-6M	Antenna	-	2g
3	Coreless Motor	Rotary Motor	3.3V	20g

TABLE III
ELECTRONICS WEIGHT APPROXIMATION FOR TEST BED

2) Prototype:
The total weight of the prototype would be 193 grams with the mechanical components. The prototype's weight can further be reduced by redesigning the electrical system without the use of off-the-shelf components. In a scenario where off-the-shelf components are not used, the PCBs weight would be around 10 grams, as many of the repeated components of a circuit board, such as a 3.3 V circuit breaker, can be removed. Such components can further be simplified. Hence the total approximate weight of the prototype would be brought down to under 100 grams

C. WING DESIGN PROCEDURE

The 3d wing is designed in CAD software with a definite set of procedural steps. A 3D model of the wing is a necessity for any fluent-based analysis. The software used for this is DS Solidworks 2019. Solidworks is an efficient user-driven software. It has a wide range of support services in the form of forums, offline and online help. It easily allows for various other processes without the requirement of additional software for the same. Solidworks allows for animations, forces due to motion, flow, part stress, deflection, vibration, and effects of temperature analyses.

For optimal wing design within the design constraints, wing design is studied for its lift characteristics and corresponding flapping frequency. A standardized procedure is implemented for the uniformity and comparability of results in the design of wings.

A standard procedure is followed for the wing design. For each wing design trial, the wing length and the tip chord had a rate of inverse proportionality to each other. The root chord is kept constant. Further iterations of the wing design transformed the wing from a rectangular figure to a triangular outline in the later stages of the trials. A wing with a right-wing length in the range of a real hummingbird was considered. The effect of triangulation on each iteration was also taken into consideration. The geometry representations are given in the figure(10).

An image of different wings superimposed on one another to show the dimensional increments is illustrated in figure(11).

1) Validation Work: Steady-state CFD Analysis:

The procedure for the flapping wing motion of a hummingbird is broken down into steady state, unsteady-state flapping. The first step is to carry out a steady-state analysis

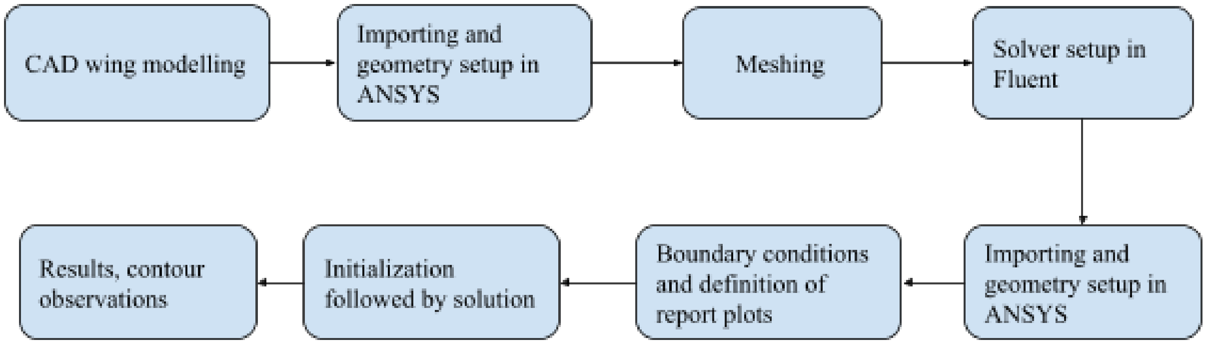


Fig. 9. Procedure flowchart

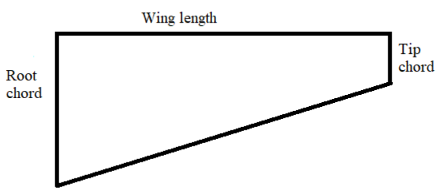


Fig. 10. Geometry specifications

to understand the aerodynamic properties. The previously designed wing models are utilized for steady-state analysis. By steady state, it is meant that the wing moves through the air with a constant velocity. In the steady-state, there is no relative wing motion with respect to the viewer, i.e.; It is a fixed-wing.To reiterate, there is no flapping motion of the wing during steady-state analysis. The first task was to obtain pressure contours of the wing and see how it behaves when it is not flapping. The result is used for validation purposes towards the project. These tests and simulations are used to understand the basic concepts of wing aerodynamics. A brief flowchart procedure as shown in figure(9) to carry out the steady-state CFD simulation is given below:

The wing model is made with the help of CAD software. This wing geometry is then imported to ANSYS FLUENT in a ".STEP file" format. The imported wing is oriented at an angle of 15, and an enclosure is made around it. In the next step, the wing is subtracted using the boolean option. The surfaces' meshing and the naming of the surfaces are

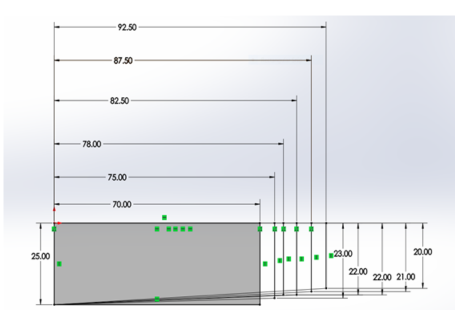


Fig. 11. Wing designs superimposed

carried out before the solving process. In the fluent database, the Spalart-Allmaras is chosen, followed by providing the appropriate boundary conditions. The boundary conditions are kept at 5m/s inlet velocity and 0 pressure outlet, respectively. Standard initialization while computing from the inlet is done, and contours in the post-processing are recorded. The resultant pressure contours are compared with a research paper [19].

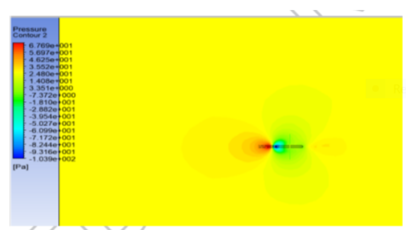


Fig. 12. Contours from research paper

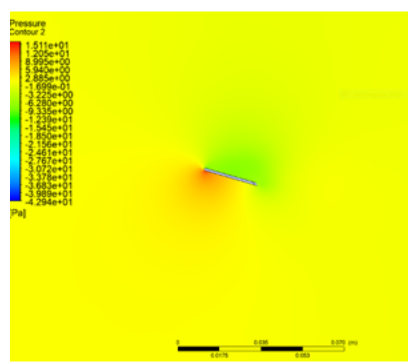


Fig. 13. Contours from present work

The figures(12) and (13) indicate that the concepts of steady-state aerodynamics hold true wherein the pressure differences on the upper and lower surfaces of the wing are distinctly visible. From the results, it is visible that steady-state aerodynamics hold good verifying the analysis procedure. The picture on the right is the same analysis with a slight variation in the angle of attack. Hence, it is inferred that the simulation is validated as the respective pressure contours from both the pictures match.

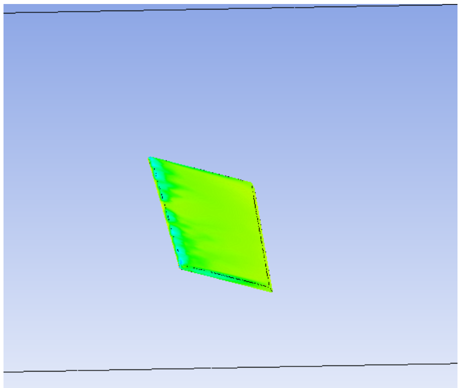


Fig. 14. Upper surface

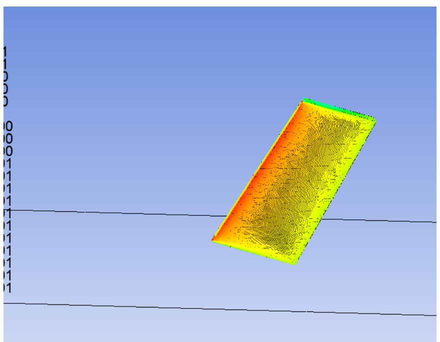


Fig. 15. Lower surface

Figure (14) represents the top surface of the aerofoil, while figure(15) on represents the bottom surface. As the intensity of the color (green - red) increases, the pressure value increases proportionally. A theoretical aerofoil has a higher pressure on the lower surface when compared to the upper surface. This trend is visible in figures (14) and (15), as mentioned earlier.

