UNIVERSITY OF CALIFORNIA,
IRVINE

Experimental Investigations of Bio-inspired Flight Mechanisms

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

Kevin Huang

Thesis Committee:
Professor Haithem E. Taha, Chair
Professor John M. McCarthy
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DEDICATION

To:

My family, who allowed me to be who I am and let me do what I needed to do over the years. I would not have gotten where I am today without the incredible amount of love, understanding, and patience.

My advisors and instructors, who gave me invaluable lessons and instructions that allowed me to mature and pursue my dreams.

My colleagues, who worked tirelessly alongside me to help me understand and discover parts of the world I didn't know existed before.

My friends, who lend me their ears and voices to help me get over myself and gave me the courage to become who I am today.

Myself, I became strong enough to fight for the things I believed in and chased the goals and dreams I set for myself. I learned to take flight in my own way and truly begin to believe in myself. For pushing through and walking away with a Master's Degree and more confidence than I've ever had before.

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ACKNOWLEDGMENTS

I would like to give my thanks and appreciation to the Henry Samueli School of Engineering at UCI to let me utilize the facilities and resources to uncover the secrets of the world and widen my viewpoint. I was allowed to discover how the world worked at my own pace. I highly doubt I would've had such an amazing experience elsewhere in the world.

Professor Taha, for trusting me and allowing me to chase my dreams. I truly don't believe any other instructors in the world would've given me the amount of freedom and patience you did. There were many moments when I didn't believe I could make things fly, but never once did you pressure or question me. Sometimes life is frantic and tumultuous so we didn't always get the chance to have constant communication, but you allowed me to learn, explore, and build. I have made something of myself and pushed myself further than I've ever expected. And it is partly due to your existence.

To Dipan Deb for being the best advisor I could've asked for. Providing me with so many chances to learn, giving me the amount of patience and care I needed, and never treating me as if I was less than because of age or seniority. I truly don't believe I could've made it to where I am in my career today if I didn't meet you.

To all of the amazing undergraduate students for aiding me in my pursuit of knowledge and growth. Who lent me their time, blood, tears, and sweat to achieve my goals. You guys allowed me to be myself and gave me the respect and patience to where I truly felt like I belonged. You guys mean more to me than you think. I hope I was able to help you and inspire you. I wish you all the best

I will forever be grateful to everyone here for everything you guys did for me.

Permission to incorporate parts of previously published work into this thesis has been granted by Professor Haithem E. Taha and Dipan Deb.

VITA

Kevin Huang

EDUCATION

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REFEREED JOURNAL PUBLICATIONS

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Bioinspiration & Biomimetics

REFEREED CONFERENCE PUBLICATIONS

Effect of Self-Induced Body Vibrations on Thrust Generation in Bio-inspired Flying Robots **Jan 2022**
AIAA SciTECH 2022

A New Bio-inspired Flying Concept: The Quad-Flapper **Jan 2019**
AIAA SciTECH 2019

SOFTWARE

MATLAB `http://https://www.mathworks.com/products/matlab.html/`
MATLAB was utilized to solve for the thrust and lift coefficients of the clap gap data.

LabVIEW `https://tinyurl.com/yc55ayn2`
LabVIEW was used as the software medium where the load cell data were sorted and gathered.

SOLIDWORKS `https://www.solidworks.com/`
SolidWorks was used as the design medium for all of the parts and rendered images of the mechanisms.

ABSTRACT OF THE THESIS

Experimental Investigations of Bio-inspired Flight Mechanisms

By

Kevin Huang

MASTER OF SCIENCE in Mechanical and Aerospace Engineering

University of California, Irvine, 2023

Professor Haithem E. Taha, Chair

In recent history, humans have discovered and constructed many different mechanisms of flight. As far as technologies have advanced, flying birds and insects still outperform the agility, maneuverability, and stability of human-made air crafts. The research of flapping-wing micro-air-vehicles (FWMAV) studies the phenomenon behind the flapping wing and examines ways to design a similarly efficient flight mechanism. FWMAV utilizes biomimetic oscillatory vibrations for propulsion and control. Engineers create these mechanisms to be used as tools for scientific discovery, as there is much to learn from how biological creatures fly. Nature utilizes phenomena such as vibrational stabilization and the clapping effects of the wings to generate their flying capabilities. Engineers at UCI have found a clever way to increase the understanding of the complex wing aerodynamics and utilize the information to create a unique drone that can be seen nowhere else in the world. With the knowledge of the clapping effect, there should exist an optimal design and selection of materials where the capacity of the FWMAV to generate thrust and lift is maximized. Using a familiar flapping mechanism, iterating the maximum wing closure to adjust the clapping effect, and gathering the thrust and lift data to find the change in the force generation capacity. With this information, any appropriate wing configuration should be able to be adjusted in such a way that the clapping effect is optimized. A deeper understanding of wing aerodynamics provides a good basis for designing more efficient FWMAV drones.

Chapter 1

Introduction

Flapping-Wing Micro-Air-Vehicle (FWMAV) and other bio-inspired flying mechanisms utilize oscillatory inputs to generate thrust and create stability, especially with high-amplitude oscillatory inputs. One example of a study on such a case is the Kapitza pendulum. An inverted pendulum with an unstable equilibrium gains asymptotic stability when the pivot gains enough oscillatory input vertically[16]. Inspired by nature, there have been numerous studies to investigate the aerodynamics of flapping flight. The leading edge separation bubble plays a prominent role in the hovering flight of insects[14]. More recent efforts by Taha et al.[25, 20, 28, 27, 26, 15, 29], proved flapping mechanisms induce "vibrational stabilization" phenomenon in the form of pitch stiffness. The specific responses of the vibrational stability with external inputs are further analyzed by Dipan et al.[12, 13].

In the case of thrust generation, the "clap-and-fling' or the "clap-and-peel" effect is essential in the increased efficiency of the aircraft's flight performance[19, 21, 23, 22, 30]. Clap-and-fling is defined as relatively stiff wing structure where the leading edge and the trailing edge move at relatively the same pace while clap-and-peel is for more relaxed wing structure where the leading edge and the trailing edge move at different paces. The previous statements imply that the shape and material selection of the leading edge, the wing, the wing structure, and the trailing edge all affect the efficiency of the generation. The stiffness and geometry have been varied throughout the community, some research teams prefer stiffer and more angular designs [11], while some teams, including UCI's FWMAV team, prefer a more flexible design. For a FWMAV mechanism with a clap-and-peel effect, the self-induced vibration enhances the thrust by moving the flapping robot away from the jet and the vortex interactions show how the self-induced vibration has to enhances the effect of clap-and-peel [12].

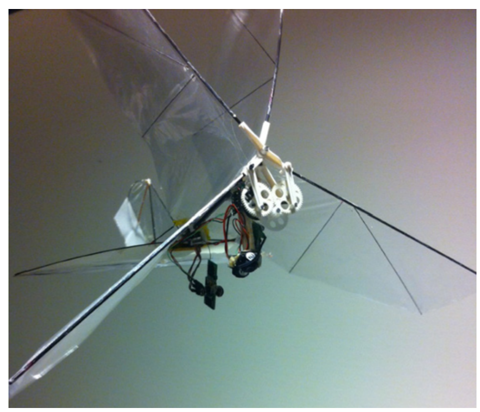
However, the flapping mechanism that was at the center of these investigations, the Alpha, had limitations. The gear ratio, motor size, and the flapping crank-and-rocker mechanism couldn't be changed easily or reliably; this limited some important research parameters that are very useful in FWMAV investigations. The durability of the mechanism also limited the breadth and depth of the investigations. This thesis centers around the new Beta mechanism, which was created to circumvent the issues mentioned above. Being able to adjust the flapping crank-and-rocker mechanism is critical in aiding further understanding of the thrust generation of the flapping wings. The increased quality control and manufacturability of the mechanism mean the amount and the strength of the experiments can be significantly increased. To study the most effective crank-and-rocker configuration, for the Beta mechanism, the "clap gap" or the angle of the wings at maximum closure is investigated. The contents of this thesis, the experimental research and development process of the flapping mechanisms are discussed. Moreover, the apparatus and techniques utilized to measure the needed values are shown. The application of the designs and research work in the form of quadflappers also will be discussed within the thesis.

1.1 Background: FWMAV at UCI

To provide more context for the development of this thesis, some background information and terminologies are defined here before delving into specific details.

Before discussing the detail of the work of FWMAVs at UCI, other bio-inspired flying mechanisms should be examined. The Defense Advanced Research Projects Agency famous designed a hummingbird-inspired FWMAV called the AeroVironment Nano Hummingbird [10]. The drone has a body shaped like a real hummingbird, a wingspan of 160 mm, and a total flying weight of 19g. Another series of capable FWMAVs are created by the DelFly project [11]. The DelFly Micro more specifically demonstrates strong flying capabilities while being incredibly light and agile. The DelFly micro has a 100 mm wing span and 3.07g of weight. The images below refer to DARPA and DelFly's drones [1.1].

(a) DARPA's Nano Hummingbird



(b) DelFly Drone

Figure 1.1: DARPA and DelFly FWMAV Drones

The precursor of the FWMAV project was an investigation into oscillatory controls by Professor Taha and his Ph.D. students. In order to verify the existence of vibrational stability in a flapping setup, the inspiration of the Alpha mechanism was purchased. A simple 4-bar crank-and-rocker system that turns rotational motion into flapping motion [3]. After successfully proving that the vibrational stability of the flapping mechanism exists in the form of time-periodic aerodynamic forces[25], whereas propellers generate a constant aerodynamic force, the team moved to create a physical application of such a phenomenon. This figure shows the Vibrational Stabilization testing apparatus [1.2].

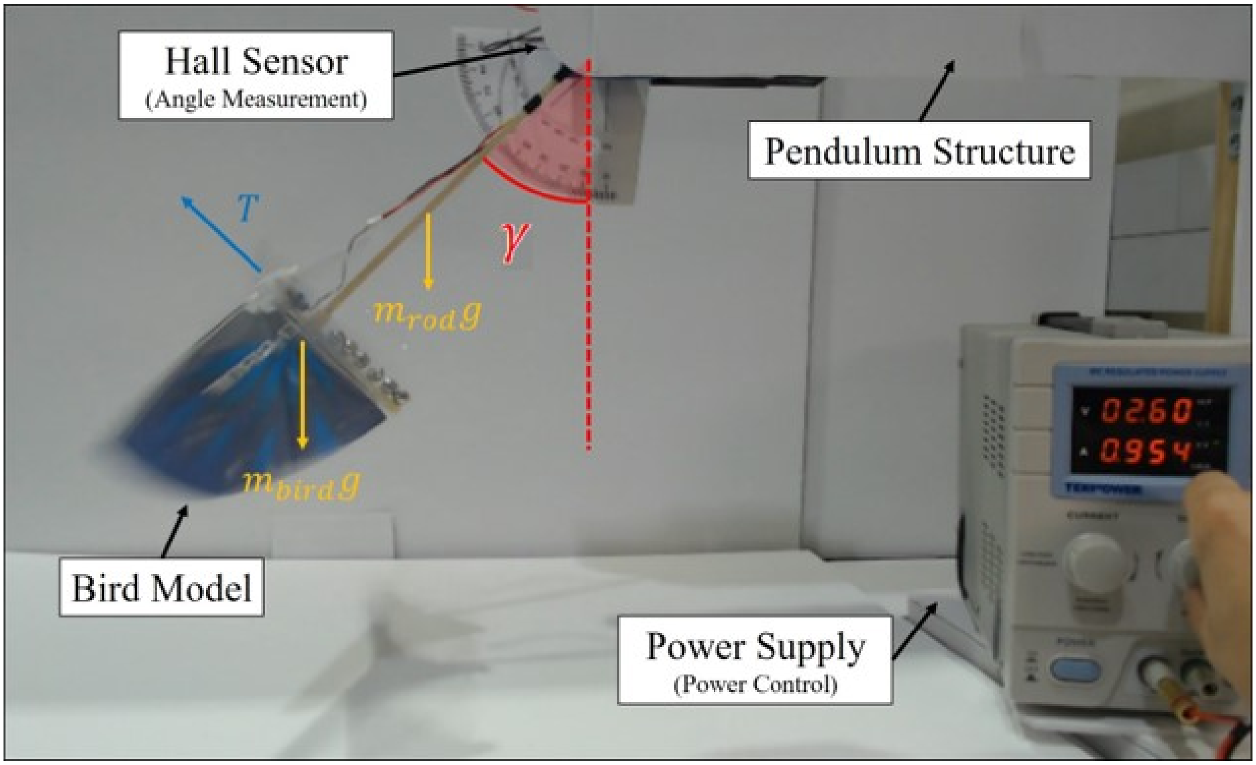
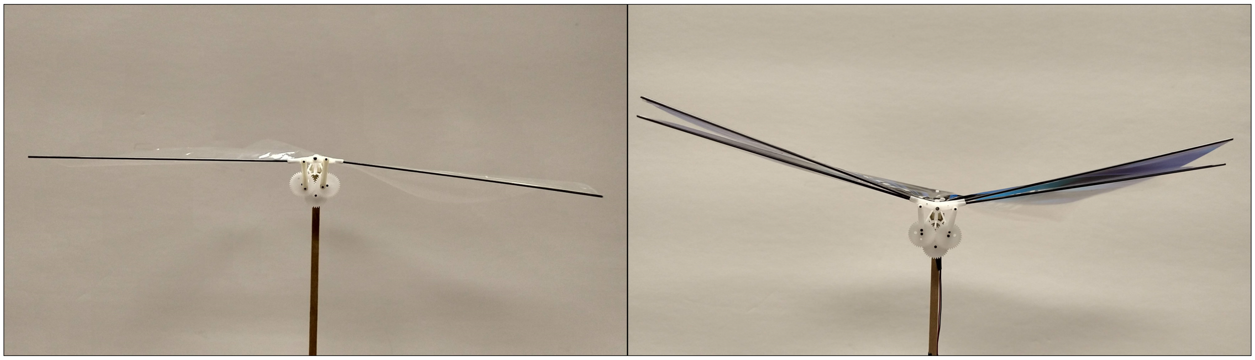


Figure 1.2: Vibrational Stabilization Testing Apparatus

Alpha Mechanism: Slight modifications were made to the off-the-shelf mechanism to increase the efficiency of the mechanism. Further research was achieved by making some changes to the motor choice, the flapping linkages, and the wings. For example, the thrust and lift coefficient, flow visualization studies, and the perturbation response of the vibrational stability were all gathered. Although the research proved to be fruitful, the team noticed significant limitations within the purchase mechanism. More details of the changes between the Alpha mechanism and the Beta mechanism will be in Chapter 2.

Beta Mechanism: The previously mentioned issues of the Alpha Mechanism, see Table [2.1], inspired the design choices of the Beta mechanism. Not only will the team have full control of the design and manufacturing process, but the amount of research flexibility also greatly



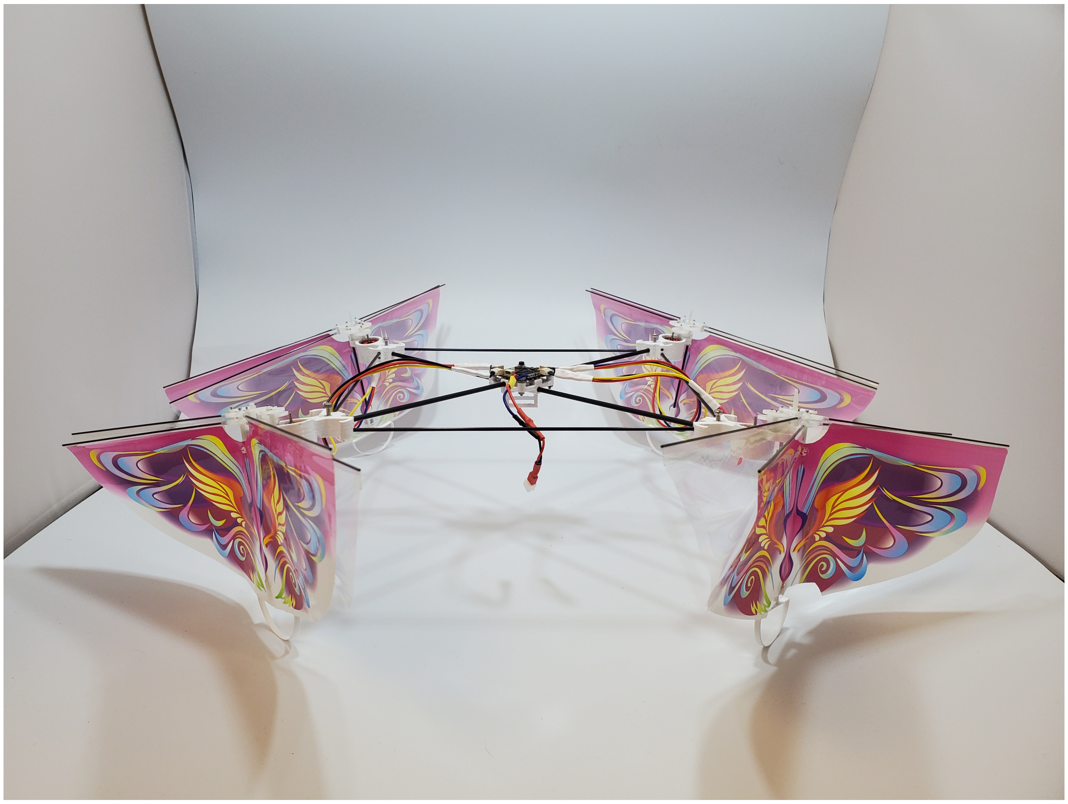
(a) Alpha 2 Wings Model (b) Alpha 4 Wings Model

Figure 1.3: Alpha 2 Wings Model versus 4 Wings Model

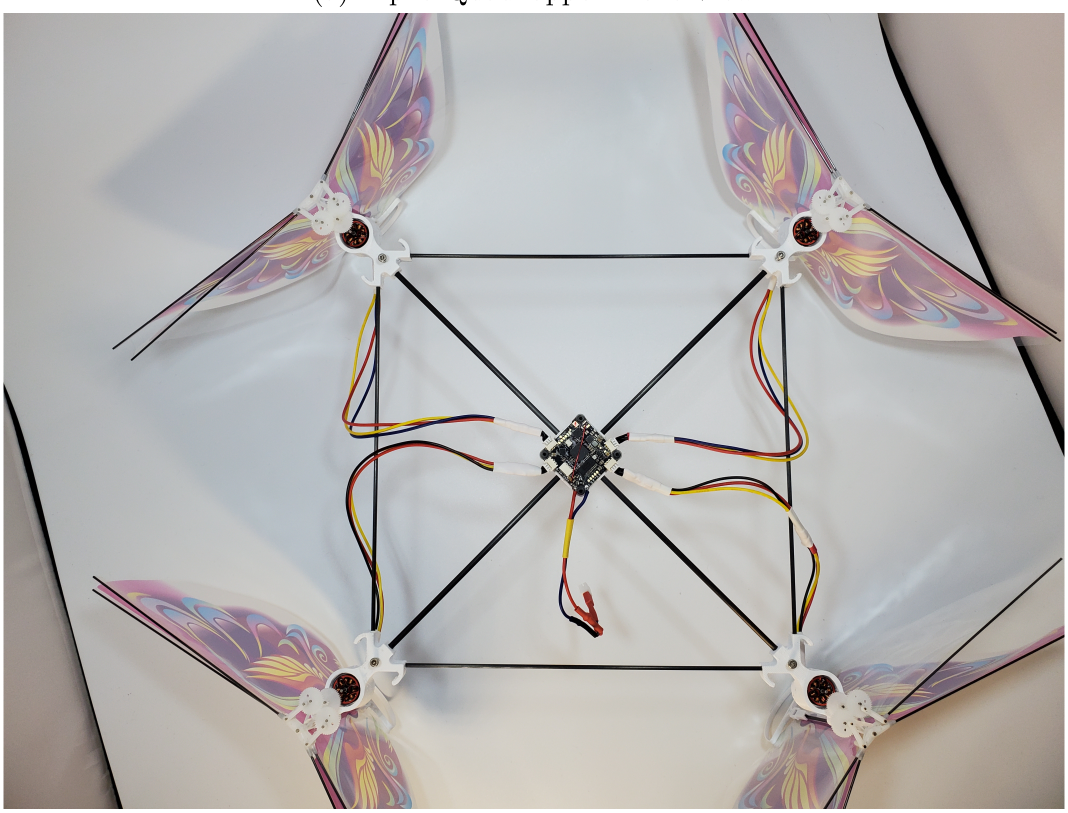
increases. The first iteration of the Beta Mechanism was designed by Moatasem Fouda, Ph.D. alumni, who helped the team develop the mechanism and helped the expansion of research. Chapter 2 delves into the specific detail of the design of the Beta Mechanism.

4 Wings: From previous research work, the team has found that when the wings are configured in such a way that two pairs of wings clap, the coefficient of thrust is highest. The images in [1.3] compare the 2 wings model and the 4 wings model. Previous results in [9, 12] showcases much better performance and stability within the 4-wings model. This is due to the clap-and-peel effect that is previously mentioned.

Quadflappers: After verifying vibrational stability with the alpha mechanism, the previous team moved to apply the concept of the Alpha mechanism in a quadcopter formation [1.4], which the term "Quadflapper" was coined [18]. The quadflapper serves as the direct application of the research work. Chapter 4 details the development of the Beta mechanism in a quadflapper. There are currently two versions of the quadflapper, one utilizing the Alpha mechanism and one with the Beta Mechanism. The images in [1.4] show one of the models of the quadflappers created using the Alpha mechanism.



(a) Alpha Quadflapper Front View



(b) Alpha Quadflapper Top View

Figure 1.4: Images of the Alpha Quadflapper

Chapter 2

Novel Flapping Mechanism Design: Beta

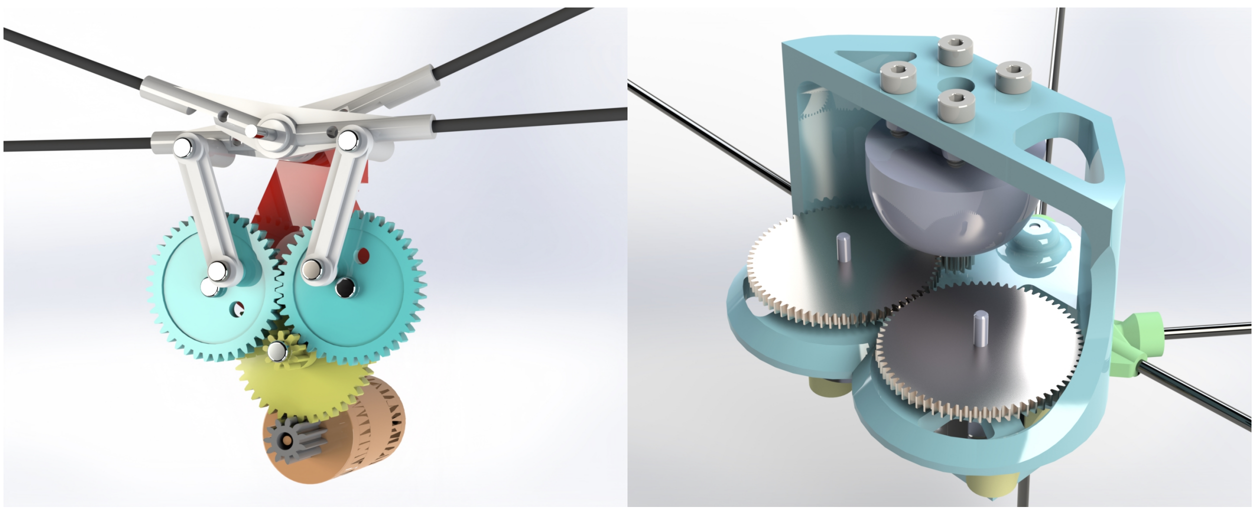
As mentioned previously, the majority of the mechanical parts of the Alpha mechanism are purchased off-the-shelf (OTS). While the Alpha mechanism allows the lab to acquire many parts to reduce manufacturing and assembly time, there are limitations that exist with constraints and parameters [2.1]. By designing an original drone with most parts manufactured in-house, various doors open for research and investigations; flapping angles, wingspan, aspect ratio, motor selection, power transmission, material . . . etc. are all available to be adjusted as needed. With current research goals, we first had to design a mechanism that can produce the results we're looking for; higher frequency and thrust. Mechanical property limitations of the Alpha Mechanism restricted the sustainable flapping frequency to around 20Hz. The durability of the mechanism also leaves much to be desired. Gaining control of the parameters allowed more quality control over the parts and better material selection.