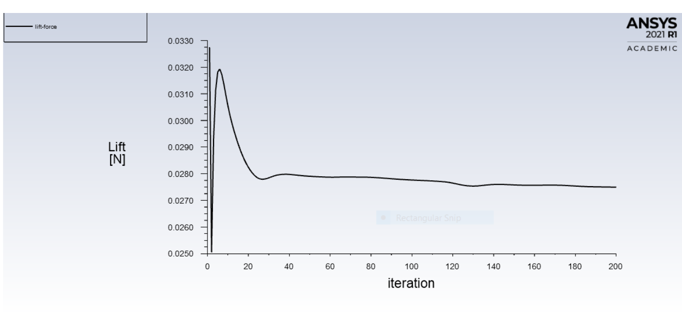


Fig. 16. Lift plot

Figures(16) and (17) indicate the lift and drag plots obtained respectively for the wing in the steady state tests.

2) The Angle of attack and its influence:

In the following section, the influence of the angle of attack is observed, and variation of lift and drag properties. The angle of attack (AOA) is the angle between the chord of a wing and the relative wind. The straight line from the leading edge to

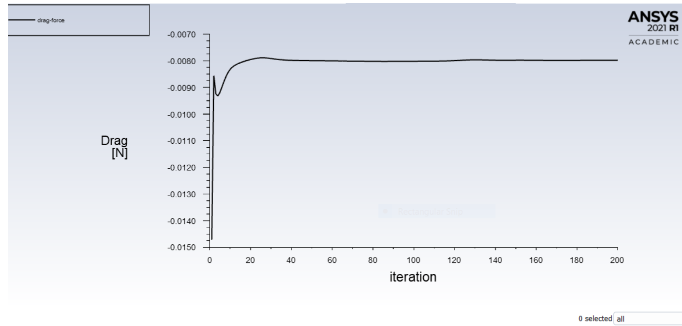


Fig. 17. Drag plot

the trailing edge is known as the wing's chord.

The procedure is started with an angle of inclination of 0 degrees, and it is then incremented by 2 degrees for every trial. The lift and drag values are recorded for each trial up to an angle of 30 degrees. This test is once again carried out in Ansys workbench with the help of the parametric analysis tool. Parametric analysis tools help the user obtain multiple results by varying a specified set of parameters. It is a fast and efficient way to find trends in results without the user having to make the changes for each calculation manually.

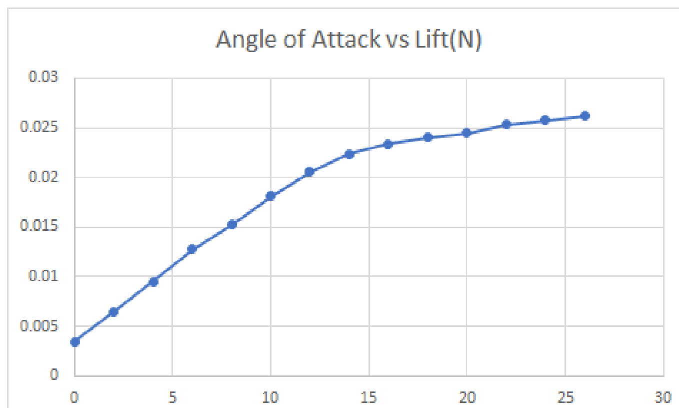


Fig. 18. Lift vs Angle of attack plot

From the results observed in figure(18) and (19), two prominent trends are observed:

1) There is an increase in a steady-state lift with an increase in Angle of Attack
2) There is a subsequent increase in the magnitude of drag force with an increase in Angle of Attack

A trend of increasing lift is noticed with an increase in the angle of attack. At first glance, this would seem favorable, but it is also observed that with an increased angle of attack, the drag force experienced increases. This hints that there is only an optimal amount up to which the angle of attack can be increased. The data presented gives us valuable information on how the wing should be inclined and at what angle it should be oriented. In the application of a hummingbird, where there is a continuous change of angle of attack, the optimal range plays a vital role.

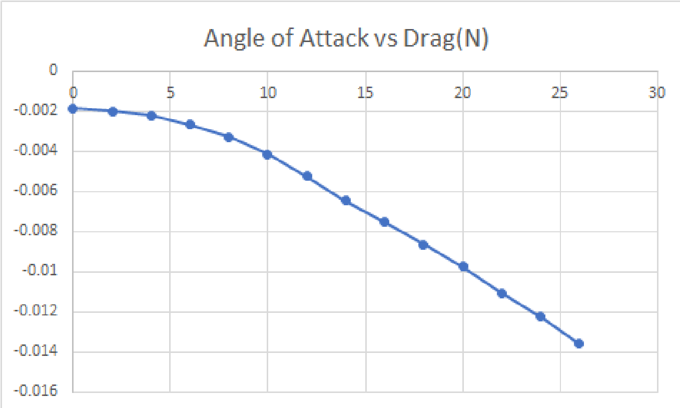


Fig. 19. Drag vs Angle of attack plot

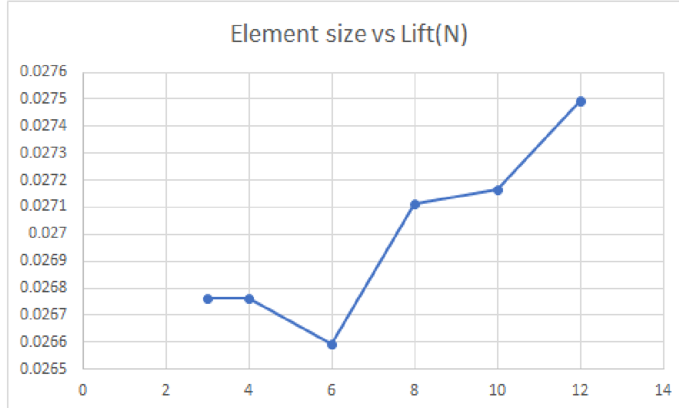


Fig. 21. Mesh Element size vs Lift(N) plot

3) Mesh Independent Study:

CFD solutions are highly dependent on the mesh(grid) size. The mesh size defines the accuracy of the analysis and the time taken for analysis. The output result of a coarser mesh and finer mesh can neither be the same. The mesh study is carried out to find how the result varies per mesh density and to reach the actual value of a CFD simulation, and it is required to do an independent mesh analysis. Grid independence test is conducted until acceptable levels of tolerances in results are reached from the variation of mesh refinement. The test is also done to facilitate the reduction of computation time and memory requirements. The Parametric analysis method of Ansys Workbench is used to perform this test. Parametric analysis is a fast and time-saving technique, as mentioned in the previous section. This tool of Ansys allows the user to vary the mesh with reference to specific inbuilt parameters utilized while meshing without having to run each calculation manually.

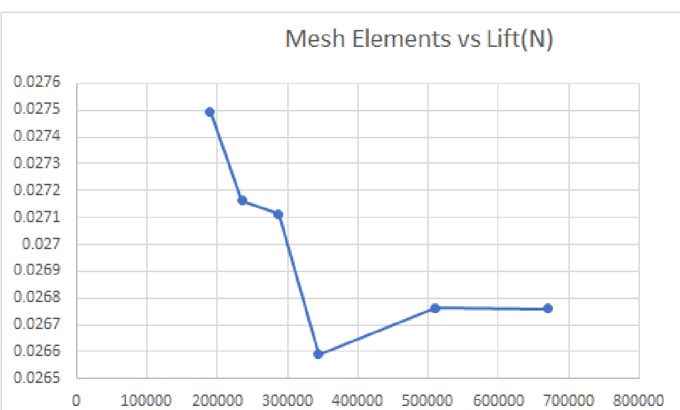


Fig. 20. Mesh elements vs Lift(N) plot

Figures(20) and (21) lead to an observation that a mesh density with 520k elements gives results very close to the mesh with 630k elements. About the element size, it is also seen that an element size of 4 gives results very close to mesh with three as the element size.

With the above observation, it is concluded that the user can use a mesh with 520k elements, with each element having a size of 3 to achieve faster computation times.

4) Lift Calculations- Wing Lift Formula:

The lift generated due to a flapping wing is significantly different from a fixed-wing, and hence the conventional formula cannot be applied to find the lift force calculations.

The flapping lift also takes into consideration a vital flight parameter which is the frequency of the wingbeat. This frequency is called " flapping frequency, "It is the number of wingbeats completed in one second.