Table 2.1: Alpha Drone Limitations

Type	*Cause*	*Effect*
Motor Durability	Motor Burnout	Short sustained flight time ($<$ 15mins)
Gear Durability	Gear Shredding	Limited Flapping Frequency ($<$ 23Hz)
Rockers Pin Durability	Part failure	Limited Testing
Betaflight Software	Limited Understanding	Extensive Fine Tuning Needed
Research	Limited changes	Low variation in research pathways

2.1 Design Breakdown and Comparison

In order to move away from the Alpha mechanism, the team studied the mechanism to see what design aspects we can draw inspiration from. Between the images [2.1], there are significant changes within the designs but many fundamental elements remain similar. The three major changes occur within the gearbox, the crank-and-rocker, and the wings. Which will be discussed further in this chapter.



(a) Alpha Flapping Mechanism (b) Beta Flapping Mechanism

Figure 2.1: Images of the Alpha and Beta Flapping Mechanism

2.1.1 Materials and Manufacturing Methods

The following tables compare the materials and the manufacturing methods of the Alpha Mechanism and the Beta Mechanism. The table [2.2] compares the major moving components of the flapping mechanisms to show the increase in the control of the parameter of the components. All of the parts within the Beta mechanism have been drafted and designed in-house. We also worked hard to make most of the parts available for rapid prototyping via 3D printing and laser cutting. 3D printing and laser cutting are widely available for students to access at UCI. From the manufacturing column in [2.2], the team now moved most of the manufacturing to the UCI campus.

(a) Alpha Drone Materials and Manufacturing Methods

$Part$	$Material$	$ManufacturingMethod$
Gears	Teflon	OTS
Chassis/Motor Mount	Teflon & ABS	OTS
Rockers	Teflon	OTS
Connecting Bars	Teflon	OTS
Leading Edges and Tail Rods	Carbon Fiber Rods	OTS
Rotary Shafts	Polished Aluminum	OTS
Wings	Polyester Plastic Sheet	OTS

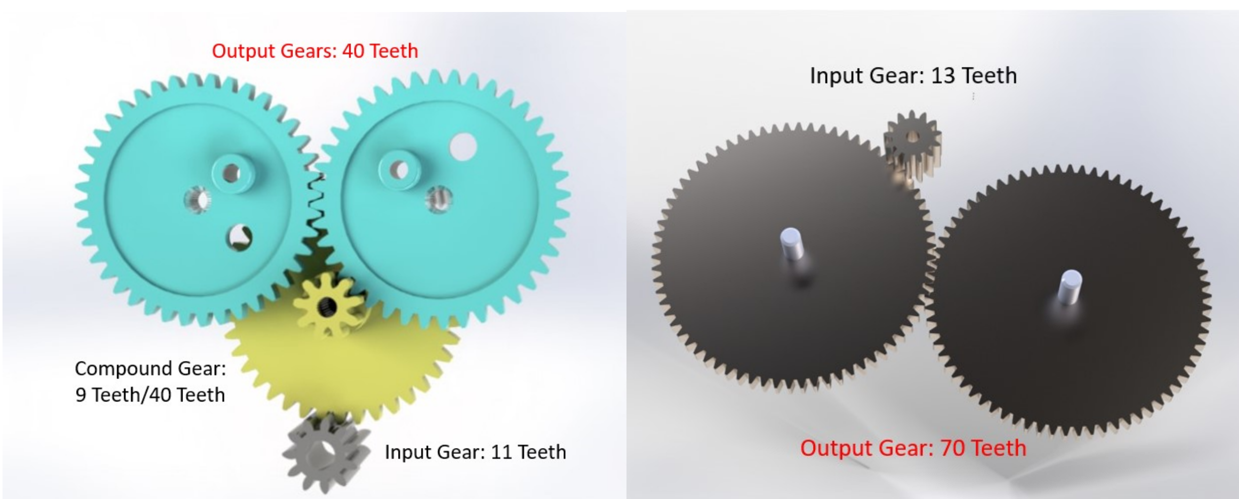
(b) Beta Drone Materials and Manufacturing Methods

$Part$	$Material$	$ManufacturingMethod$
Gears	Stainless Steel	Wire Electrical Discharge Machining
Chassis/Motor Mount	ABS	3D Printed
Rockers	ABS	3D Printed
Connecting Bars	ABS	3D Printed
Crank Disk	Acrylic	Laser Cut
Leading Edge and Tail Rods	Carbon Fiber Rods	OTS and Modified
Rotary Shafts	Polished Stainless Steel	OTS and Modified
Wings	Polyester Plastic Sheet	OTS and Modified

Table 2.2: Alpha Mechanism vs Beta Mechanism: Materials and Manufacturing Methods

2.1.2 Motor and Gearbox

The part that existed as a major performance issue for the Alpha mechanism were the gears. The gears are subjected to deformation and failure after extended flights or if any problems were encountered during flight. By ordering wire EDM [5] cut stainless steel gears [2.2], the team was able to perform various testing of the mechanism without any worry of material failure. The ability to do rapid prototyping with 3D printing and laser cutting increased the over all efficiency of the team. Even though the gearbox became much more sustainable than the Alpha Mechanism, it also became a constraining factor. The initial selection of stainless steel Due to limited resources and knowledge, the team was hesitant to develop the gearbox as we had difficulties to rapid prototype compound gears. Although wire EDM provides the accuracy we needed, the cost and production time is no where near ideal. The stainless steel gears provided a great foundation for repetitive testing as it is incredibly durable, the weight however is incredibly undesirable.



(a) Alpha Gearbox (b) Beta Gearbox

Figure 2.2: Images of the Alpha and Beta Gearbox

The biggest difference between the gearboxes of Alpha and Beta is the utilization of compound gear. Within the Alpha mechanism, the compound gear acts as a speed reduction gear to increase the amount of torque output. As seen in the figure [2.2], the inclusion of the compound gear greatly increases the mechanical advantage. The Alpha gearbox receives 16.16-time torque output while the Beta gearbox has a torque output of 5.38-times the input. This allow the Alpha mechanism to select a less powerful motor while still being able to achieve flight, however, previous brushed motors often suffered from burnouts after extended flight time as mentioned in [2.1]. The motor has to have a torque profile to sustain the mechanism at a high frequency, but because the flexible materials on the wings change behavior with increasing speed, it is hard to predict the torque, power, and speed performance of the motors. Originally, the team selected an inrunner motor with a relatively high rpm per voltage setting, however, the motor lacked the torque to sustain rotation at a higher speed. Also, inrunner motors have a cogging problem with lower torque output at lower voltages. We then transitioned into using outrunner motors, which have a higher torque at lower voltages. Also, for the current gearbox, the system seemed to perform a lot better with a stronger motor. The initial selection of the 3400KV motor did not provide the strength to combat the increased wind resistance. The current motor choice is an outrunner motor with 2750KV which lead the team to a good ratio of thrust to weight ratio.

Table 2.3: Motor Choices for the Beta Mechanism

$MotorType$	KV	$Weight$	$Issue$
Inrunner	4500KV	12g	Motor Cogging
Outrunner	3400KV	5g	Limited Torque
Outrunner	2750KV	10g	Heavy

2.1.3 Crank-and-Rocker

The crank-and-rocker mechanism, or crank-and-flapper, on the Beta Mechanism, is responsible for the actuation of the flapping motion. This mechanism also serves as the main research topic of Chapter 3. It is integral that we are able to design a linkage system that is able to sustain the flapping frequency we desired at a plethora of different configurations. The team took inspiration from the 4-bar linkage system that Alpha utilizes to achieve flight. The Beta mechanism aimed to achieve a flapping frequency of around 30Hz which was previously not sustainable by the Alpha Mechanism. Figure [2.3] shows the back of the Beta Mechanism which the crank and rocker mechanism resides while [2.4] shows the crank and rocker mechanism in detail. The main difference between the Alpha and Beta crank-and-rockers is that the output gear also serves as the crank, as seen in [2.1a], for the Alpha mechanism while the Beta mechanism has a separate part acting as the crank. The team finds that utilizing the gear as the crank introduces a lot of vibrations to the linkage during high-frequency flapping.

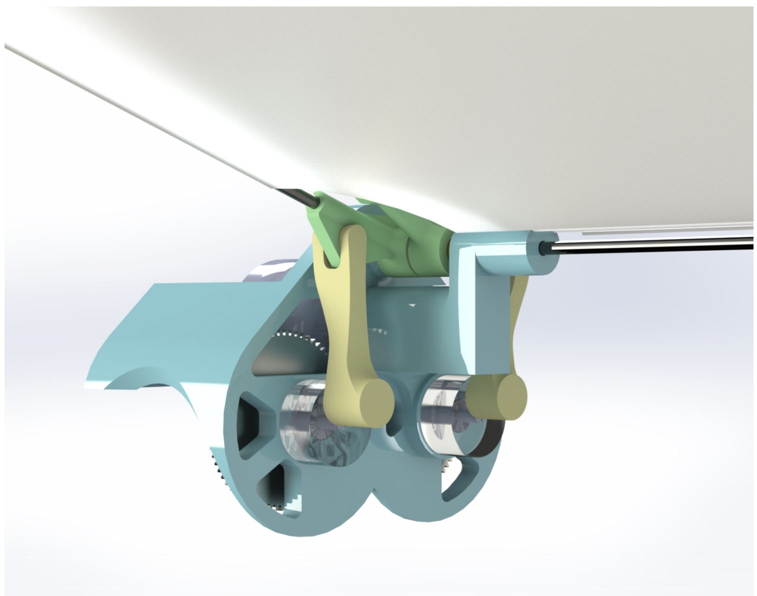


Figure 2.3: Isometric (back) View of Rendered Image of the Beta Flapping Mechanism

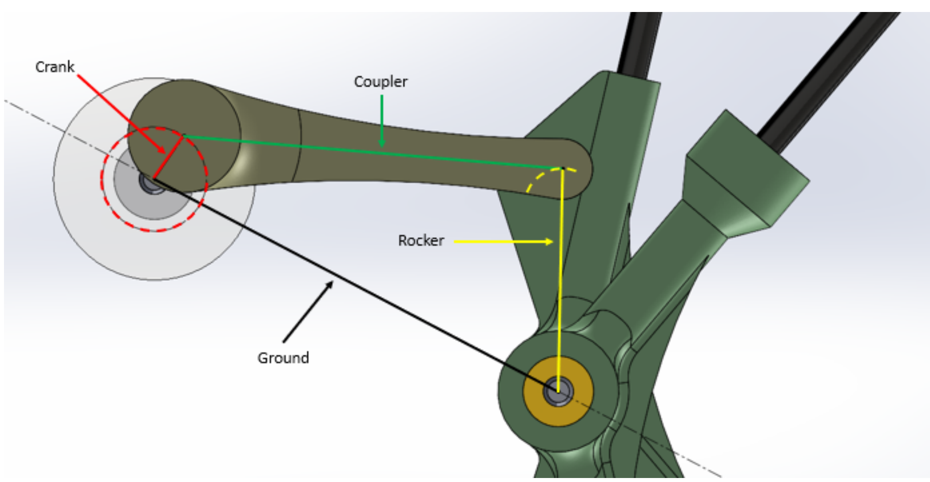
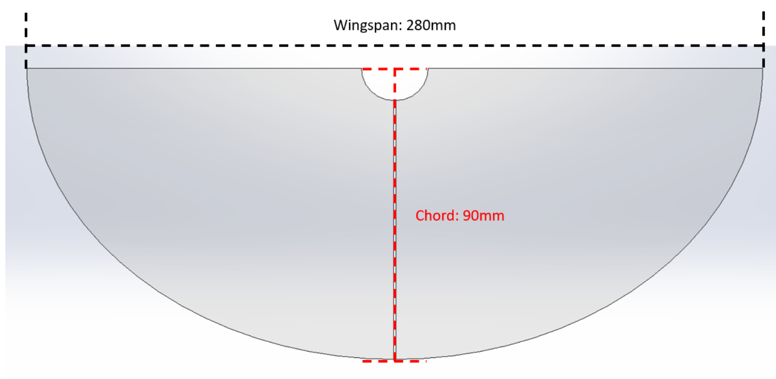


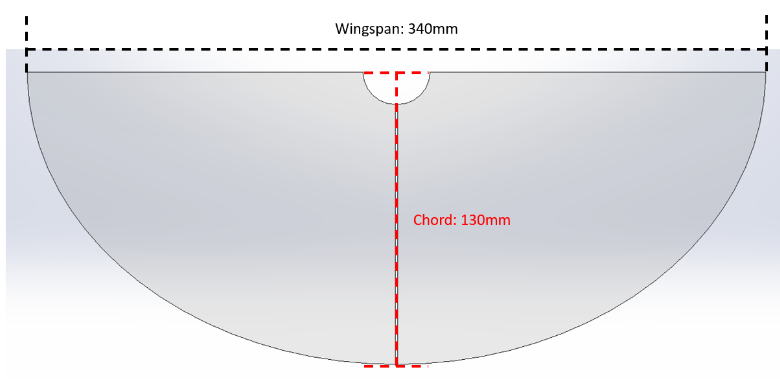
Figure 2.4: Crank and Rocker Flapping Mechanism

2.1.4 Wings

The materials of the wings have been a major topic of concern throughout the FWMAV community as it is the main form of thrust generation. The shape and material selection of the leading edge, the wing, the wing structure, and the trailing edge all affect the efficiency of the generation. This team has devoted some time to improving the efficiency of the thrust generation, however, due to the number of parameters and iterations required limited work has been done. Without wanting to change the shape of the wings too much, the team simply increased the dimensions of the wing span and the root chord seen in [2.5], while preserving the general curvature of the wings. Currently, the material of the wing is a polyester film at 0.0127mm thick. [6]. The material is easy to work with, easily accessible, and generates relatively good thrust.



(a) Alpha Wing Dimensions



(b) Beta Wing Dimensions

Figure 2.5: Images of the Alpha and Beta Flapping Mechanism

Chapter 3

Clapping Aerodynamic Mechanism: Effect of the Clap Gap Angle

3.1 An Introduction to Clap Gap

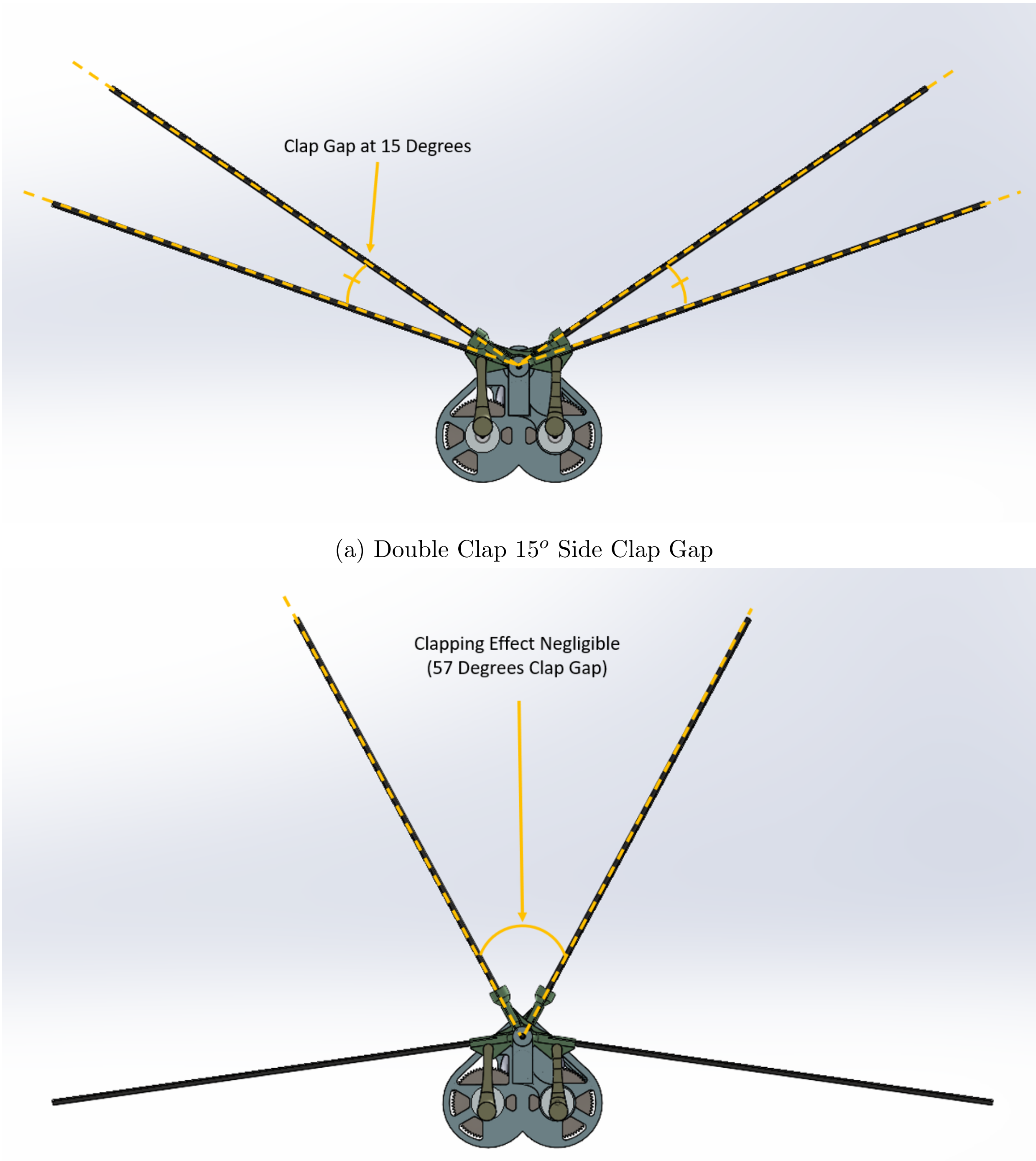
As mentioned previously, the Beta Flapping Mechanism utilizes a four-bar linkage crank-and-rocker system in order to create a flapping motion. There are a couple of major parameters that the design of the crank-and-rocker controls: the wing stroke angle and the clap gap. The wing stroke angle refers to the maximum range, in degrees, of motion of the wings while the clap gap refers to the angle between the wings at maximum closure. For example, the ϕ_o symbol in [3.7] represents the stroke angle, while [3.1] refers to the clap gap angle.

The clap gap investigation was inspired by past efforts to study the "clapping" effects of different models of the wings [9]. The results of the research mentioned that a full clap enjoys more thrust generation and stability compared to a partial clap. In the paper, a full clap is defined as a minimal clap gap of 0^o while a partial clap is defined as 23^o. The line of thought follows, if varying the clap gap changes the ability of the mechanism to generate thrust, there must be an optimal angle that works well with the configuration and material properties of the wing setup. By iterating the clap gap while keeping all other parameters the same, the wing's ability to generate thrust changes, especially at higher frequencies. Another hypothesis followed, if the clap-and-peel effect generates stability and thrust then more clap would produce even more stability and thrust. Moatasem Fouda, Ph.D. alumni, discovered that by setting the stroke angle and the clap angle of the rockers at a specific configuration, we are able to achieve what we call "double clap" and "triple clap". The terms double clap and triple clap describe the amount of clapping that occurs in one flapping cycle. The focus of the clap gap investigation is to constrain the stroke angle while varying the Clap Gap angle to find the most efficient configuration between the double clap and the triple clap model.

3.1.1 Double Clap vs Triple Clap

The images in [3.1] and [3.2] illustrate the difference between the clap angles of the double clap and triple clap. With reference to the image [3.1], the double clap shows a clap gap of 15^o on the sides while having a top clap of 57^o where wings are too far apart to generate notable clapping effect. For triple clap, in [3.2] the clap gap has 15^o on the sides while having a top clap also being 15^o.

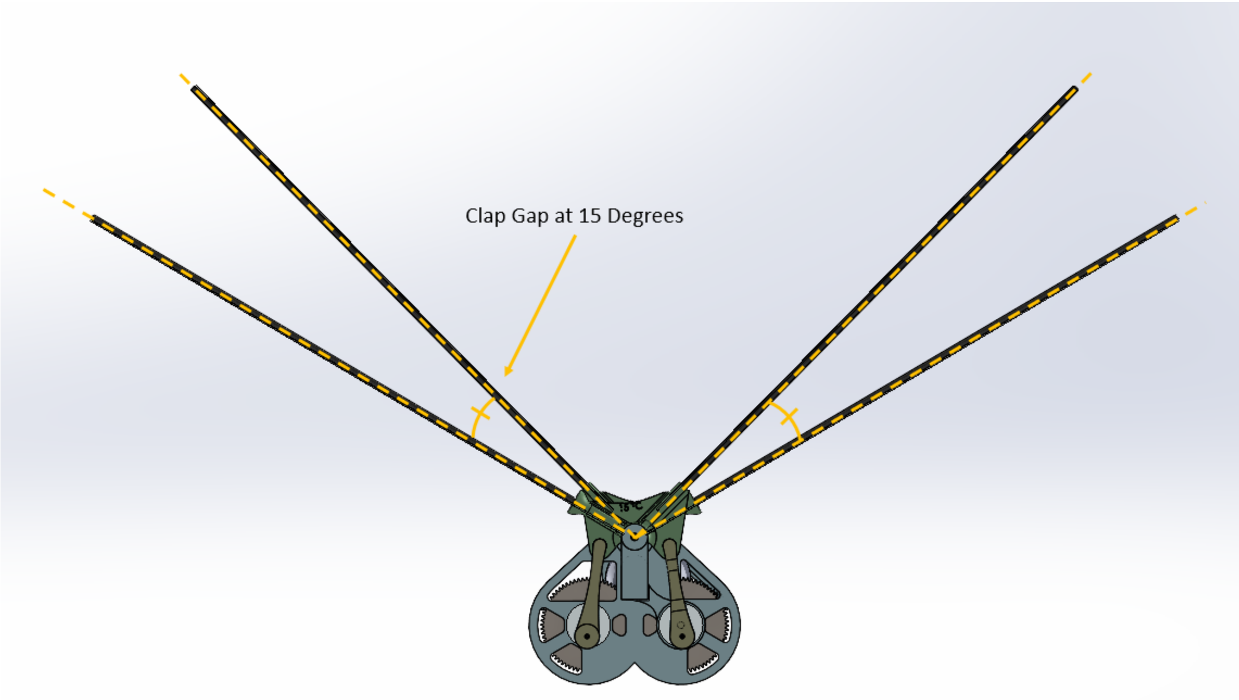
In order to achieve the changes with the clap gap angles, the coupler length and the location of the coupler to rocker pin were adjusted. By changing the dimensions shown in [3.3], we can achieve the clap configuration as well as the clap gap angles we set out to test as shown in [3.1] and [3.2]. In both of the clap models, we seek to compare three different claps configuration to see which one performed the best. For double clap, we compared 5^o, 10^o, and 15^o of clap gap angles. For the triple clap model, we compared 10^o, 15^o, and 20^o of clap gap angles. The reason why the range of investigation is different between double clap and triple clap is due to the fact that the stroke angle is constrained. The couple and rocker pin would intersect the leading edge carbon fiber rods if we were to match the range