The formula used here is derived from the reference[14]. The mean lift force for flapping wings is found by approximating classical theory for the fixed-wing in steady flow while using cycle-averaged quantities. A few assumptions are made:

1) The wing is flat and rigid.
2) The center of pressure is placed at mid-length(RCP)= R/2.

It is found that when a wing flaps at a certain frequency f with amplitude of $\phi = 2\phi m$, then its CP (Centre of pressure) moves at a mean velocity of $Ucp = 2\phi f Rcp = \phi f R$ The cycle average lift force for a pair of wings is written as $FL = 1/2\rho \times CL \times (2S) \times U^2 \times cp = \rho CLS \times (\phi f R)^2$ Here S is the area of a single wing and CL is the mean lift coefficient After including the wing aspect ratio definition as Aspect Ratio(AR) = R^2/S, The final expression for lift force due to a frequency induced flapping motion can be given by $FL = 1/2\rho CL \times AR \times (\phi f S)^2$

The specific terminologies and the aspect ratio definition are provided in figure(22).

The above formula is further used to find the lift of different wings, each flapping with a range of frequencies. The calculations are tabulated and shown below.

The results obtained from the lift calculations are plotted in table(3.5). The frequencies are calculated from within the range of 30 - 80Hz keeping in mind the limits provided by the motor.

The above results drawn from tables(3.5) and (3.6) conclude two significant trends concerning flapping flight. It is found

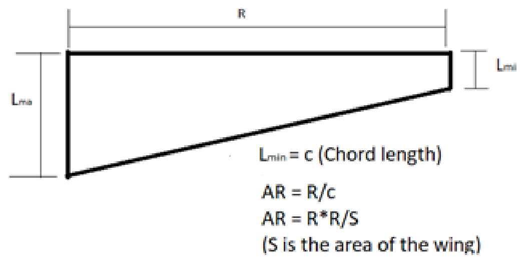


Fig. 22. Wing geometry terms and aspect ratio definition

that that the corresponding flapping lift force:

1) Increases with increase in wing area and
2) Increases with an increase in flapping frequency

5) Wing Modelling:
Once the appropriate dimensions for the wing are selected, the wing is then modeled in CAD software. The suitable materials are also decided upon based on their properties. The wing is conveniently made with an aperture so that it can be attached to the mechanism.

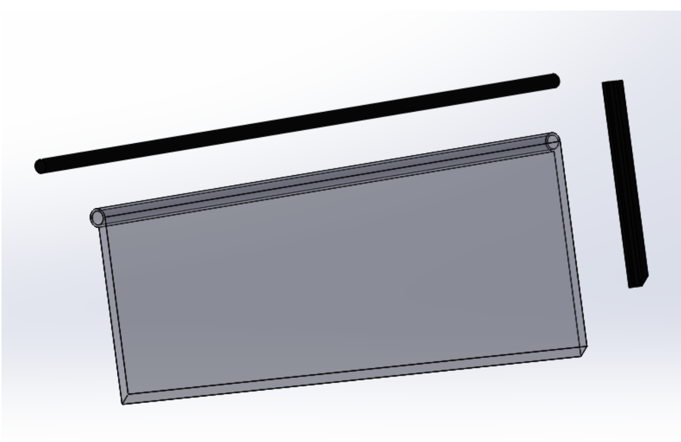


Fig. 23. Wing CAD modelling

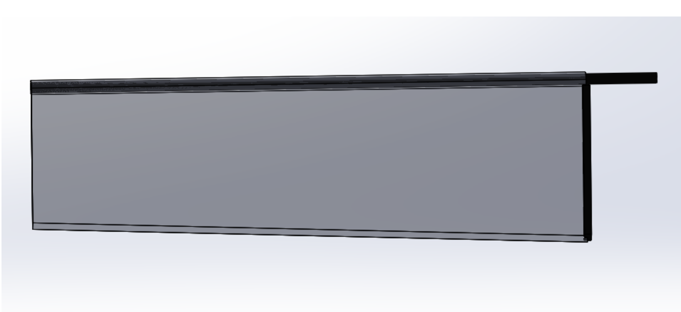


Fig. 24. Exploded view of CAD model

Figure(23) and figure(24) illustrate the wing's CAD model and its exploded view respectively. The wing film is made with the substance PET, which stands for polyethylene terephthalate. PET is a standard commercial polymer having a wide range of applications ranging from packaging, fabrics, films to molded parts for automotive, electronics, and many more. The material was specifically chosen in this case due to a few stand-out properties:

1) PET has high strength and stiffness
2) It is very strong while being lightweight hence best suited for our application
3) It does not break or fracture, and its shatters resistant
4) Another critical property is the fact that it is an excellent material that is used in additive manufacturing processes

Rods of 1.5 mm thickness made from carbon fibre reinforce the wing films and act as a support structure for the PET film. One of the rods is made in such a way that it accommodates a fixture that is used to join it with the mechanism.

D. Mechanism Design and Analysis

1) Validation:
The first choice for a flapping mechanism that employs a rocking motion would be a four-bar mechanism in which the output link generally takes a rotary motion at the input link from an actuator like a DC motor. However, there are certain limitations that we come across while going for a simple four-bar mechanism: the output angle generated is very low for our application. Therefore, a few modifications are necessary for the four-bar mechanism for implementation for the application.

It is still possible to use a simple four-bar mechanism without any modifications, but this has limitations. The mechanism used by Michael et al. [12] achieves this by using a piezoelectric actuator instead of a rotary one as the tip of the input link is to be varied between ±1mm, and this gives any output angle variation of ±60° as shown in figure(26) and figure(27), which is more than a traditional four-bar mechanism with a rotary actuator. The link lengths are taken from the paper, and the same is modeled in Solidworks as shown in figure(25).

Controlling the input link for such a small displacement can be difficult. Instead, a rotary actuator like a DC motor would be preferred as they are widely used in similar applications.

To overcome the difficulties mentioned above, we will look into the mechanism used by David et al. [13], which is a 5-bar linkage but is essentially a simple four-bar mechanism with an added fifth linkage and a slider. The purpose of adding this additional link and a slider is to amplify the output of the four-bar mechanism to obtain the required results. The input to this mechanism is of the rotary type, and the output is a rocking motion with an amplitude of ±60°. The link lengths were taken from the paper. The same is modeled in Solidworks as shown in figure(28) and figure(29) and the positional, velocity, and acceleration graphs are also plotted.

The results of the positional analysis were compared to the ones shown in the paper and were found to be similar as shown in figure(30). The following graphs show the results for the modified four-bar mechanism and the four-bar mechanism

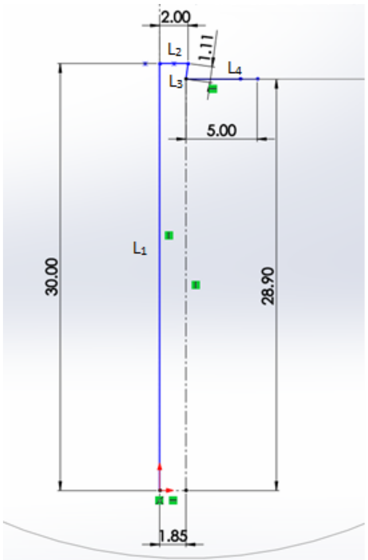


Fig. 25. 26 Free body diagram of Mechanism 1 (all measurements are in mm and degrees)

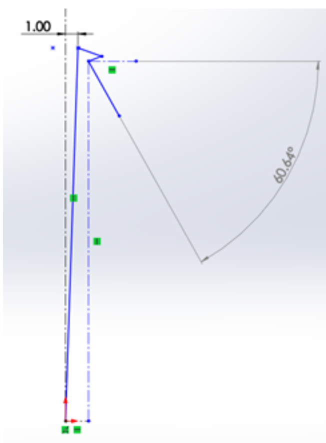


Fig. 26. 27 Showing -60° (all measurements are in mm and degrees)

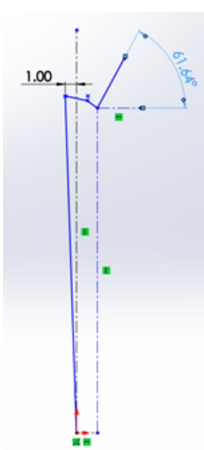


Fig. 27. Showing +60° (all measurements are in mm and degrees)

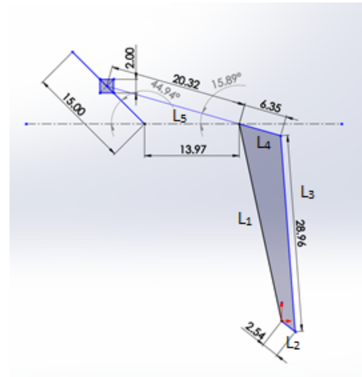


Fig. 28. Free Body Diagram of Mechanism 2 (all measurements are in mm and degrees)

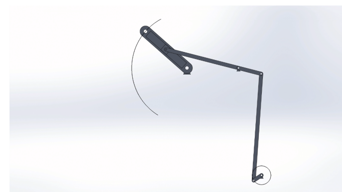


Fig. 29. A still from the motion analysis of Mechanism 2

component. Observations show that only considering the four-bar mechanism, an output of ±20° is achieved, which is lesser than an output of ±60° produced after amplification. The results align with our previous discussion about how low the output is when we use only a simple four-bar mechanism, which justifies the modifications introduced.

The velocity and acceleration graphs shown in figure(31) will help us compare mechanisms which are modelled further.

The following mechanism by Mat ˇej et al. [14] has some similarities compared to the previous one. It is similar because it uses a modified four-bar mechanism, a rotary actuator at the input link, and an output of about ±60°. The difference in mechanisms is the introduction of a slider-crank at the input instead of at the output.

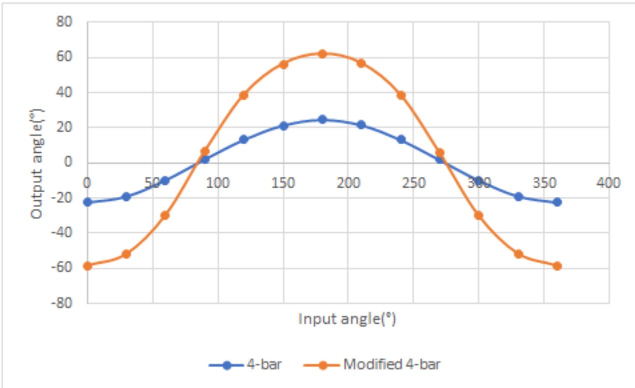
The slider-crank is further linked to a four-bar mechanism, successfully converting the sliding motion to a rocking motion. The link lengths were taken from the paper and an image of the same is shown in figure(32), it was then modeled as shown in figure(33) and figure(34).

Observation of the positional analysis was found to be the same as in the referred paper. Furthermore, the results were also compared to a harmonic function as seen in figure(35).

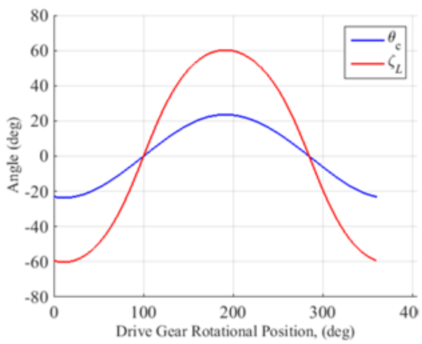
Velocity and acceleration graphs are also plotted as shown in figure(36) and they will help us compare mechanisms which are modelled further.

Another iteration of the same mechanism is performed, the free body diagram is as shown in figure(37) and reasons being:

1) In the first Iteration, L3 was considered as the distance between the mounting points. The link between the cam and L4 was ignored.



(a)



(b)

Fig. 30. (a)Results of mechanism 2 (b)David et al Comparison with the research paper

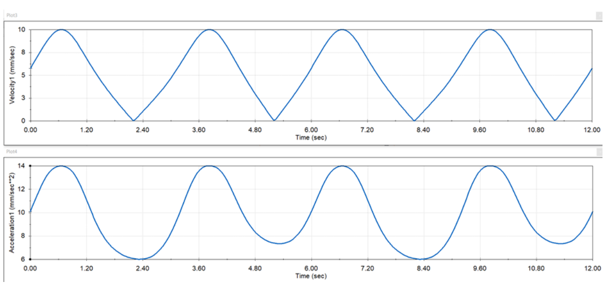


Fig. 31. A still from the motion analysis of Mechanism 2

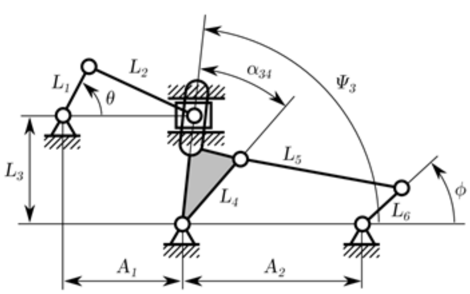


Fig. 32. Image of mechanism given in the paper

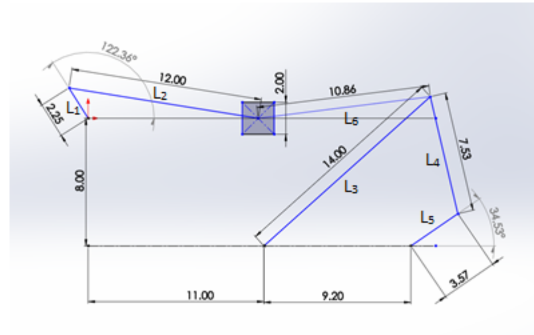


Fig. 33. Free Body Diagram of Mechanism 3 (all measurements are in mm and degrees)

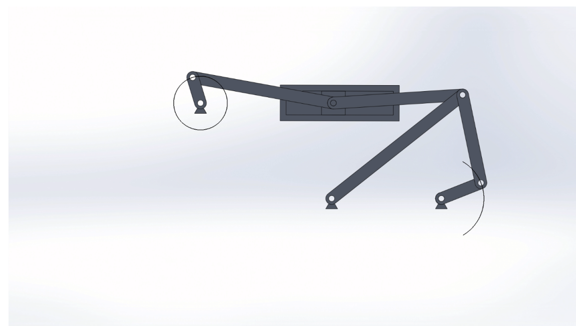
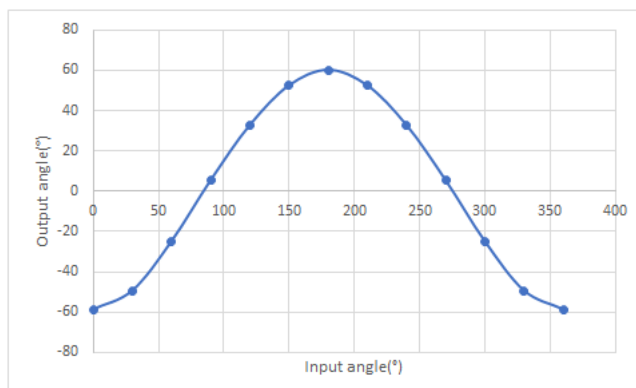
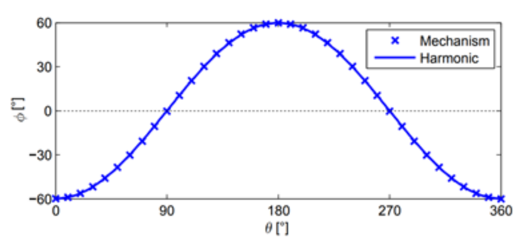


Fig. 34. A still from the motion analysis of Mechanism 3



(a)



(b)

Fig. 35. (a)Results of mechanism 3 (b)David et al Comparison with the research paper

2) In the second iteration, L3 was considered the distance between the mounting points and the length of the link between the cam and L4 mounting point.