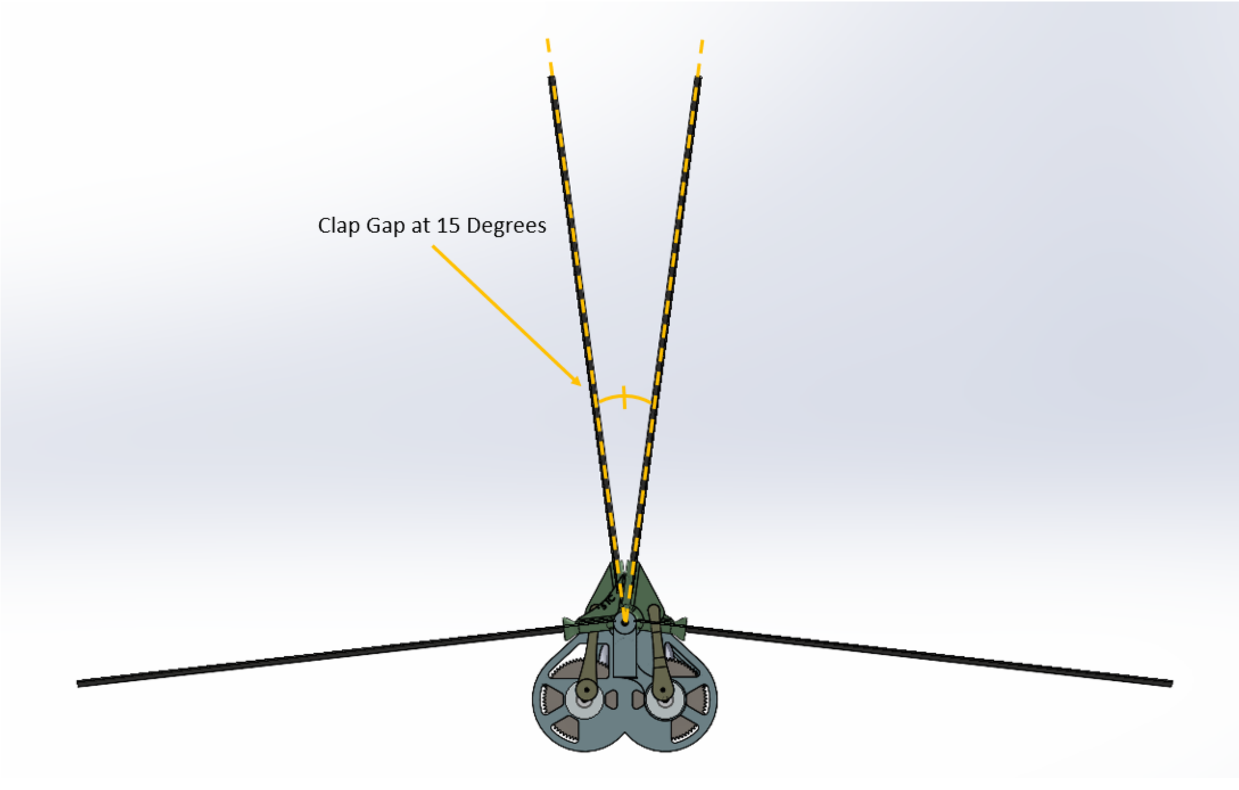
(a) Double Clap 15^o Side Clap Gap

(b) Double Clap 15^o Top Clap Gap

Figure 3.1: Maximum Closure Angles of Double Clap on the sides and the top



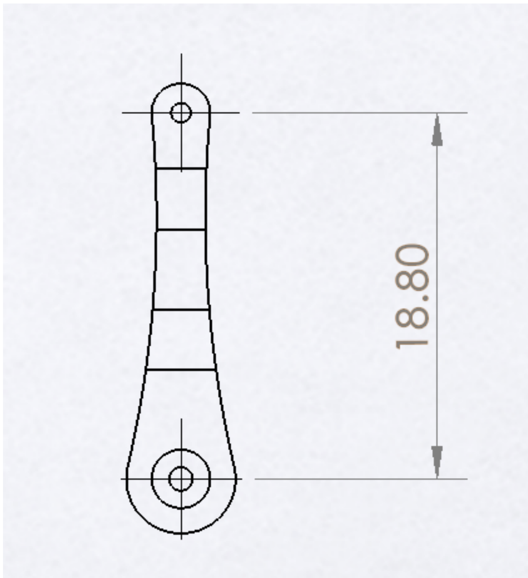
(a) Triple Clap 15^o Side Clap Gap



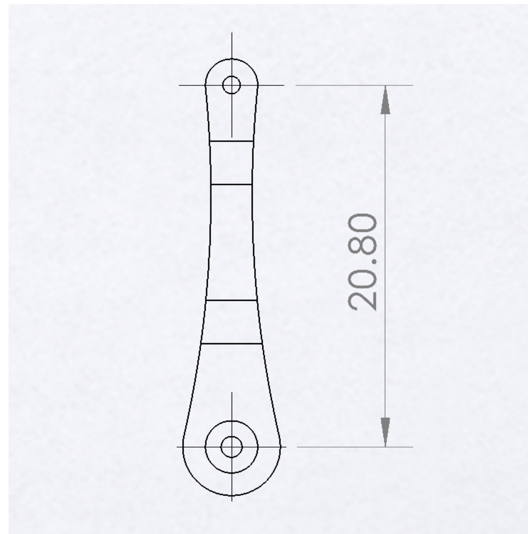
(b) Triple Clap 15^os Top Clap Gap

Figure 3.2: Maximum Closure Angles of Triple Clap on the sides and the top

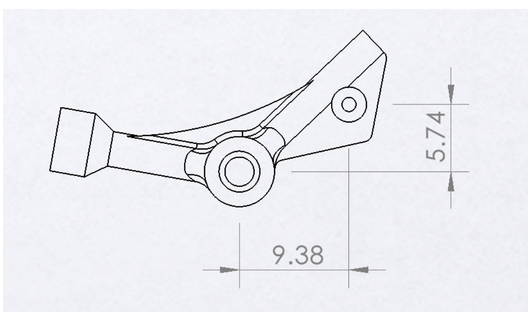
of investigation exactly. In future designs, we can circumvent this issue by changing the design so more thorough research can be done.



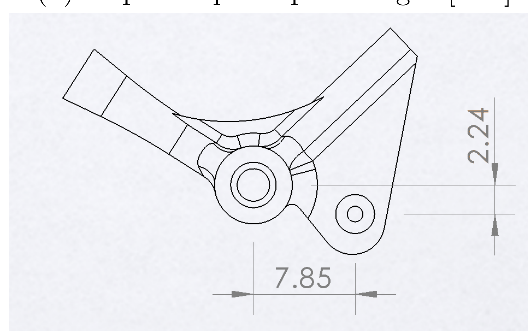
(a) Double Clap Coupler Length [mm]



(b) Triple Clap Coupler Length [mm]



(c) Double Clap Rocker Dimensions [mm]

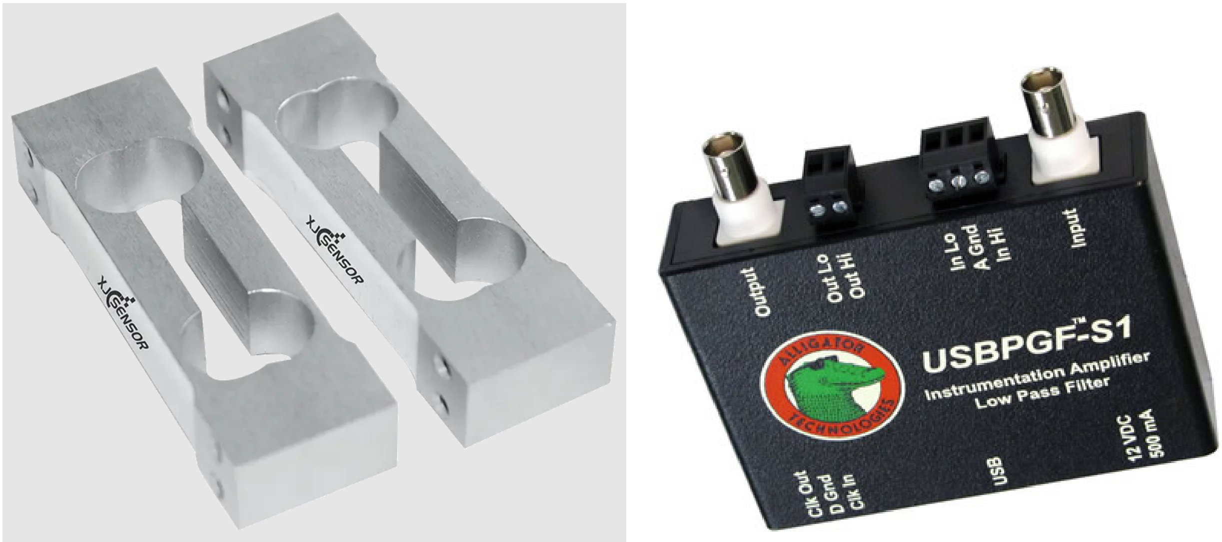


(d) Triple Clap Rocker Dimensions [mm]

Figure 3.3: Crank and Rocker Dimensions [mm]

3.2 Apparatus to Acquire Lift and Thrust

To gather the data of the different 'Clap Gap' designs, an experimental setup was designed and implemented. Two strain gauge load cells are attached perpendicular to each other to collect the lift and the thrust forces as seen in [3.6] and more specifically in [3.6]. The load cells, [3.4a], are rated at 500g with 0.02% Full Scale Accuracy[8] and each load cell



(a) 500g Load Cell (b) Amplifier Low Pass Filter

Figure 3.4: Amplifier Low Pass Filter and Load Cells

Table 3.1: Lift and Thrust Gather Experimental Setup

Amount	*Part*	*Purpose*
2	Load Cells	Gather Force Data
2	Low Pass Filter and Amplifier	Reduce Noise and Increase Gain
1	National Instrument Data Acquisition	Centralize Data
1	Electronic Speed Controller (ESC)	Control Brushless Motors

is paired with a amplifier low pass filter, [3.4b] to help limit high frequency noise as well as to increase the gain of the input signals [7]. The brushless motor is controlled by an external electronic speed controller (ESC) to perform tests and data collection [4]. Table [3.1] shows the list of items used in the experimental setup and [3.5] shows the flowchart and schematic of the force data acquisition setup. The flow chart shows how the mechanism is mounted on to the load cell in such a configuration where both the lift and thrust data can be gathered at the same time. Each trial includes one second record of data with a sampling frequency of 5000 samples per second. The data are averaged out over the whole data acquisition time span of one second. Fast fourier transform (FFT) is then performed for the time series of the measured thrust to estimate the flapping frequency. For each crank-and-flapper configuration, more than ten sets of data were taken with three trials in each set. The data is then filtered through the amplifier low pass filters, centralized in the data acquisition unit, and finally into LabVIEW. The data is then saved, processed, and plotted through MATLAB.

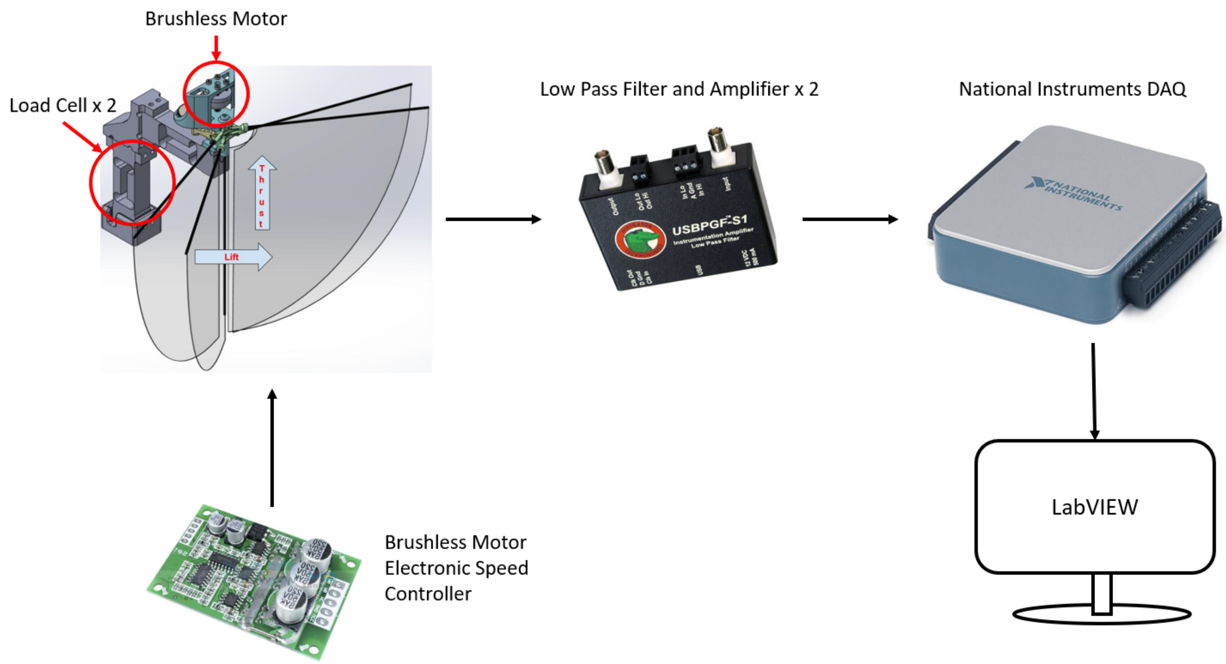


Figure 3.5: Flowchart of the Load Cell System

3.3 Measuring the Coefficient of Lift and Thrust

Table 3.2: Double Clap and Triple Clap Max Thrust at Different Clap Gaps

Clap Gap	Double Clap Thrust	Triple Clap Thrust
5^o	66.9g	X
10^o	65.6g	66.1g
15^o	79.8g	68.1g
20^o	X	72.5g

Table [3.2] shows the pure thrust generation ability of the rocker configuration. However, to compare fairly, the coefficient of thrust should be compared to see the innate thrust generation ability. While adjusting the crank-and-rocker dimensions to create the triple clap configuration, the team had to change the stroke angle to keep the clap angles consistent.