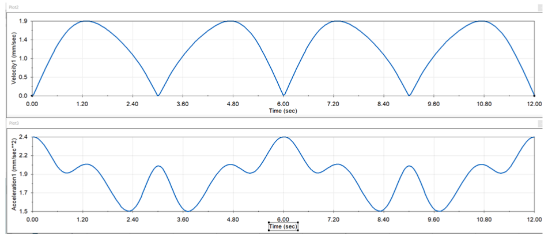


Fig. 36. Velocity and acceleration analysis of Mechanism 3

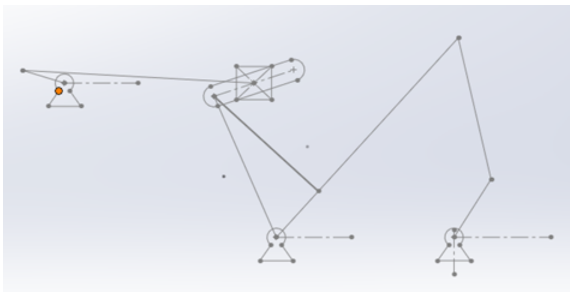


Fig. 37. Free Body Diagram of Mechanism 3 (iteration 2)

The results of the second iteration were compared to the first iteration and the results are in figure(38) -

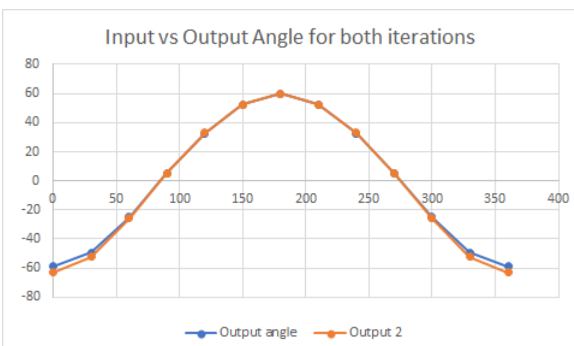


Fig. 38. Comparing results of iteration 1 and 2

2) Design of a four-bar mechanism: The previous designs were taken from papers, as mentioned. A new iteration of a four-bar mechanism is designed to achieve a total flapping amplitude of 120° and a time ratio of 1.

The design procedure is the graphical method for synthesizing crank rocker linkages for specified rocker amplitude as mentioned in the book "Kinematics, Dynamics, and Design of Machinery by Kenneth, Gary, and Sunil."[20]

The initial parameters are the time ratio, input angle, output angle, and one assumed link length. The input angle is 360° as the input of the mechanism is actuated through a rotary actuator, which is assumed to be a coreless DC motor. The time ratio is the time taken between the forward and backward stroke. In a mechanism where the flapping simulation of the wing is being considered, we assume the motion to be symmetric, i.e., the time taken for both strokes to be equal. Hence the considered time ratio is 1. The output angle is considered as 120° to maintain symmetry. A real-life hummingbird motion ranges from +60 to -80 degrees. These values of time ratio and output angle are inferred through a literature survey and the various resources surveyed on flapping mechanisms used for the hummingbird. Through the graphical method and the known input parameters, we can extract the lengths of the remaining links and the free body diagram is as drawn as shown in figure(39). A similar design procedure has been followed throughout the paper. A graph of output angle vs input angle is shown in figure(40) which is asymmetric unlike previous mechanisms and the velocity and acceleration graphs are shown in figure(41).

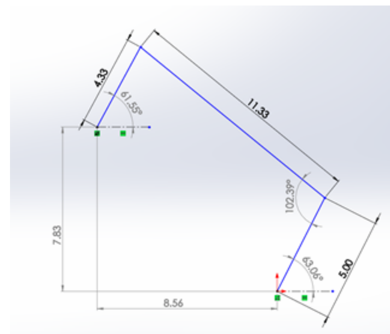


Fig. 39. Free Body Diagram of Mechanism 4 (all measurements are in mm and degrees)

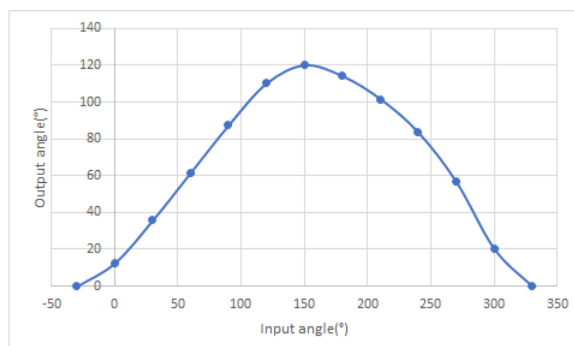


Fig. 40. Position analysis of Mechanism 4

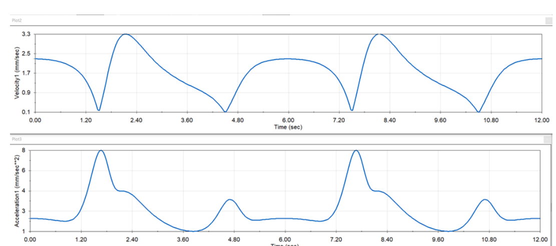


Fig. 41. Velocity and acceleration analysis of Mechanism 4

This mechanism's maximum and minimum transmission angles (ηmax and ηmin respectively) are not feasible as they are very far from the optimal value of 90°; they need to be as close as possible to 90°. Hence this design is not feasible.

$$\eta max \approx 152 \tag{1}$$

$$\eta min \approx 27 \tag{2}$$

The velocity graph of this mechanism is also very different from the velocity graphs of mechanisms 2 & 3 (Figure 31 and figure 36 respectively).

A four-bar mechanism with a total flapping amplitude of 40° is designed to address the above-stated shortcomings. The reduction in flapping amplitude ensures that the transmission angle is in a feasible range. In subsequent iterations, an addition of an amplifier helps in reaching the required design amplitude. The results are compared with the second and third mechanisms discussed above.

The mechanism is modelled as shown in figure(42) and figure(43) with the position analysis in figure(44) which shows that it is much more symmetric than the position analysis of mechanism 4.

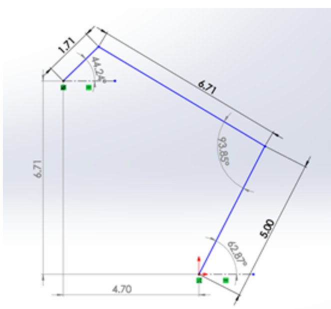


Fig. 42. Free Body Diagram of Mechanism 5 (all measurements are in mm and degrees)

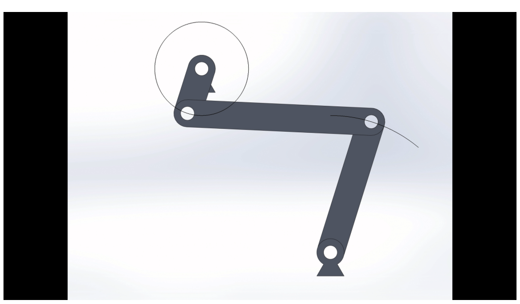


Fig. 43. A still from the motion analysis of Mechanism 5

The velocity graph as shown in figure(45) is similar to the velocity graphs of mechanisms 2 & 3 (Figure 31 and figure 36 respectively), and the transmission angles are feasible and much better than the previous four-bar mechanism.

$$\eta max \approx 114 \tag{3}$$

$$\eta min \approx 65 \tag{4}$$

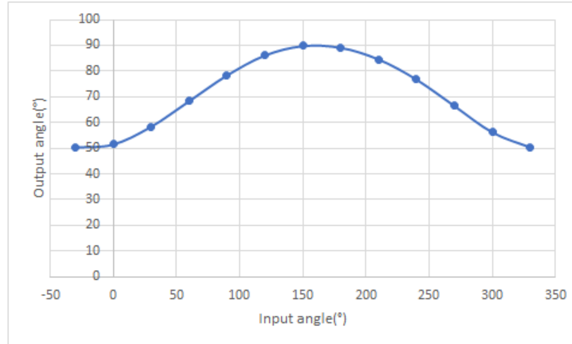


Fig. 44. Position analysis of Mechanism 5

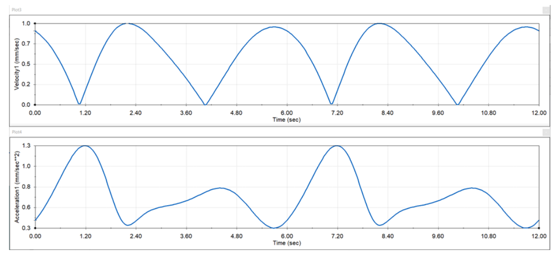


Fig. 45. Velocity and acceleration analysis of Mechanism 5

3) Design of modified four-bar mechanism: We have the four-bar mechanism, which gives us a flapping amplitude of ±20°. The next step would be to modify this mechanism to give us a flapping amplitude of ±60°.

The method to go about this is inspired by one of the mechanisms reviewed earlier in this project (Mechanism 2 - Figure 28). The modification is done by adding an extra linkage with a slider as shown in figure(46) and figure(49), and the velocity and acceleration analysis for the output linkage is done as shown in figure(48).

The position, velocity and acceleration graphs are all very similar to mechanism 2 which was reviewed earlier.

The slider mechanism in mechanism 6 can be replaced by

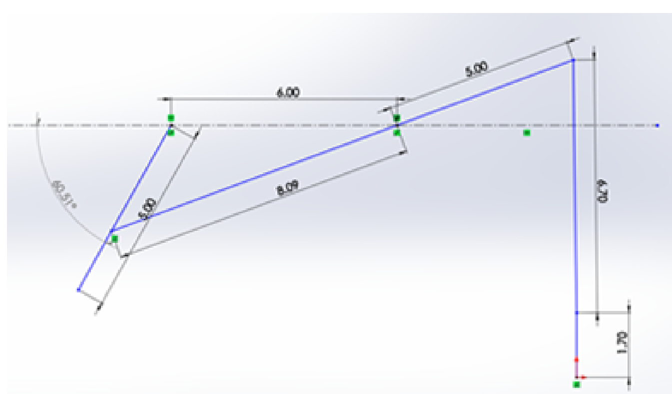


Fig. 46. Free Body Diagram of Mechanism 6 (all measurements are in mm and degrees)

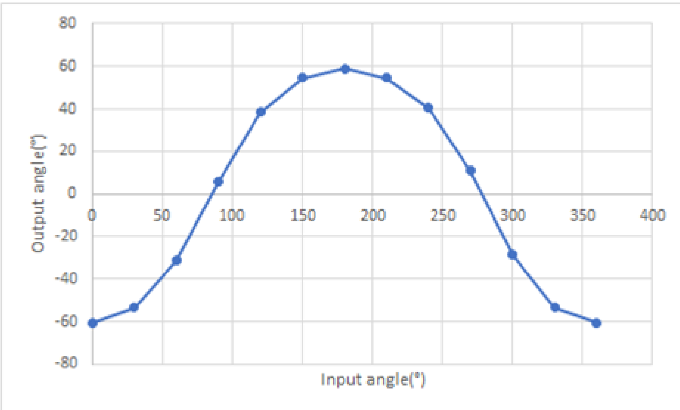


Fig. 47. Position analysis of Mechanism 6

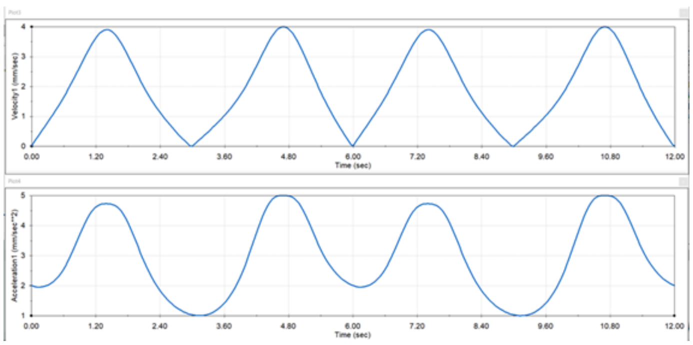


Fig. 48. Velocity and acceleration analysis of Mechanism 6

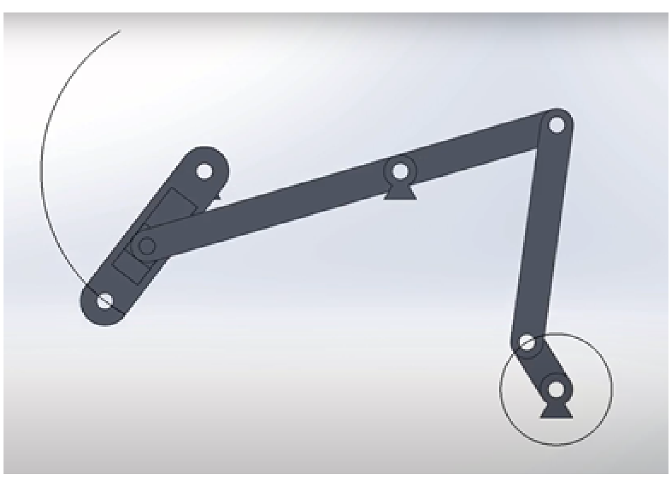


Fig. 49. A still from the motion analysis of Mechanism 6

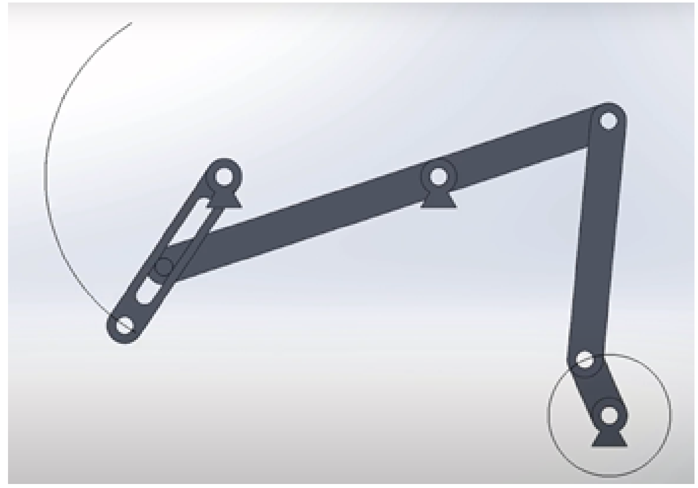


Fig. 50. A still from the motion analysis of Mechanism 6 (Pin and slot variation)

a pin and slot as a possible iteration of the same as shown in figure(50). A pin and slot help reduce frictional forces and allow for precise manufacturing in the scenario of smaller components. The position, velocity, and acceleration plots remain the same.

IV. Results

A. *Photogrammetry and Kinematic Path*

The kinematic path analysis through image processing technique shows that the hummingbird flight contains two specific strokes, the eight shape followed by the wingtip and the harmonic flapping in the front view. The report contains the mechanism for the flapping shown in the front view, which is essential for hovering.

B. *Weight Approximation*

Upon estimating the mechanical and electrical components, it is approximated that the total testbed weight to be 52 grams, and the prototype weight with the telemetry devices weight to be 80 grams.

C. *Wing Design and Analysis*

1) Angle of attack:
From the parametric tests concluded it is found that the lift forces increase with an increase in the angle of attack while the optimum angle of attack at which the wing is oriented lies in the range of 10-15 degrees.

2) Lift Calculations:
From the wing lift formula derived and the values calculated for each wing model corresponding to a specific frequency, two important features are noticed. The trends observed from figure(51) and figure(52) indicate that -

1) Increases with increase in wing area and
2) Increases with an increase in flapping frequency

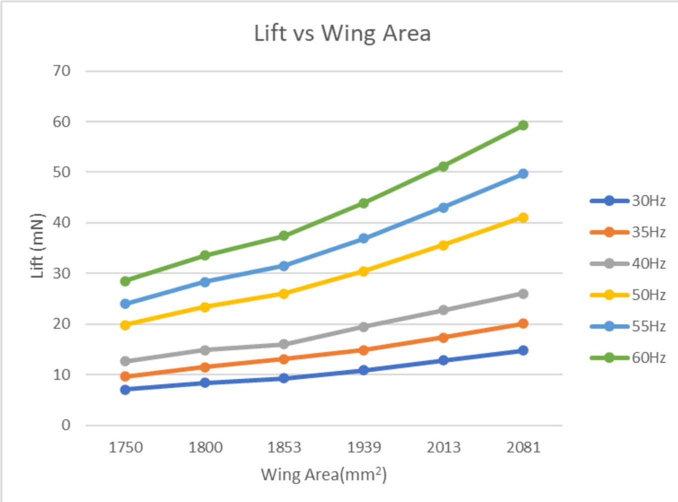


Fig. 51. Lift vs Wing area plot for different frequencies

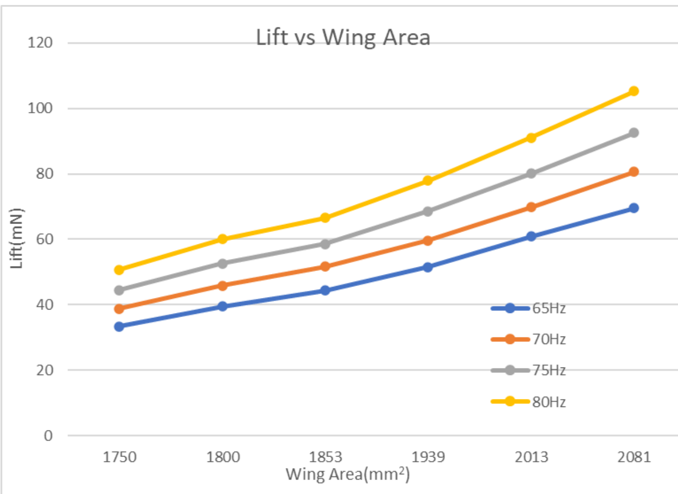


Fig. 52. Lift vs Wing area plot for different frequencies

3) Wing dimensions and flapping frequency: Based on the weight approximations calculated, the required lift force needed for the ornithopter liftoff is chosen from tables (3.5) and (3.6). For the current work, a wing of length 82.5 mm and 22mm tip chord is chosen. The wing is found to have an aspect ratio of 7.5. The required flapping frequency is 70Hz. The coreless motor chosen for this task is rated at 60000 rpm, which exceeds the required flapping frequency.