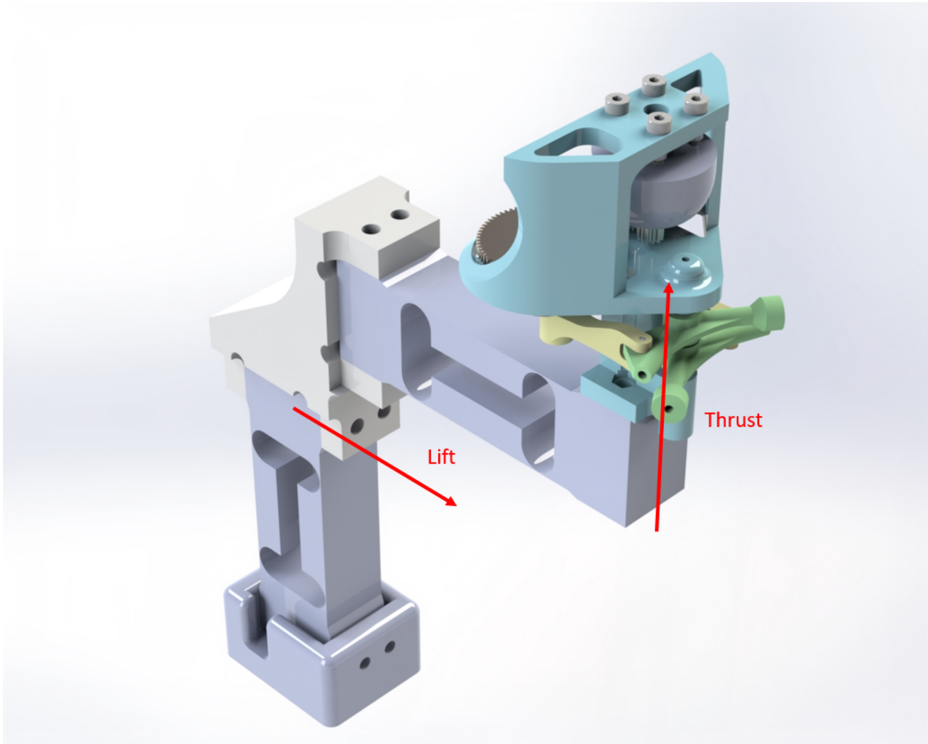


Figure 3.6: Closer View of the Load Cell Apparatus w/ Beta Mechanism

To mitigate the differences within the clap gap we normalized the stroke angle within the calculations. In previous works [9, 12], we non-dimensionalize the measured thrust for dynamic similarity. However, it is important to note that the generated thrust depends on the angle swept by the wings, wing surface area, flapping frequency, number of wings, and wing span. So, we non-dimensionalize the thrust force by $\frac{1}{2}\rho V_{ref}^2 SN$, where $V_{ref} = 2\pi f R\Phi$ is a reference speed, taken here the maximum speed of the wing tip, similar to helicopters and propellers. Also, f denotes flapping frequency, R denotes wing span and Φ, shown in the [3.7] is the amplitude of the flapping angle for a single wing. So $\Phi = \phi_0$ & $N = 4$ are for our 4-wing model.

For a 4-wing model, the coefficient of thrust can be written as:

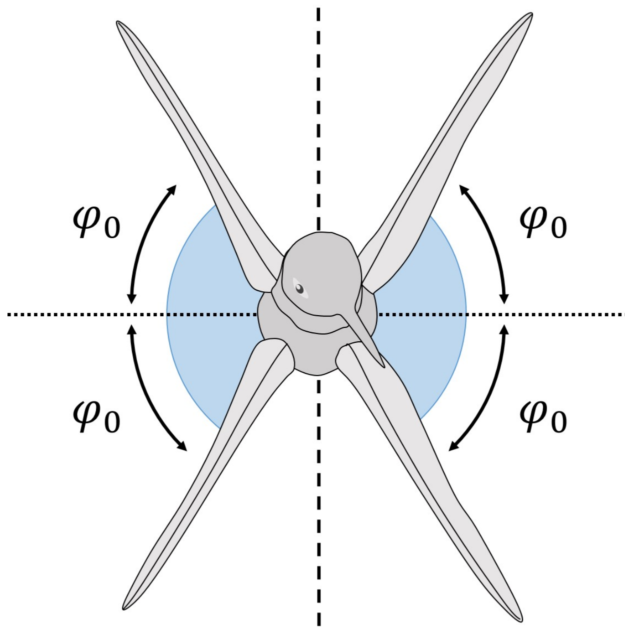


Figure 3.7: Flapping Mechanism with 4 Wings

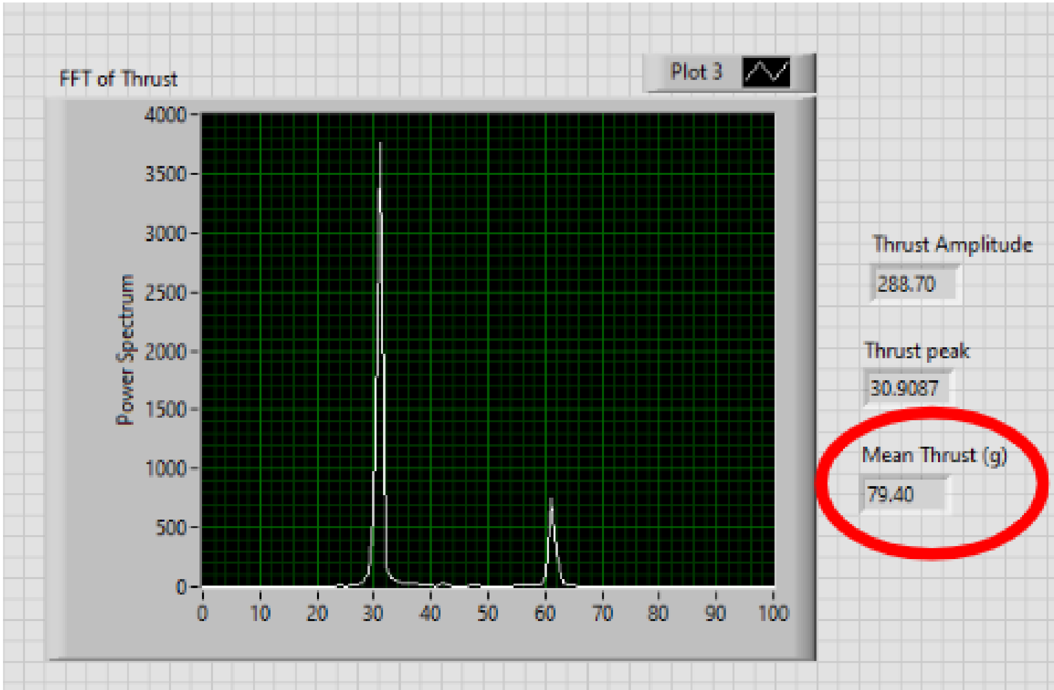
$$C_T = \frac{T}{\frac{1}{2}\rho(V_{ref})^2 NS} \tag{3.1}$$

3.4 Results and Discussions

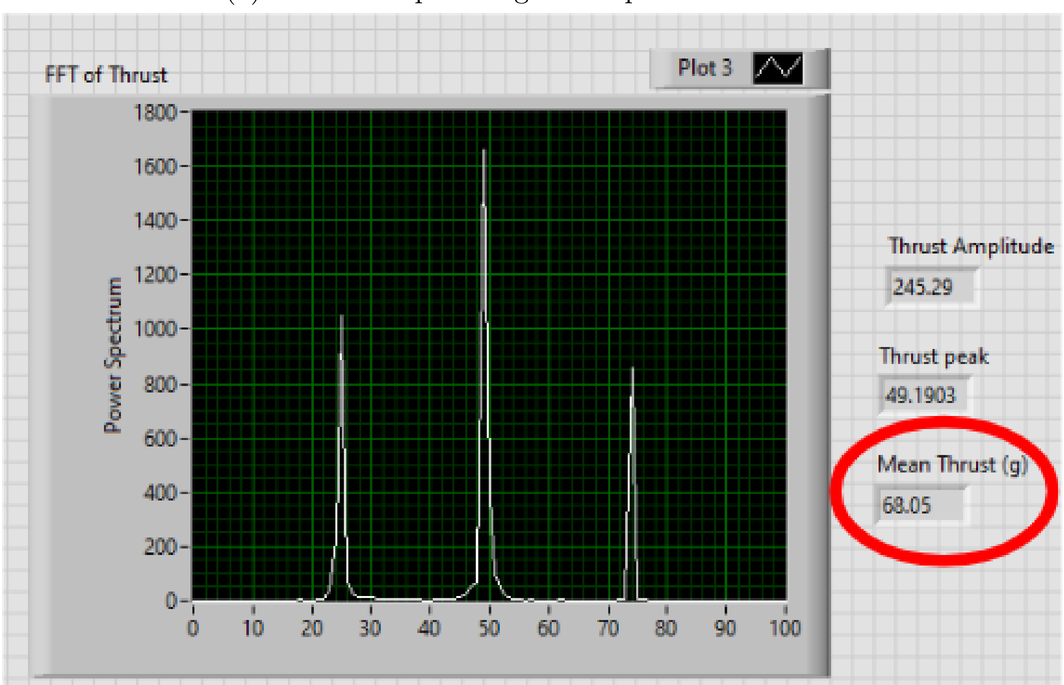
This section is dedicated to the discussion of the results obtained for the aerodynamic force measurements. We mainly focused on the average thrust generation at a given flapping frequency for different clap gaps spanning two different models. The aforementioned models refer to double and triple clap enabled ones.

Figure [3.8] shows the maximum thrust generation possible at the maximum attainable flapping frequencies. The triple clap model cannot attain the same maximum flapping frequency as the double clap model. The maximum flapping frequency for triple clap is about 25Hz while double clap reaches around 30Hz. Figure [3.9a] shows the average thrust generated at given flapping frequencies for different flapping robots. In this figure, double clap is denoted by "DC" and "TC" denotes triple clap. Within the attainable range, the thrust produced by the triple clap model is comparatively higher. Out of all triple clap models the one with 20^o clap gap generates the most amount of thrust. Naturally, we expected the triple clap models to generate more thrust due to the increased amount of clapping effect. We in return also expect the thrust generation capacity of the triple clap configurations to be higher. However, when looking at the coefficient of thrust after normalizing the flapping parameters we found the opposite. Figure [3.9b] shows the average coefficient of thrust at given flapping frequencies for different flapping robots. Within the same range, the coefficient of thrust produced by the triple clap model is comparatively lower than the double clap. This is due to the increase of the stroke angle, in reference to the figure [3.7] from triple clap at 37.3^o to double clap at 27.1^o.

The results show that the double clap model has a higher coefficient of thrust and it is also able to achieve a higher flapping frequency compared to the triple clap model. The double clap model at 15^o generates the most thrust and has a larger thrust generation capacity as shown in [3.9]. This model will be the basis for future research and will be the configuration of the mechanism that will be applied to the Beta quadflapper.