D. Mechanism Design and Analysis

After reviewing multiple flapping mechanisms, the kinematic design of a mechanism has been obtained, giving us the required flapping amplitude of ±60° with the input angle being 360°. The maximum transmission angle is 114°, and the minimum transmission angle is 65°(of the four-bar component). Another point to note is that the link lengths mentioned in the free body diagram are not the final dimensions and can be scaled depending on the requirements and on any further analysis which would be done.

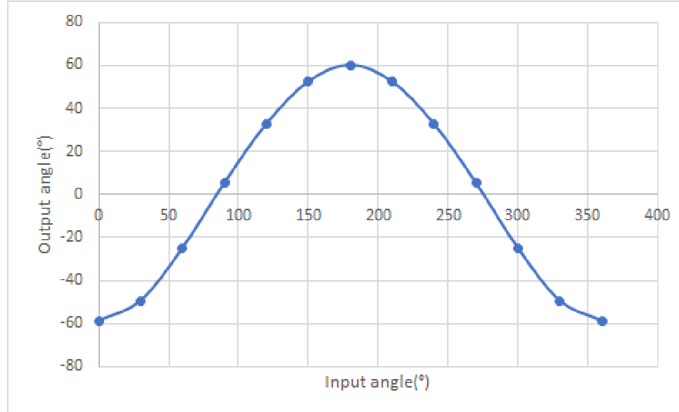


Fig. 53. 4 Position analysis of Mechanism 6

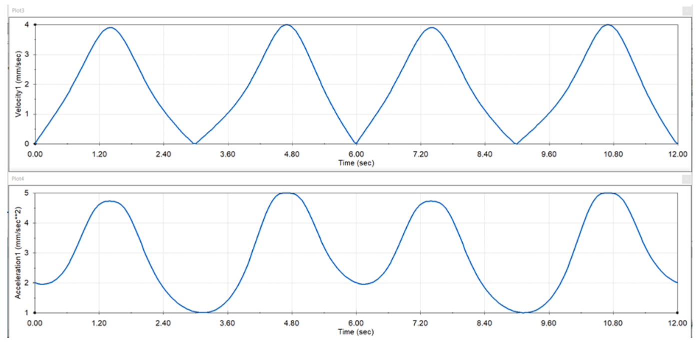


Fig. 54. Velocity and acceleration analysis of Mechanism 6

The output link's position, velocity, and acceleration graphs have been plotted as shown in figure(53) and figure(54) respectively which are similar to the mechanism 2 from which it is inspired.

V. Conclusions and Future Work

The kinematic study gives the designer an understanding of which motion of the hummingbird plays a significant role. This is important as the considerable pitfall of biomimicry is the lack of understanding of a process being simulated. A weight approximation study is conducted to ensure that the designer has an approximate weight to perform any form of aerodynamic research. The aerodynamic research is undertaken with weight approximation being a crucial input parameter. The mechanism design uses the required flapping frequency found by the aerodynamic study to design a suitable mechanism.

In each design stage, a few essential characteristics were observed for the successful design of the hummingbird. In the stage of path analysis, the various motions involved and the contributing factors were found for the three modes of flight of a hummingbird; hover, backward, and forward.

In the aerodynamic study, the effect of various factors plays a major role. The hummingbird wing flaps in an eight-shape motion, except standard wing parameters; all other parameters vary with time. Hence, a wing designer must understand every

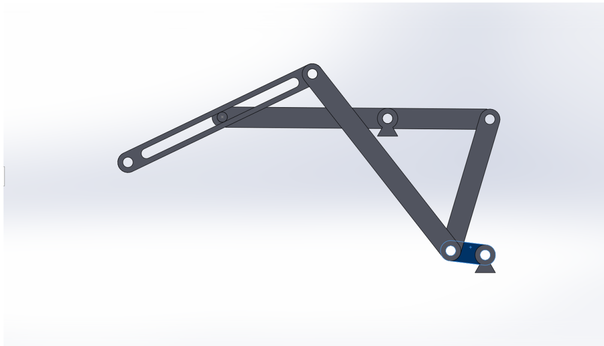


Fig. 55. Velocity and acceleration analysis of Mechanism 6

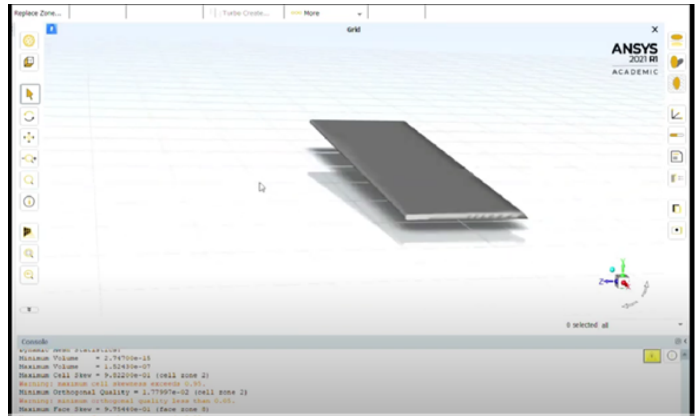


Fig. 56. Velocity and acceleration analysis of Mechanism 6

parameter's trend and effect that varies with respect to time. One such example would be the angle of attack, where there is an optimal range after which an increase of angle of attack leads to detrimental effects.

In the mechanism design, a designer can design a mechanism that achieves a particular flapping motion but must ensure that the design mechanism's transmission angle lies in the feasible range. This ensures the feasibility of the mechanism, which is an essential factor for realizing a mechanism. The complete replication of the various movements of a hummingbird, a spatial mechanism, is more suitable when compared to a linkage mechanism. A designer can make various improvements at each stage of the design process.

One such improvement would be a spatial mechanism or the design of a linkage mechanism that can follow an eight shape. One such mechanism is illustrated in figure(55). Here the first set of links draw an oval shape while the slider link creates motion in the x-direction simulating an eight motion. The major drawback of this type of mechanism is that an additional mechanism requires another mechanism to cause the flapping motion. The second drawback is that such a mechanism cannot generate the eight motions from all locations, i.e., highly dependent on the initial and final position.

The second scope of improvement would be in the aerodynamic study, i.e., to better understand wing flapping and its associated aerodynamic properties. It is crucial to perform Dynamic CFD simulations, as shown in figure(56). Dynamic meshing tool in Ansys helps the user achieve such tasks by enabling the object's movement and mesh while computing. These features are obtained by implementing a UDF (user-defined function) that acts as the mesh movement's command mode. Simulations are carried out on a 2D scale to understand and grasp the concept of dynamic meshing and UDF. A flat rectangular 2d plate is made to oscillate harmonically with the help of a user-defined function. The corresponding aerodynamic properties, contours are noted and observed. A similar procedure is carried onto a 3d wing model designed from CAD software.

Another improvement for the flight path analysis would be to use better image processing techniques and libraries where the wing boundaries can be recognized through contour detection but would initially require the grayscaling of the picture for computational reasons. The next step would be to obtain the individual points of the contour and plot them in 3D space to analyze each flap and arrive at a generalized function. The generalized process can then be implemented into UDF in simulation software such as Ansys to understand the flight and aerodynamic properties further. Figure(56) illustrates the wing model undergoing trial flapping motion in the Ansys dynamic mesh environment.