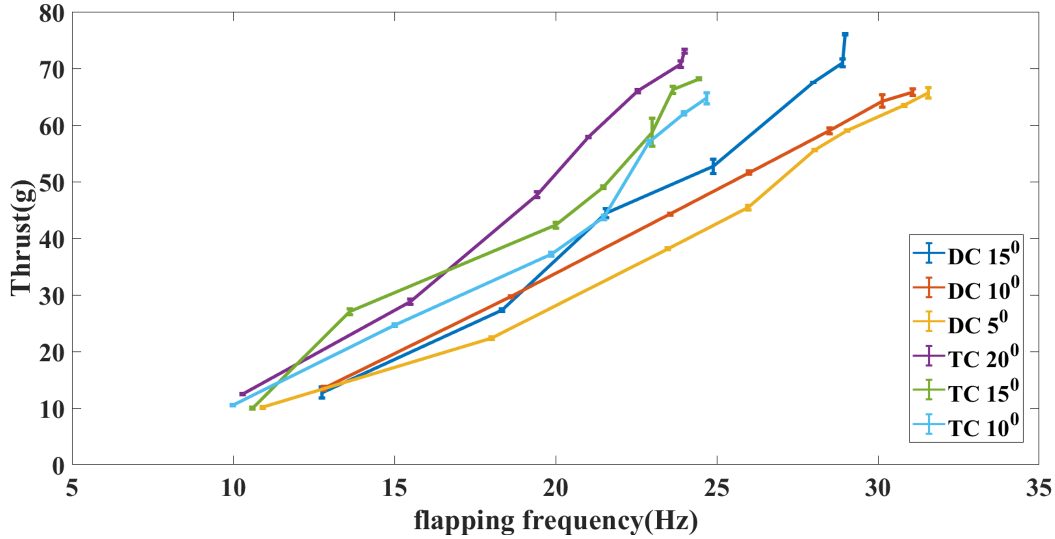


(a) Double Clap 15 Degrees Gap at Max Thrust

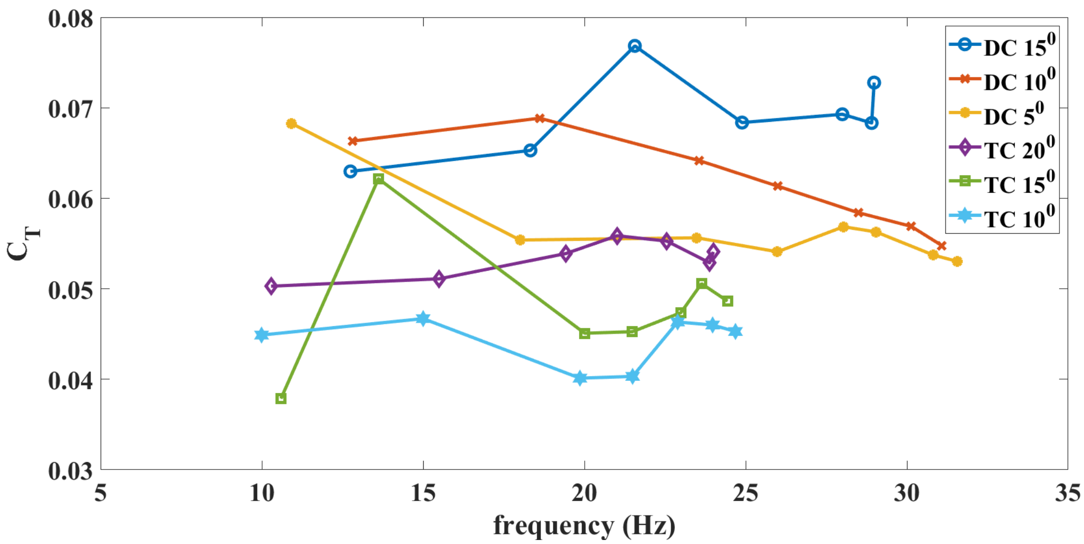


(b) Triple Clap 15 Degrees Gap at Max Thrust

Figure 3.8: Clap Gap at Max Thrust [LabVIEW]



(a) Clap Gap Thrust Data with Error Bars



(b) Clap Gap Coefficient of Thrust

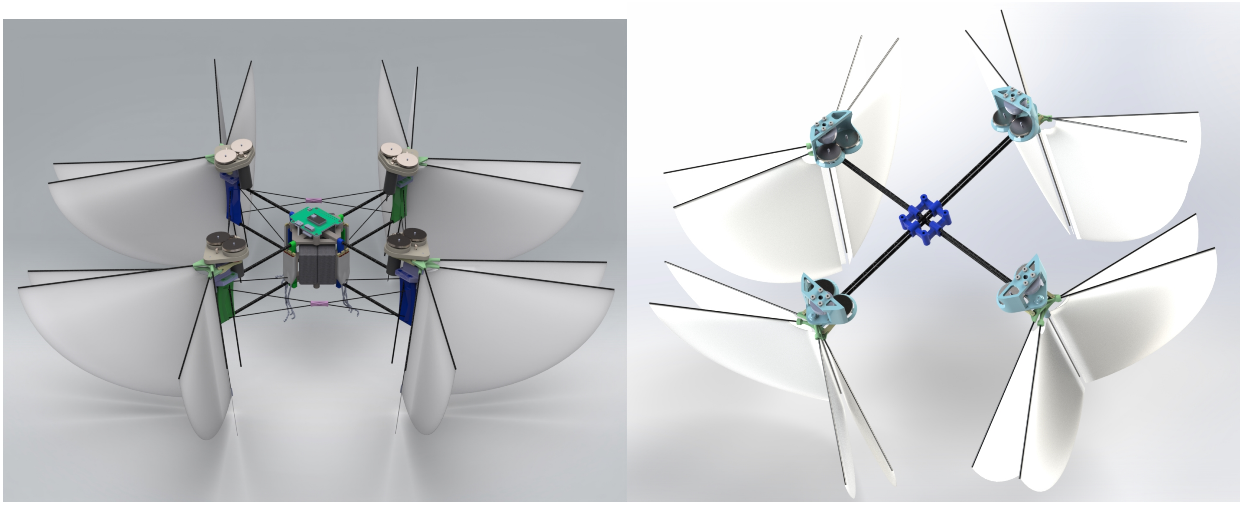
Figure 3.9: Clap Gap Data between Double Clap and Triple Clap

Chapter 4

Beta Quadflappers

Quadflapper exists as one of the most unique applications of flapping wing technology. Professor Taha's Lab at UCI is the only known university that has utilizes the application of the flapping wing in this way. This application has major potential for growth, especially paired with the research aspects of the team. As a way to direct the application of the results of the majority of the research into the wings, the Quadflapper is a great way to showcase the research work that has been done. Using the Alpha Quadflapper as a reference, the Beta Mechanism is mounted in a similar fashion. Using the knowledge from previous studies, the current drone is merely a few iterations away from being able to achieve flight. Once the quadflappers are mature in design and function, much investigative work can be done on controls and aerodynamics.

There currently exist 3 versions of the Beta Quadflapper: version 0, which is designed by Moatasem Fouda, and version 1.0 and 2.0 which are designed by the current FWMAV team. The images [4.1] show the development between the different versions of the drone.



(a) Beta 1.0 Full Drone Assembly (b) Beta 2.0 Full Drone Assembly

Figure 4.1: Images of the Beta Quadflappers

4.1 Beta Mechanism in Quadflapper

The Clap Gap research provided more insight into the interaction between flexible wings and thrust generation. The most efficient rockers, double clap at 15^o, are used on the Beta 2.0 drone. By applying the best rocker configuration results from the "Clap Gap" testing, the team increased the average max thrust production by 220% (from around 25g to almost 80g). The flapping frequency also increased from Alpha's 20Hz to Beta's 30Hz. At this point, we feel safe to proceed with implementing the Beta mechanism into a drone.

4.2 Beta Quadflapper vs Alpha Quadflapper

In order to develop a design that could possibly achieve flight, the team kept in might the thrust-to-weight ratio. With the knowledge of the Alpha quadflapper, the team made sure to aim for a similar thrust-to-weight ratio. For the estimation of the thrust-to-weight ratio, the same technique of thrust data gathering from Chapter 3 was utilized. The estimated thrust for the Beta quadflapper was able to achieve a similar ratio to the Alpha quadflapper [4.2].

The Alpha quadflapper has a weight around 70g and is able to produce about 88g of thrust, while the Beta quadflapper has a weight of 252g and can produce about 320g of thrust. The Alpha quadflapper's thrust-to-weight ratio is about 1.25 while the Beta quadflapper's ratio is about 1.27. In order to have an efficient way to track the weight of the quadflappers, we separated the drones into three categories, the team is able to aim for similar weight distribution across the two flappers. From [4.5], the weight percentage of each drone is very similar across each category; structure around 10%, flapping wing mechanism around 50%, and electronics around 40%. Having this information helps to set constraints on the material selection of the drone and avoid having an inefficient thrust-to-weight ratio.

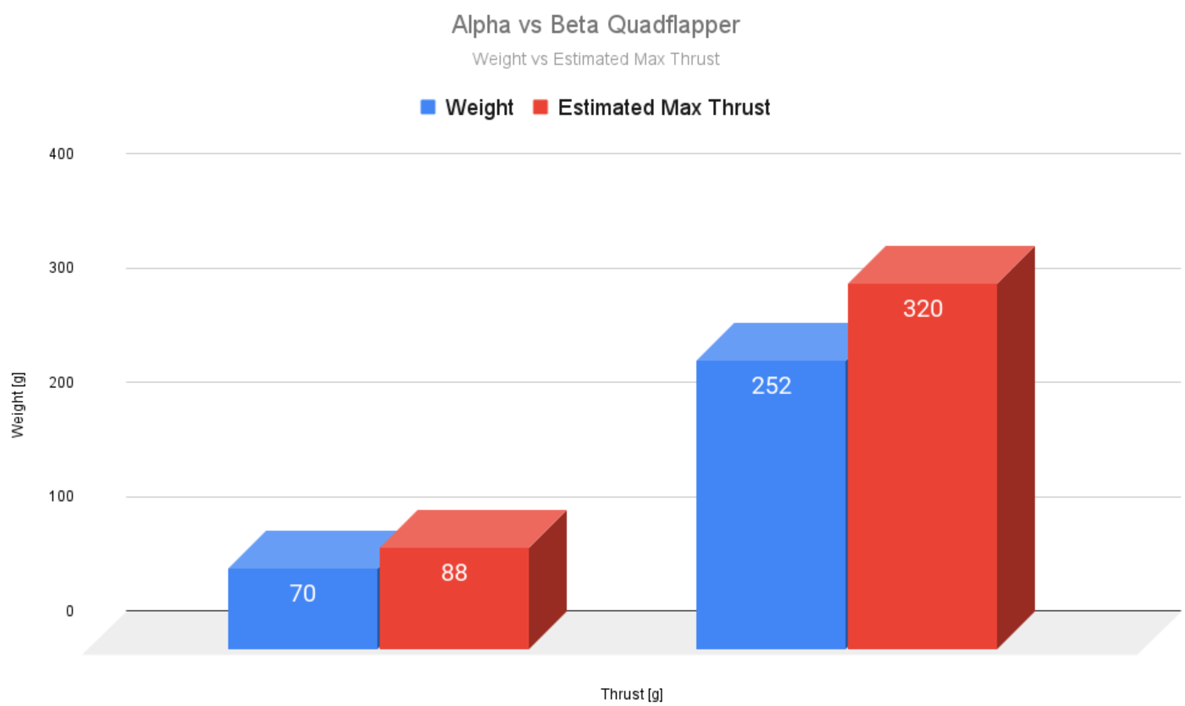


Figure 4.2: Alpha vs Beta Quadflapper Thrust to Weight Ratio

4.2.1 Quadflapper Structure

The structure of the Alpha and Beta quadflapper has a similar arrangement where the centerpiece is 3D printed while the frames consist of carbon fiber rods. Carbon fiber rods are lightweight and durable so it is an obvious choice for the team to use it for the frame. The figure [4.3] shows some of the specifications of the over dimensions of the drone. At when the wings are at full extension, which is when the wings are at the max distance away from one another, the total length is about 510mm. The max wing closure, which is when the clapping effect occurs, the length is about 425mm. Comparatively, the full extension length for the Alpha quadflapper is at 450mm while the max wing closure length is at about 370mm.

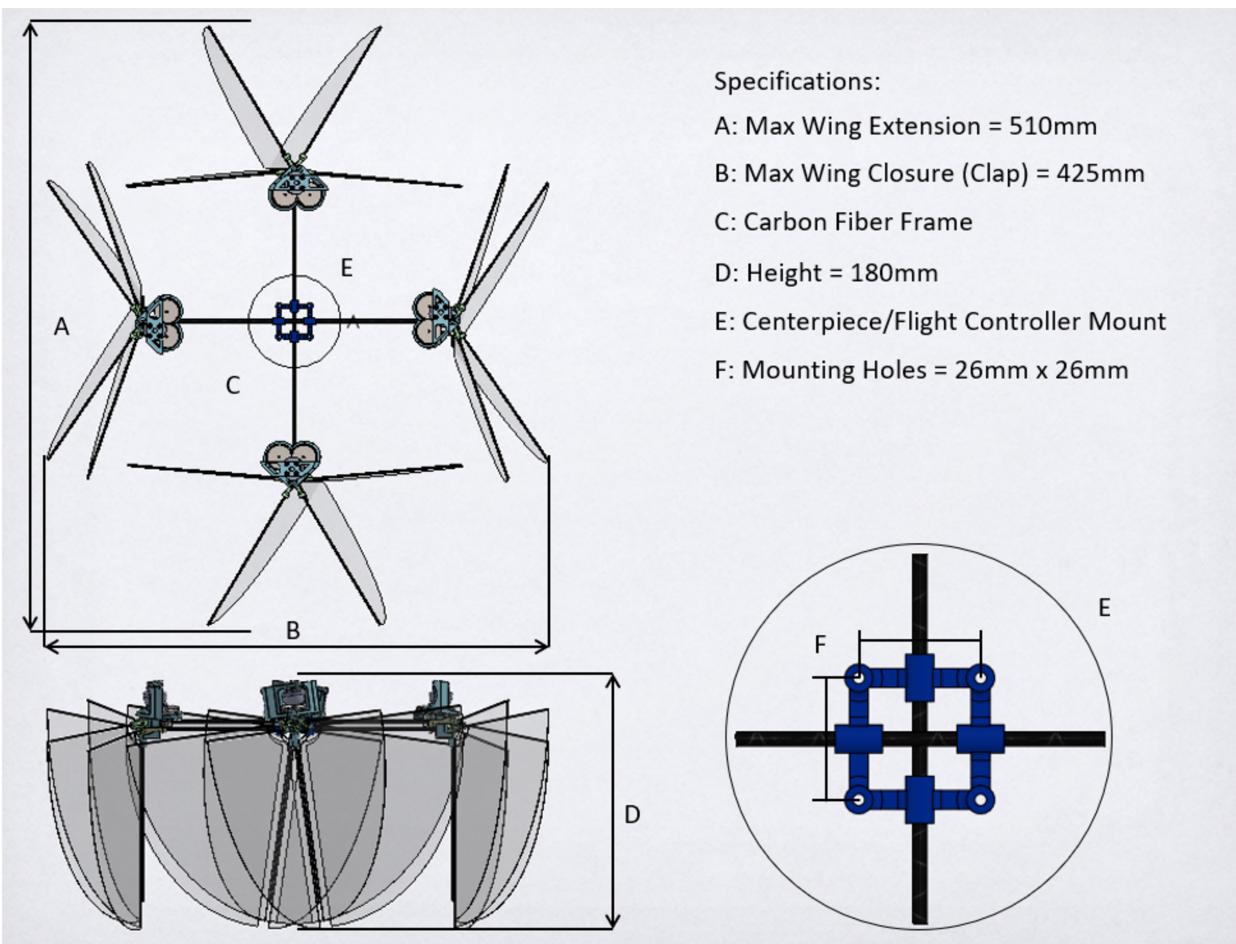


Figure 4.3: Beta Drone Specifications

4.3 Betaflight and Flight Controller

In FWMAV certain vibrations are desired in order to increase thrust generation and stability. However, in most traditional propeller drones, most vibrations are worked to be eliminated. The flight electronics and software of a propeller have various built-in features to dampen and filter out vibrations which have negative effects on FWMAV. With the current flight hardware and software, F722 35A AIO brushless flight controller [1] and Betaflight [2], the team worked hard on finding the right settings for the drone. For example, within the proportional-integral-derivative (PID) controller, the integral and derivative feedback is detrimental to the quadflapper to achieve flight. After changing the PID control settings, the Beta quadflapper shows promising signs of flight. Also, the all-in-one (AIO) flight controller helped to eliminate the need for external ESCs which reduced the drone by about 40g. While the software and hardware changes advanced the quadflapper closer to flight, the mechanism is not able to sustain airtime due to a combination of software tuning and mechanical failure. The team is currently exploring ways to fix these issues by doing more research on the filter of the onboard gyroscope, the rate profile of the motors, and a more secure way to stabilize the drone.

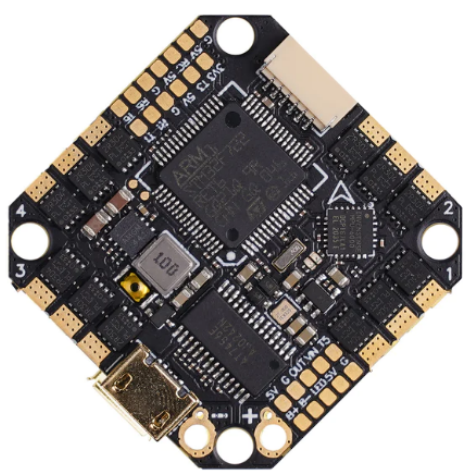
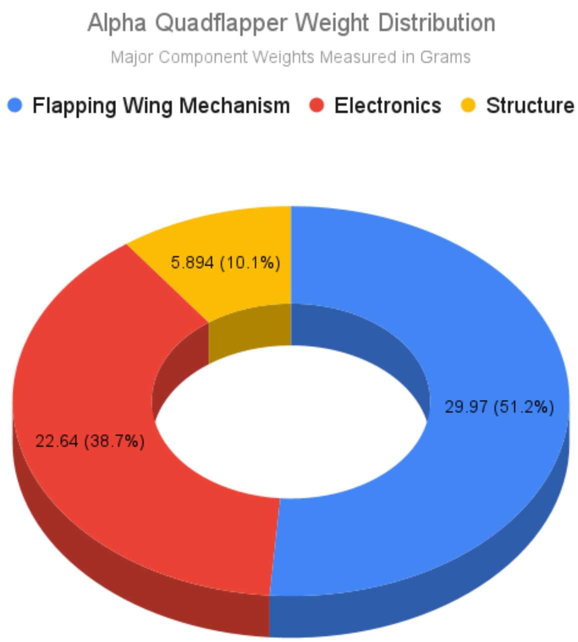
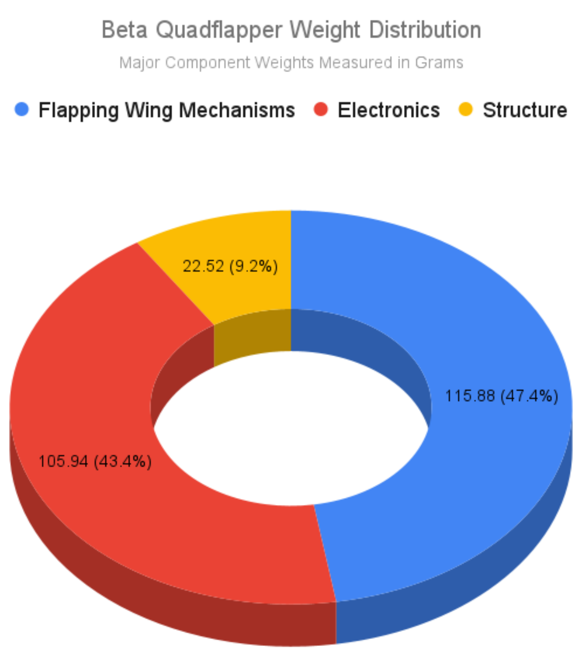


Figure 4.4: Beta Quadflapper Flight Controller



(a) Alpha Quadflapper Weight Distribution



(b) Beta Quadflapper Weight Distribution

Figure 4.5: Alpha vs Beta Quadflapper Weight Distribution

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The flapping-wing micro-air-vehicle team at UCI has had an increased understanding of the manipulation of the flapping mechanism and the aerodynamic interactions between the wings over the past couple of years. It has been proven that insects and FWMAVs benefit from the phenomenon of vibrational stabilization and it has been proven that specific clapping configurations produce better results in terms of thrust generation and stability. However, the research on the best clap gap, which is defined as the maximum closure distance during one flapping cycle, has not been explored yet. In order to explore this line of inquiry, a crank-and-rocker mechanism has to be designed. The mechanism should also be able to sustain repeated high-frequency flapping. Although the previous Alpha mechanism was able to showcase vibrational stability and can achieve flight when applied to a quadflapper drone, the mechanism has recurring mechanical issues that prevented further research. With these limitations, the team decided that it was best to use an original mechanism. With the original crank-and-rocker mechanism, we made iterative changes to the clap gap while keeping all other parameters the same. The team also utilized the different clapping models when varying the clap gap angles; double clap and triple clap. The terms double clap and triple clap describe the amount of clapping that occurs in one flapping cycle. The focus of the clap gap investigation is to constrain the stroke angle while varying the clap gap angle to find the most efficient configuration between the double clap and the triple clap model. The results show that while the double clap model generates less thrust at the same frequency as the triple clap model, it is able to reach a higher frequency and has a higher coefficient of thrust after being non-dimensionalized. The most efficient clap gap angle exists with the double clap model at 15^o when compared with all other clap gap configurations. Although due to the number of parameters, the effects of any changes to the mechanism are sensitive. At this stage of research work, it is concluded that there exists an optimal closure distance with the current iteration of the mechanism.

5.2 Ongoing & Future Work

5.2.1 Beta Mechanism Redesign

As of now, the Beta mechanism is on the second iteration. Yet we still encounter a myriad of issues varying from mechanical properties to a lack of understanding of flight software. As we are moving forward with the new development of the Beta Quadflapper, there are many major changes that should be made for the third iteration. One of the biggest limitations the flapping mechanisms have is the gearbox. The gears prove to be a challenge to manufacture for students due to limited resources. The rapid prototyping available on campus that can produce gears at the dimensions we need is mostly 2D, like laser cutters. The laser cutter also limits the materials that can be used to manufacture the gears. Once the team figures out this bottleneck, many design constraints are lifted. For the motor selection, we have to understand the maximum torque requirement in order to choose the best motor choice for the design. If we are able to pinpoint the best combination of gearbox and motor, future research and the Beta quadflapper can no doubt takeoff.

5.2.2 Wing Aeroelastic Design

The wing still holds a lot of unknown parameters that might allow further thrust enhancement. As of now, the FWMAV team at UCI utilizes wings without additional spars. Many other famous FWMAV designs such as Delfly[11] and DARPA's Nanohummingbird[17] have wings with stiffeners to make the wings more rigid. But in return their wings are much smaller and flaps at a much higher frequency. To gain a more statistical understanding of how the aspect ratio, size, and stiffness of the wings affect thrust generation and the material in which the wings are used also differs widely across the FWMAV community. A wide net needs to be cast to figure out the best material for the current configuration. The current material, polyester[6], performs relatively well, however much more work should be done on the material selection.

5.2.3 Dragonfly-Inspired

While the concept of the quadflapper is novel and relatively new, many engineers and scientists still view FWMAV drones with a single set of wings. There could be efforts made by modifying the current mechanisms to attempt flying with just one set of wings. Different wing configurations could also be tested on the standalone mechanism that won't work as well for the quadflapper.

5.2.4 In-depth Clapping Investigation

Although we were able to pinpoint a specific crank-and-rocker configuration that provided the most potential in thrust generation for the current version of the mechanism, the research is still in it's infancy. While double clap at 15^o clap gap and 27.1^o stroke angle provided the best results, smaller changes within the degrees could be performed around 15^o of clap gap. The stroke angle could also be varied while constraining the clap gap at the most efficient setting. In the future, possible scalable aerodyanmic models can be developed so engineers and researchers can use it as a reference when designing FWMAV.

5.2.5 Quadflapper and Quadcopter comparison

Once the quadflappers mechanisms are mature enough to fly, there should be a major effort into making the comparison between many different parameters between quadcopters and quadflappers. Understanding the specific strengths of the quadflappers is important for the development of designs of the drone. For example, flight time and flight stability are some of the major topics of investigation. The angle of attack, throttle response time, and control (roll, pitch, yaw) should be looked into as well. With this knowledge in mind, there could be efforts to strengthen the weaknesses of the quadflappers as well as to make particular abilities the defining feature of the quadflapper.

As mentioned before one of the cornerstone ideas of FWMAV technology is vibrational stability, which is the ability of the quadflapper to return to its steady state flight conditions when its flight path is disrupted, and to maintain a near-perfect hover, when unperturbed. To capture the free-flying performance of the drones, a 3D motion capture system can be used to investigate some worthwhile topics, including the capability of the quadflapper to pitch, roll, and yaw, along with its ability to recover from certain disruptions. The drones can also be tested in one of UCI's low-Speed Wind Tunnels, in different orientations, and at various angles of attack. The purpose of these tests is to measure the power input required for certain airspeeds. The Wind Tunnel can also be used for flow visualization experiments, to see how the air interacts with the full drone prototype.

5.2.6 Fundamental Fluid Mechanics Study

It was initially assumed that triple clap would have more potential in thrust generation than double clap due to the increased amount of burst of air, however, the results showed otherwise. One way to seek the answer to that question is with fluid flow visualization. By visualizing the flow, we can analyze the interactions of the vortices and see if the 3rd clap is detrimental to the overall thrust generation. To properly quantify the strength of the vortices and have a closer inspection of the aerodynamics of the wings, Particle Image Velocimetry (PIV) might be a good solution. The lab has access to a basic PIV system and have yet to have the chance to utilize the machine. PIV combines an air particle seeder, synchronizer, high-power laser, and high-speed camera alongside capture software to trace individual air particle flow and eventually quantify the velocity vectors of the flow field around the aircraft. This paints the picture for the unsteady aerodynamic flow field of the flapping mechanism and shows how the flow generated by each wing interacts with one another. By utilizing similar techniques developed in [24], more can be understood about the aerodynamics of FWMAV, allowing engineers to understand more regarding each iteration of the design of the wings.

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