References

Please number citations consecutively within brackets [1]. The sentence punctuation follows the bracket [2]. Refer simply to the reference number, as in [3]—do not use "Ref. [3]" or "reference [3]" except at the beginning of a sentence: "Reference [3] was the first . . ."

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Biomimetic of a hummingbird: Design and analysis of wing and flapping mechanism

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Introduction:
Our work focuses on analyzing flight path, required flapping rate, and kinematic study of a mechanism to achieve the flight path that a hummingbird generally exhibits. There is a portion of weight approximation and wing analysis; this is a part of the project works as it provides a range of input parameters for consideration during the kinematic design of the flapping mechanism.

Objectives:
Following the design procedure of biomimicry, the design procedure is split into the following stages:

- Photogrammetry and Kinematic Path of Flight
- Weight Approximation
- Wing Design and Analysis
- Mechanism Design and Analysis

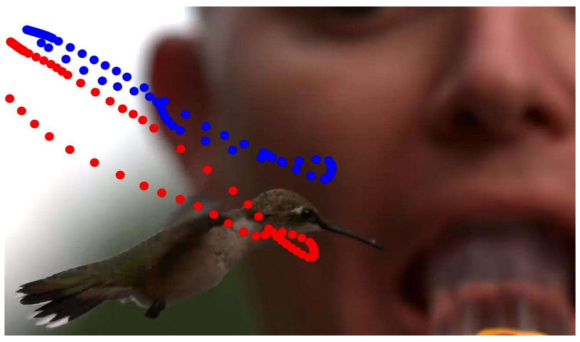


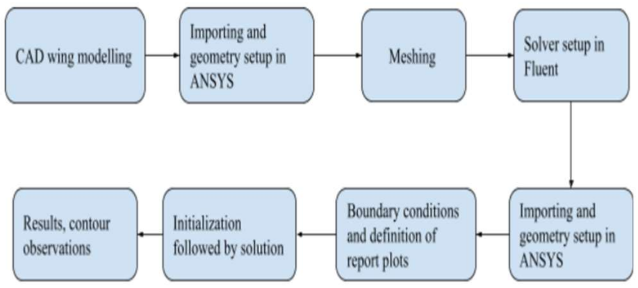
Fig. 1 Two strokes plotted side by side

Fig. 2 Front view of flapping

Table 1 Electronics Weight Approximation for Test Bed

Sl.No	Name	Type	Voltage/Ampere per Hour	Weight(grams)
1	MPU-9520	Inertial Measurement Unit	3.3/60 mAh	4g
2	Neo-6M	Antenna	-	2g
3	Coreless Motor	Rotary Motor	3.3V	20g

A brief procedure to carry out the steady-state CFD simulation:



Wing lift formula:

- Frequency induced flapping lift
- Flat and rigid wing
- **Lift = ρCLS (ΦfR) ² (mN)**

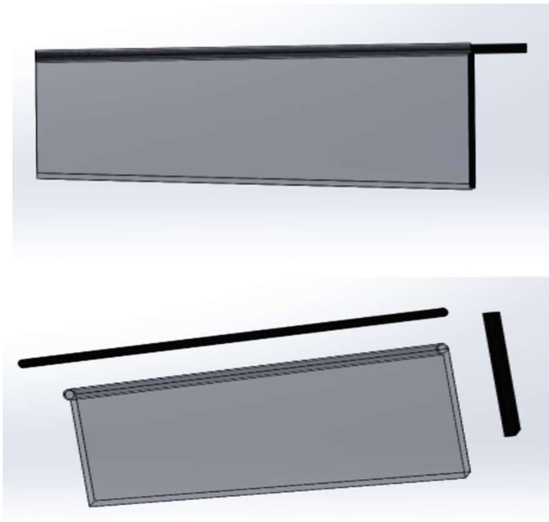
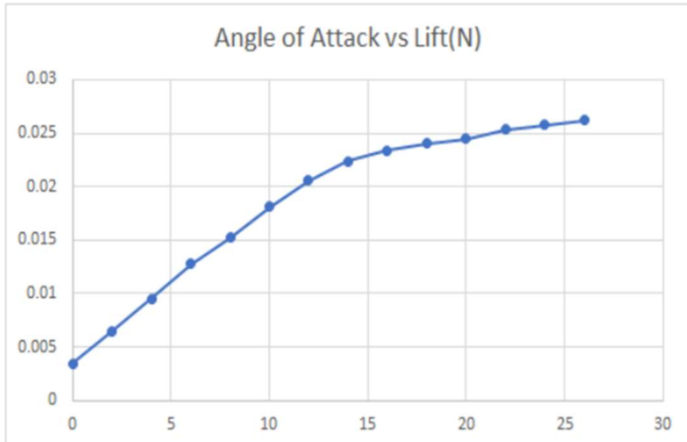


Fig 3 Wing CAD modelling

Lift vs Angle of attack plot:



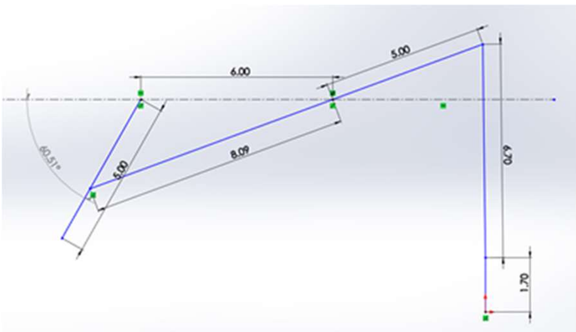


Fig 4 Free body diagram

Transmission angles (of 4-bar component):

$\eta\_max \approx 114°$

$\eta\_min \approx 65°$

Conceptual model:

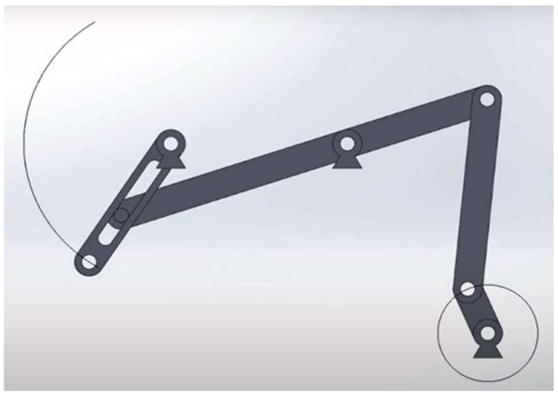
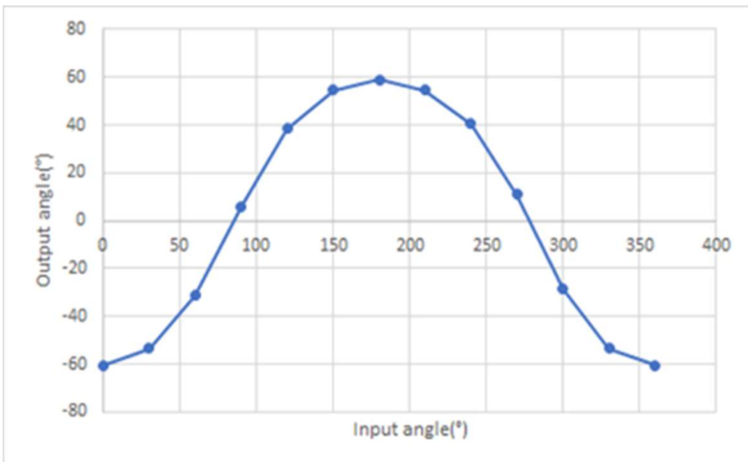


Fig. 5 A still from the motion analysis

Position acceleration graph:



Results and conclusions:

- Kinematic path analysis is carried out using image processing
- The total testbed weight is approximated to be 52 grams
- The optimal angle of attack is in the range of 10-15 degrees
- Wing dimensions; Wing length = 82.5mm, tip chord = 22mm, Flapping frequency = 70Hz
- The mechanism gives a flapping amplitude of ±60° with the input angle being 360°. The dimensions mentioned can be scaled to appropriately fit with other components.

Future work:

- Use of better image processing techniques and libraries for enhanced flight path analysis
- An improved aerodynamic study by implementing dynamic mesh analysis with an appropriate UDF
- Mechanism improvement which can achieve the figure of eight motion
- Progressing towards synthesizing spatial mechanism to ensure transmission angle lies in the feasible range

Velocity and acceleration graphs: