INVESTIGATING MANUFACTURING TECHNIQUES, TESTING, AND DESIGN TO ENHANCE CONFIDENCE IN THRUST PRODUCTION FOR SYNTHETIC FLEXIBLE SMALL FLAPPING WINGS

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my family, friends, and all that supported me throughout the years

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LIST OF ABBREVIATIONS

AR	Aspect Ratio, b^2/S
b	Total wingspan (wing tip to wing tip)
CA	Cyanoacrylate glue
CAD	Computer aided design program, which in this case was SolidWorks
CNC	Computer numerically controlled automated machine
CV	Coefficient of Variation
DAQ	Data acquisition device
DIC	Digital Image Correlation
FWMAV	Flapping Wing Micro Air Vehicle
LE	Leading edge
MAV	Micro Air Vehicle
PTFE	Polytetrafluoroethylene, a synthetic polymer commonly known as Teflon®
S	Entire wing area
UAV	Unmanned Aerial Vehicle

Abstract of Thesis Presented to the Graduate School
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Flapping wing technology exists and continues to expand on many fronts, although without a solid understanding behind the physics of flapping flight, a purely experimental approach can be taken. This study focuses on small synthetic wings which were biologically inspired by hummingbirds as they are comparable in size, shape, and flapping frequency. The focus was aimed at the average thrust production from a one degree of freedom flapping mechanism and the weight of each wing. The motivation arises with the final application of a standalone hovering device but brings to attention a question of whether or not to trust the current manufacturing process that consists of a carbon fiber hand lay-up method. The main objective of this work was to create a high-fidelity manufacturing process having repeatable and robust wings resulting in improved results where minute variations in average thrust production can be detected while in hover mode. To advance the possibilities and expand the testing envelope four distinct methods were proposed, the carbon fiber hand lay-up, a Teflon® CNC milled mold, a milled plastic frame combined with a carbon fiber rod for support, and a unique attachment method with a 3M transfer tape.

A multitude of methods were performed along with a validation comparison of two different geometric structures and several wing duplicates. Conclusions heeded a significant drop of approximately 74% in the coefficient of variation describing the weight distribution between duplicate wings and an over 84% decrease for the average thrust.

Now that this is accomplished, there are hopes that further research can be done to find how the characteristics such as structural stiffness and geometric topology have an effect on flight.

CHAPTER 1
INTRODUCTION

Literature Review

Ever since human powered flight was imagined, fixed and rotary wing aircraft have been prominently used in designs. As technology has developed, these designs have taken on a new realm, shrinking in size and gaining the ability to fly with controls given on the ground. Small unmanned aerial vehicles (UAVs) and micro air vehicles (MAVs), usually not exceeding a range of 150 mm [1], continue to grow in popularity. After smaller UAVs and MAVs were introduced, traditional propulsion continued to be on the forefront of thought, although a new track started to develop: flapping wings. Fixed and rotary wings, especially at a lesser scale level, introduce numerous problems that flapping could *potentially* solve. Stability issues at the reduced scale along with the inability to hover or sustain slow flight plague fixed wing aircraft while rotary wings have relatively low efficiency and a high noise signature. Flapping wing micro air vehicles (FWMAVs) theoretically could have the ability to hover in addition to forward flight, require only a short or vertical takeoff, and have high maneuverability, all advantages over the others. These properties are ideal for various indoor applications or in situations where a disguised vehicle is critical. With optimization, flapping technology has the *potential*, shown from nature, to have a superior efficiency. For these reasons, flapping is worth acknowledging as a propulsion source.

Work in the flapping wing field entails both experimental and modeling efforts. Computational analysis, such as that done by Lee et al. [2], shows the complexities of the fluid-structure interactions for flapping objects and the realities of low Reynolds number situations. Even studies like Ansari et al. [3] that characterized the effect of wing geometry, for example, finding a nearly linear relationship between aspect ratio and mean lift, make major assumptions. Here, the wing sections were assumed to be rigid flat plates and the simulations were obtained for just one wing, leaving out the possibility for wing interactions. The harsh nature of calculating accurate unsteady aerodynamic loads generated throughout the cycle and lack of a complete multidimensional, multi-degree of freedom, high fidelity dynamic model has driven this study to focus on developments by means of experimentation. Familiarity with such testing also came from previous graduate students within the department, which is explained in the next section. Numerous studies have focused on flapping mechanics or aerodynamics [4-9]. These touched on the effects of flexibility like Zhao et al. or Mazaheri or even creating an insect-mimicking flapping device where a roughly 10 g flapper was able to sustain 25 Hz and produce 3 g of average thrust [6]. Another group emphasized on natural species [10-17] like insects or birds to learn what nature has provided. Several also touched on specific animals such as the Hawkmoth (*Manduca sexta)* [18-19] or hummingbirds [20-23]. As with many FWMAVs, so much effort goes into areas like keeping weight restraints or building the flapping mechanism, that repeatability in wing manufacturing may not be considered. As additional topics are researched and more is understood, the uncertainty of manufacturing needs to be quantified. The question of whether studies such as [5-6, 10, 24-29] can be duplicated arises since they did not show an in depth look as to whether manufacturing could be consistently reiterated. This even spreads to past experiments done at the University of Florida [1, 30-32] and makes the point that attention should be brought to this area.

Background Work

The pursued investigation was the successor of flapping wing research done by Pin Wu [33] and Justin McIntire [34]. Both scholars worked extensively with small two dimensional flapping wings that consisted of a carbon fiber frame and a thin nylon based membrane. The wingspan of 150 mm (25 mm root) was chosen by Wu so that the wing would remain within the maximum definition of a MAV and the aspect ratio of a hummingbird. Each wing took on a Zimmerman shape, formed by two ellipses which intersect at the quarter-chord point, and had a triangular section to which it was attached to the flapping mechanism. This is depicted in Figure1 -1A. His work was developed by employing a single degree of freedom flapping mechanism where he gathered data, such as the averaged thrust over a period of time, with a load sensor. With two sets of cameras and Digital Image Correlation (DIC) methods, he was able to produce deformations along the entire flapping cycle.

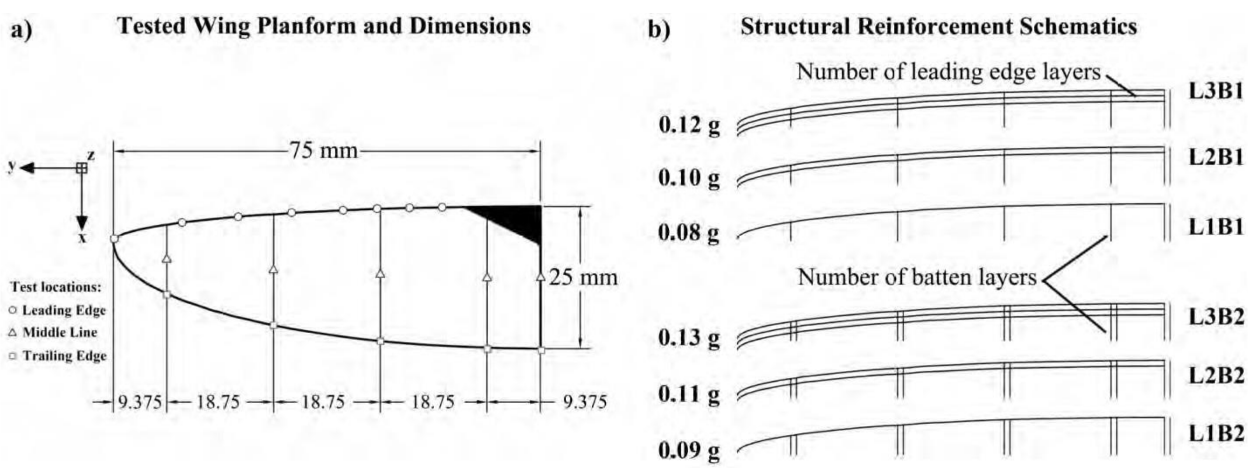


Figure 1-1. Wu's test of varying a wing's leading edge stiffness. A) Seen here is the frame lay out used in the test. B) Displays the variables in this particular experiment.

Although a bizarre use of this technique, it can be compared to Jin's work [12] of measuring the material properties of a real beetle wing as exceptional creativity. A comprehensive look at the deformations is given in Figure 1-2.

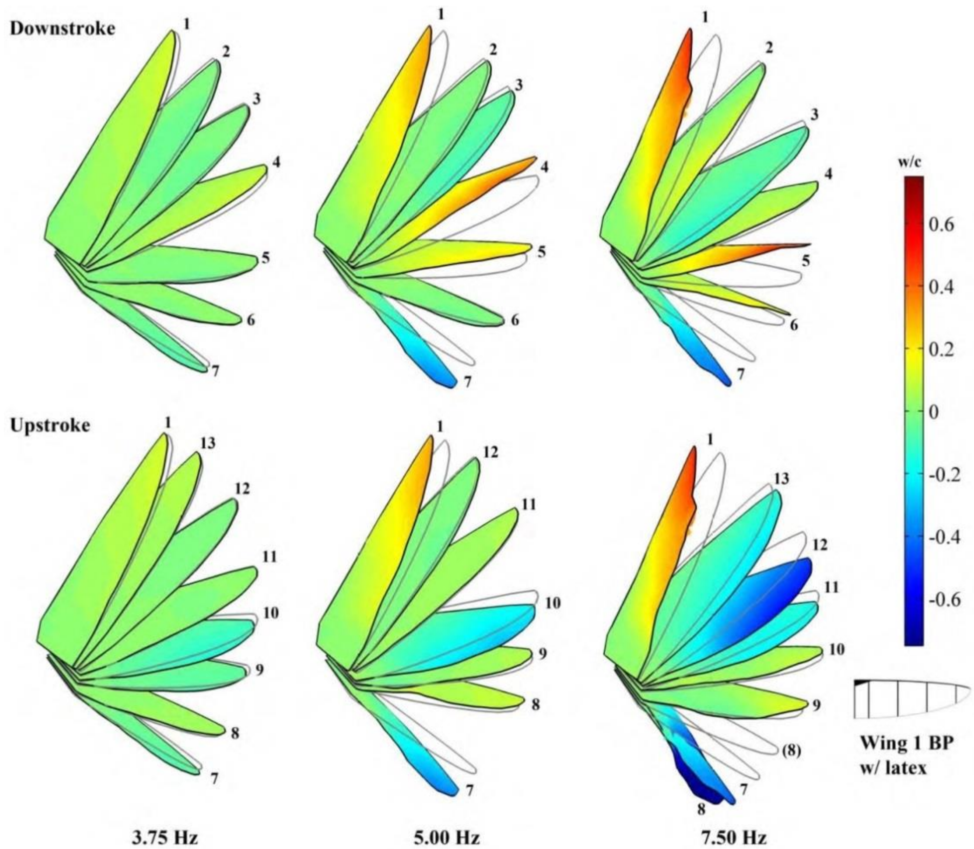


Figure 1-2. Full field deformation measurements taken with DIC software and two sets of cameras.

A vacuum chamber enabled him to find differences in flight and collect information about wing loading. Wu found after several evaluations that passive wing deformation can be used to enhance aerodynamic performance. The deformation reflects the aeroelastic effects produced by both the aerodynamic and inertial loads. One significant finding was that wing stiffness and mass distribution are both highly influential to thrust production. This was a similar finding to Zhao et al. who found that as flexibility of the wing increases, the ability to generate aerodynamic forces decrease [4]. Mazaheri established that while in hovering mode, more flexible wings produce approximately 20% lower thrust albeit for frequencies much lower than used in this study [5]. Six pairs of wings were part of the stiffness test and were labeled as L(#)B(#), for L gives the number of carbon fiber layers cured on the leading edge and B for the number of layers on each batten.

Wu also looked at changing the wing membrane to better suit the characteristics required for the experiments. After deliberating over several materials including Mylar®, Tyvek®, Kapton®, or latex rubber, it was concluded that CAPRAN® fit the lightweight, strength, and surface opacity needs for the flapping wings.

The idea of using different manufacturing processes was also noted by Wu who attempted to enhance the frame's stiffness and bolster the carbon fiber's moment of inertia. By using a CNC milled aluminum mold with a release coat, he filled a mold with carbon fiber to above the top surface, cured the material, and proceeded to sand down any excess. As a precursor to this work, this thought brought about the inclination to use a mold as a tool to better the wing's characteristics.

Wing fabrication has also been a topic for several experimentalists including Robert Wood of Harvard University. He explained in [35] and [36] that advances in Smart Composite Microstructures allowed him to produce a 60-70 mg insect like vehicle that used two 16 mm carbon fiber flapping wings (~100 Hz) to generate lift. The recent micromanufacturing technology gave the group confidence that they could mass produce identical parts. He then worked to constrain the variability in the component assembly to produce repeatable and reliable wings. It was concluded that the prototype vehicle had not been symmetric and that it was necessary for this fabrication to construct a reliable, symmetric vehicle. Even on a different scale, this proves a link between wing fabrication and repeatability.

McIntire worked to understand if increasing twist about a wing's leading edge or altering other associated deformations would produce larger average thrust values. He continued aspects set forth by Wu while also establishing a finite element model confirmed by thrust testing and DIC in hopes to reduce testing time. He began with a Zimmerman planform and identical wing manufacturing procedures as Wu while focusing on three main frames as illustrated in Figure 1-3.

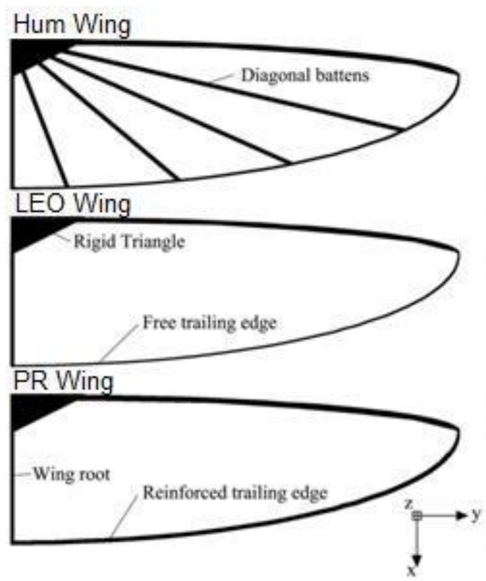


Figure 1-3. Three main wing designs focused on by McIntire including one based on a hummingbird, a leading edge only design, and one reinforced on its perimeter.

The first, *Hum Wing*, is described as having radial battens that were biologically inspired by a hummingbird. The *LEO Wing* (leading edge only) had a strip of carbon fiber along the leading edge and one along the root length. Thirdly, the *PR Wing* was reinforced along the entire perimeter.

Multiple series of these wings were tested using a load sensor along with full-field DIC. McIntire then produced results presenting that the movement of the wing's centroid highly correlated with the average thrust output. Figure 1-4 exemplifies a trend found linking the Z Centroid with thrust and adding merit to his hypothesis.

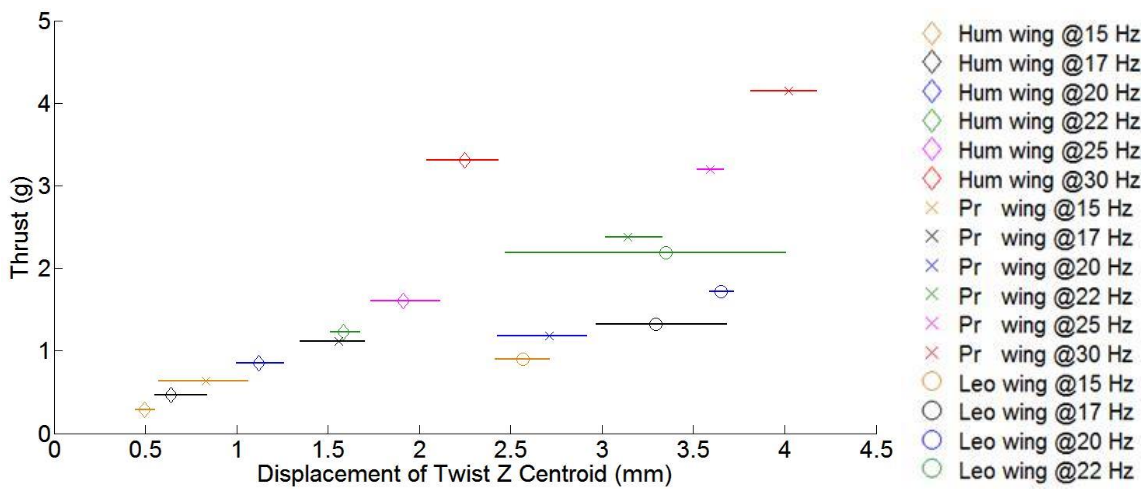


Figure 1-4. McIntire's results showing centroid movement as it related to thrust. The horizontal error bars represent the range of values between flap angles -5° and 5° with the mean denoted as a marker.

The finite element model was completed in Abaqus and fine-tuned with results from the aforementioned wings. Various wing designs were modeled, tabulated, and verified experimentally. After a few slight modifications, he was able to find wings with increased torsional aptitude as well as higher average thrust values.

Motivation

Crucial aspects of flapping technology have intrigued hobbyists and toy manufacturers, such as the WowWee® Flytech™ Dragonfly. Released in 2007, this 28.35 gram [37] forward flying dragonfly shows that even a simple design can endure repeated flights and require little wing optimization to be effective.

As advancements ensued, universities and companies began additional in-depth research. In 2011, a company called AeroVironment Inc. unveiled a 19 gram hovering UAV which was biologically motivated by a hummingbird. Despite taking about six years to complete and having a significant expense which was funded by the Defense

Advanced Research Projects Agency (DARPA), the project constructed a vehicle worthy of praise.

Figure 1-5. WowWee® toy Dragonfly [37].

Having a wingspan of 165 mm, the Nano Hummingbird demonstrated the ability to hover with a flap rate of 30 Hz, fly forward, and transmit a live color video to a remote ground station [20]. As impressive as this technology may be, one drawback of the limited tools showed in the inadequate endurance of a measly four minutes.

Figure 1-6. AeroVironment Hummingbird [20].

Another study, extensively described in [29], showed the progression of a 50 cm wingspan (21 g) and 28 cm wingspan (16.07 g) ornithopter and how that developed into the DelFly Micro, the smallest flying ornithopter with a camera and transmitter onboard at 10 cm (3.07 g). Two of the flapping vehicles are pictured in Figure 1-7. The ability to observe places that are inherently dangerous are continuous reminders of the possibilities for FWMAVs and the need for more research.

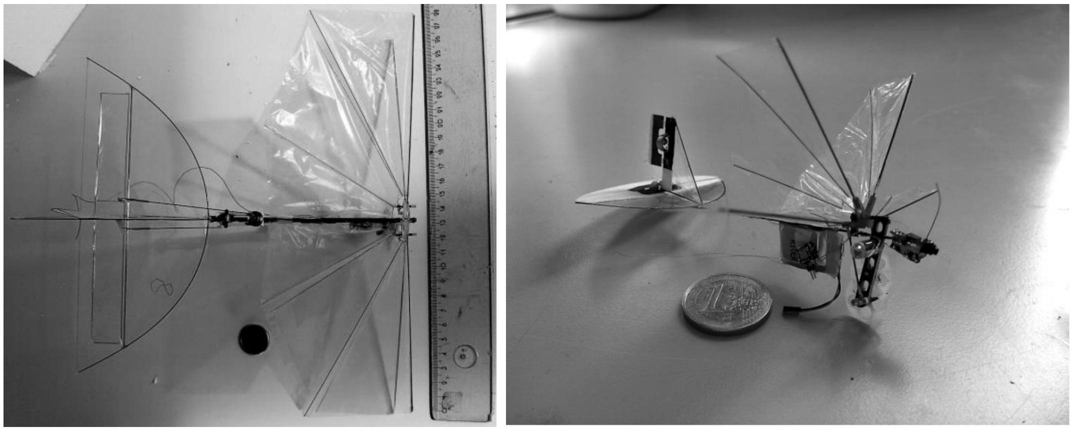
A  B

Figure 1-7. The DelFly autonomous ornithopters [29]. A) Top view of DelFly II. B) DelFly Micro

Even though interest exists within the world of flapping technology, accurate flapping models remain difficult to produce while little is known about the physics behind such movements. Until unsteady aerodynamics and wing structure optimization is further understood, an experimentalist approach will be the most direct and convincing strategy for future progress.

Goals and Objectives

To further the knowledge of this field, this project took on “the objective to expand/explore the design space for synthetic flapping wings by advancing fabrication techniques and implementing experiment-based optimization” [38]. Along with Dr. Peter Ifju at the University of Florida (UF) with the knowledge of micro air vehicles, two additional professors were brought onto the assignment due to their expertise- Dr. Raphael Haftka at the University of Florida for optimization and Dr. Tony Schmitz at the University of North Carolina at Charlotte (UNCC) for advanced fabrication.

The main objective of this paper was to create a high-fidelity manufacturing process having repeatable and robust wings resulting in improved results where minute variations in average thrust production can be detected while in hover mode. The goal was to create a systematic approach based on previous studies that limits errors and breeds full confidence in the accuracy of data collection. If done correctly, it would lend others a superior method to produce wings and allow for a more precise optimization.

The ultimate goal after a thorough understanding of the flapping process is completed will be to create a free standing hovering mechanism that utilizes the gained knowledge of flapping wing technology. Although this was not researched directly in this paper, the idea rests that certain aspects, such as wingspan or flapping frequency, should not exceed power constraints or size limitations available on that type of MAV and is carried out in the entirety of this paper.

CHAPTER 2
EXPERIMENTAL CHARACTERIZATION OF MANUFACTURING PROCESSES

Wing Structure

The chosen overall wing dimensions were essential in this study to remain within the realm of restrictions for a standalone hovering MAV. In terms of size, the wings need to be small enough to limit inertial effects yet large enough to ultimately hover and carry a payload. Continuing from the work of Wu and McIntire, a 150 mm span (b) wing (75 mm half span) with an aspect ratio [39] of 7.64 was chosen. The wing also remained flat without a camber.

$$Aspect\ Ratio, AR \equiv \frac{b^2}{S}\ where\ b \equiv span\ \&\ S \equiv reference\ area$$

This falls within the range of a honeybee (*Apis mellifica*) at an AR of 6.65 and a Rufous Hummingbird (*Selasphorus rufus*) at 9 [7]. Keeping this general size was also significant, as nature follows a similar trend in requiring small wings to hover. Warrick et al. mentions that "data from analyses of aerodynamic models and from empirical studies of the mechanical power and metabolic cost of flight at different speeds in birds all agree that hovering flight is much more expensive than intermediate speed forward flight" [21]. If similar to nature, it could be expected to use wings smaller than many fixed wing, forward moving, MAV wings. He continues to explain that due to the high power loads necessary, hovering has become only an attainable goal for small birds. Since these wings are on the same scale as a hummingbird, the dimensions were deemed acceptable.

A popular approach among experimentalists to obtain a wing structure has been to mimic natural species, like Nguyen mimicking a beetle [10]. Rather a separate methodology takes on the understanding that nature may not develop a geometrically optimized wing structure in terms of thrust output, for it takes into account nutrients, a complicated multi-degree of freedom flapping motion, other flight dynamics, and an animal's growth. A certain bird or insect may need to grow to a specific size to fend off predators in the wild while possibly surpassing ideal dimensions for hovering flight. Although inspired by these natural flyers, the wing frames established in this study had the opportunity to evolve past natural configurations to include complicated topologies. It should also be noted that flyers, like hummingbirds, commonly have intricate flapping strokes including many active degrees of freedom and multiple hinge joints, comprising of asymmetrical stroke paths [22]. Therefore the simplistic wings actuated with a single degree of freedom created here may behave differently and hold a varied optimized structure for maximum thrust output due to their altered kinematics, inability to change during flight, and complicated nonlinear geometries.

The Zimmerman planform used by Wu and McIntire was abbreviated to a quarter elliptical area to ease manufacturing and gain repeatability. Figure 2-1 expresses a fraction of the frame topologies possible to investigate.

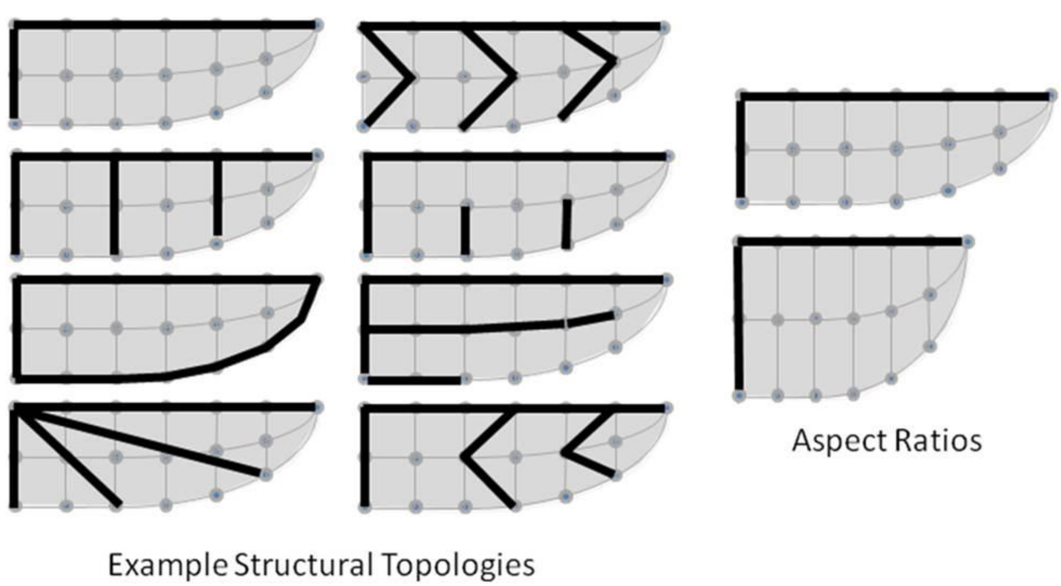


Figure 2-1. Examples of wing combinations with different frame topologies.

Together with using the verbiage of quarter elliptical area in this paper, a few other terms in Figure 2-2 are defined. Half span will describe the distance the wing extends along the leading edge (LE) while root is the distance in the chord direction at its inner most edge.

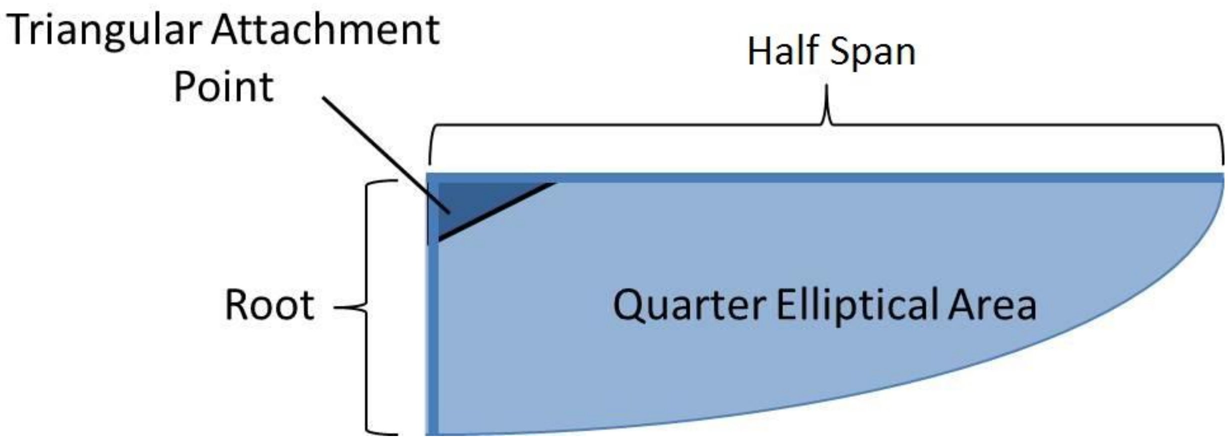


Figure 2-2. Wing area along with notation used in this paper.

Flapping Mechanism

A challenge arises when numerous goals are being kept in mind. The flapping mechanism must be robust and able to bear months of continuous use although it must actuate the wings symmetrically, have an easily fixable structure, and have the wings detach effortlessly. As this project began, the first version of the flapping mechanism was in use and able to flap wings up to roughly 45 Hz, limited by the frame, motor, and controller components. This was deemed acceptable for the subsequent versions for it compares to examples in nature with similar wingspans. A Hawkmoth (*Manduca sexta*) with a span of 96.6 mm flaps at 26.1 Hz while a Rufous Hummingbird (*Selasphorus rufus*) with a span of 109 mm flaps 41 Hz [7]. Also, the wings would need to produce enough thrust so that in hover mode, a standalone flapping mechanism could offset its own weight. Nguyen et al. molded a 10.26 g device that flapped wings with a span of

125 mm up to 37 Hz [11]. This coincides well with the work done by previous students and adds a proof of concept.

Mechanism Version 1

The first flapping mechanism was fabricated by a former PhD student, Pin Wu and was still in use under Justin McIntire. This mechanism, and each described thereafter, is powered by a brushless 15W EC16 DC Maxon motor (http://www.maxonmotorusa.com) with a 57/13 reduction ratio planetary gear head, a 256 counts per revolution encoder, and an EPOS 24 controller. The Maxon motor is able to turn an output crank module up to 45 Hz or a torsional component of 21 N·mm. This motion was transferred to linear single degree of freedom by a push rod to a mount and reciprocator to create a flapping motion as seen in Figure 2-3. This was largely done for the sake of reducing weight and requiring fewer parts, along with adequately resembling a hovering MAV. Wings were then glued onto the carbon fiber wing mounts with cyanoacrylate (CA) adhesive.

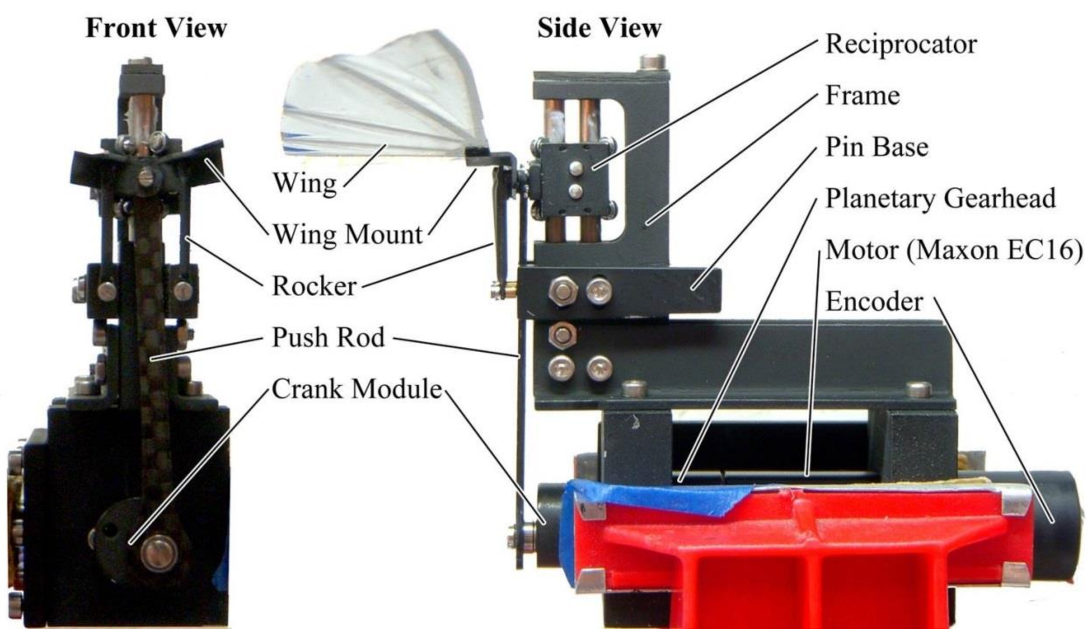


Figure 2-3. Flapping Mechanism 1 capable of 45 Hz and ±60° flap angle. Comprised of many hand scupted parts and numerous screws. Courtesy of Pin Wu.

Unfortunately, this version had significant issues with unnecessary friction and screw misalignment along with being constantly under repair. The frame and parts were put together by many M1 screws that were loosened by the vibrations of the push rod and also needed lubrication amidst trials. Due to the complexity of the device and the way it was designed, fixing certain parts, like the reciprocator, would require a large majority of the flapper to be disassembled. Another concern was how the wings were attached as glue residue built up on the mounts and carbon fiber frame. This led to difficulties if either a wing was to be tested again or removed for a variety of reasons. The motor was controlled by a LabVIEW program that was later exhaustively overhauled by fellow lab mate Kelvin Chang to improve efficiency and add viable options.

Mechanism Version 2

The next iteration held slight upgrades to Version 1 to condense the number of parts and decrease certain errors. The first adjustment was to remove the former reciprocator and replace it with a CNC (computer numerical control) milled block of nylon. The advantages to this change included the reduction of parts for the reciprocator from around 12 to 1 and not needing to rely on frequent applications of lubricant. Next, the wing mounts and rockers were milled out of aluminum to provide easily replaceable parts, considerably enhanced connections, and a more symmetric flapping motion as opposed to the hand-made originals. The mounts also had a recessed area to better repeatedly position the wings. The actual machining, for this and future versions, was done by Dr. Tony Schmitz and the graduate students in his department. Lastly, the mechanism was painted white, largely to help with DIC measurements where black dots were tracked on the wings. In Version 1, there were times where the edge of the wing was indistinguishable with the device in the background.

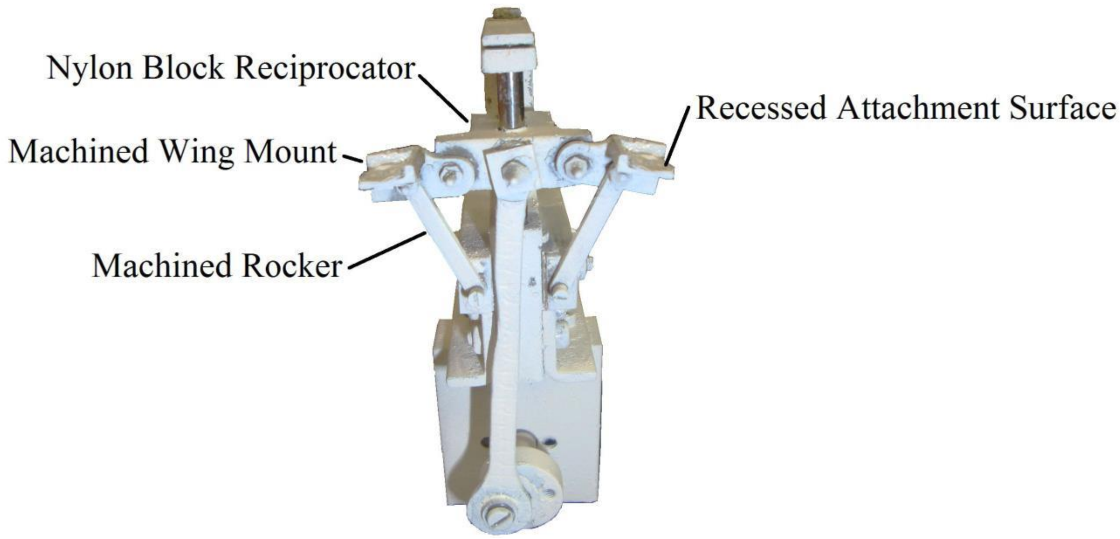


Figure 2-4. Flapping Mechanism 2 equipped with a nylon block and machined parts. Courtesy of Justin McIntire.

Even though great strides were taken with this step, ultimately, the complications that propagated throughout this version lead to the creation of Version 3.

Mechanism Version 3

A substantial renovation was done for Version 3 to reach a flapper that could be refurbished quicker with fewer parts while having less friction and wear on the motor. To start, a brand new motor, encoder, and gear head—a direct copy of those used prior—were coupled to an all-aluminum frame, as can be viewed in Figure 2-5. A set of nylon gears transferred the spinning motion of the motor to two cranks and pushrods while the wing mounts pivoted around a screw. This removed the problematic reciprocator along with the friction that accompanied it. Four holes in the cranks allowed the flapping angle, the angle above and below mid-plane the wings travel, to be altered to four settings: ±21°, ±32°, ±48°, ±52°. One large improvement was the move to larger and fewer screws, permitting less slop and maintenance.

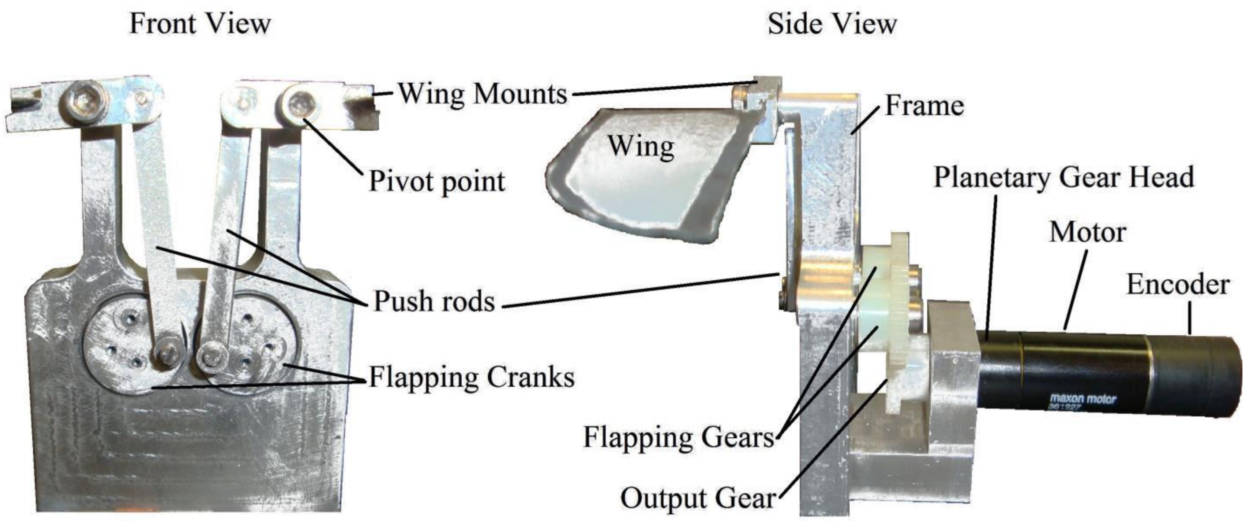


Figure 2-5. Flapping Mechanism 3 furnished with aluminum frame and fewer parts. Courtesy of Justin McIntire

Again, small issues crept up as experiments continued, especially that of how the wings were connected, although, this version stood as a significant upgrade to any past mechanism.

Mechanism Version 4

Many of the same options exist on the most current flapping mechanism as in Version 3. The main difference for this flapper is the insertion of two bearings where the wing mounts pivot to further reduce friction. This creates an effortless movement that improves controllability and lengthens the life of the motor components. Another huge advancement was in the wing attachment points. Up until this flapper, the tester would need to glue the wings into place, taking up time and leaving behind residue. Instead, the wing would be inserted into a corner slot and held in place by a tightened screw (Figure 2-6). This reduces the time needed to change wings, elongates the life of the wings, and still allows for proper placement.

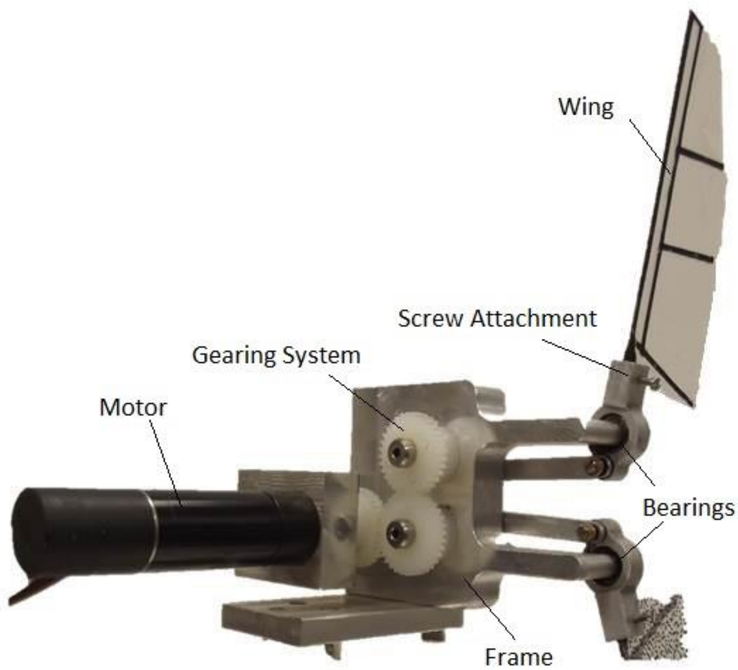


Figure 2-6. Flapping Mechanism 4 with screw attachment and bearings. Photo courtesy of Jason Rue.

Other than wear and tear with typical expected replacement parts, this version suits every need for the current experiments and can be changed quickly with new aluminum parts if new ideas arise, such as a different flapping angle or wing attachment.

Data Collection

A 6 axis (3 force, 3 moment) force/torque sensor, Nano17 [40], was used to measure the thrust and lift with a resolution of 0.318 g and read through to the computer 30k times per second by a National Instruments NI USB 6251 16 bit data acquisition (DAQ) device (http://www.ni.com) while being controlled by LabVIEW. Figure 2-7 shows the elaborate control panel for the experiment. The leftmost screen has the options to regulate the motor and adjust features such as the device settings, acceleration, the testing ramp period, frequencies, and a custom file naming system. The dial also gives the commanded target frequency along with what frequency the motor is currently running. The right panel controls the DAQ device and details like the record rate while dumping the data into text files. Every file was labeled with a custom naming scheme to not only stay organized but to later read them through MATLAB®. Text files began with a seven digit number the takes into account a specified wing number, the frequency, and the trial number (WWWFFTT) and followed by several terms relating back to either lift or thrust.

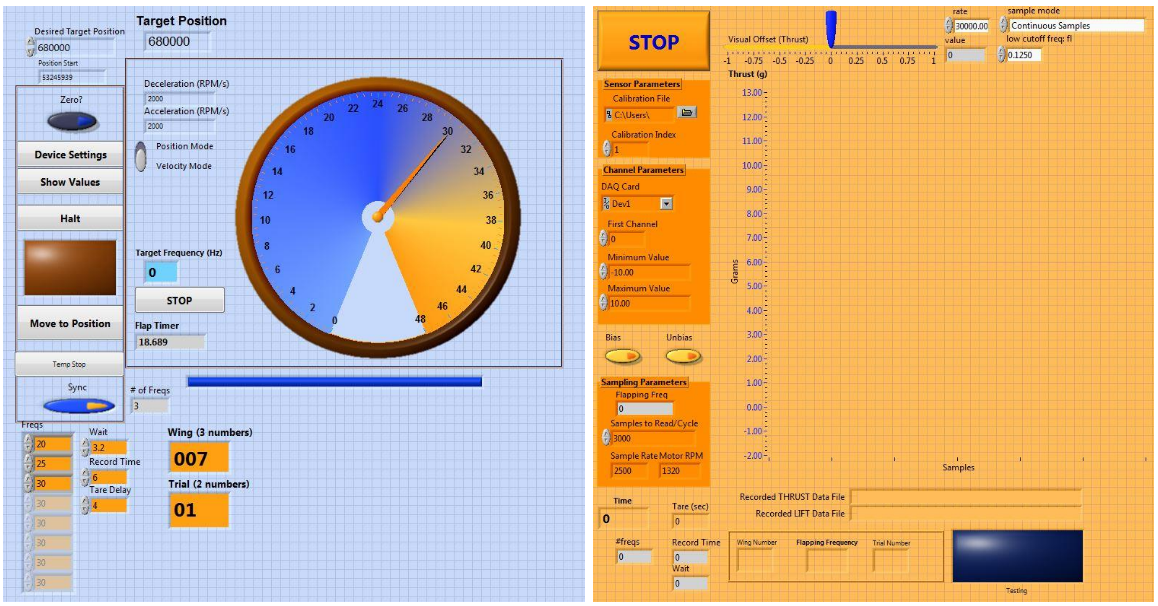
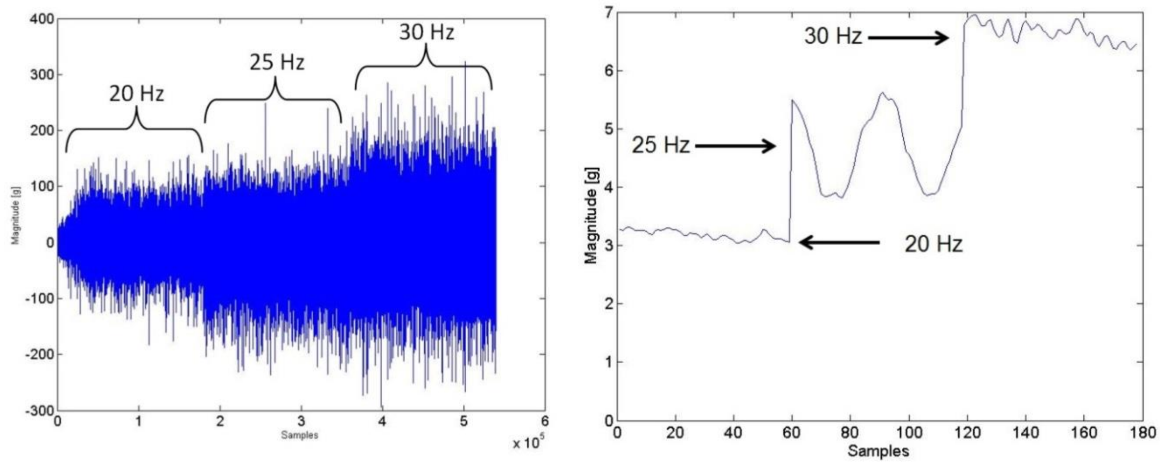
A  B

Figure 2-7. LabVIEW virtual instruments that control the testing procedure. A) Motor control. B) Sensor Readings.

Changes were implemented to adjust the rate at which the data was read because a correlation amongst rate and overall thrust scatter was discovered. 30k readings per second were chosen to still benefit but not bog the computer down. The load cell generates a rather noisy signal making it challenging to interpret any results before post processing occurs, therefore, to ease deducing results a filter was inserted into the LabVIEW code. “A point by point low pass Butterworth filter was used real time in the LabVIEW software code to process the noisy signal to present the low frequency thrust offset data that is desired for each frequency. This filter provides the operator of the experiment real time performance that is easy to interpret, serving as a check to assure consistency and create a warning sign for possible delamination or damage to the wing between trials" [41]. This gave the experimenter a look into the data graphically on LabVIEW as previous codes failed. It should be noted that average thrust and lift values remained the same before and after applying the filter to the system. Each continuous run was done using the ± 48° flap angle at three frequencies, 20 Hz, 25 Hz, and 30 Hz, recording for six seconds each and allowing a ramping period of 3.2 seconds in between each frequency. These ramps let the motor reach and settle on a frequency before data was collected. To prevent outliers from degrading the numbers, each wing was ideally tested ten times and averaged. The standard deviation was also noted to realize the spread. Occasionally, wings failed by either delamination of the CAPRAN® (membrane) or breakage of the frame. In these cases, the situation is noted and repaired if possible, unless a substantial disaster occurs, in which case the wing is remade. The wings were situated in such a way (Figure 2-6) so that gravity could be neglected from any measurements. At the beginning of each run, the program read off a four second tare measurement, without the mechanism moving, to take into account any offset and provide a way to "zero" the data. The length of time chosen for each section of the ramp was picked to be sure a sufficient amount of data was taken while the wings were in the correct frequency range without overburdening the flapping mechanism or damaging the wings. Figure 2-8 gives a brief example of how the data was observed before and after a filter was implemented. The cyclical nature of the 25 Hz signal and relatively flat 20/30 Hz data occurred habitually.



A B

Figure 2-8. Filtering raw data to help interpretation. A) An example of complete raw data ranging from 20 to 30 Hz. B) A separate instance after filtering for a similar flapping run.

The MATLAB® code previously used was extensively revamped and rewritten by the author to not only be exceedingly efficient as opposed to what the lab had used previously and include a GUI interface to be more user friendly, but export data to Microsoft Excel after the data was averaged. Details of the interface are shown in Figure 2-9.

Figure 2-9. MATLAB® GUI interface.

After a few user inputs like the wing number, trial, weight, and frequency range, the code is run simply by pressing three buttons. The written code reads in the text files that LabVIEW created and averages the raw data over the specific run time to get a *single* averaged lift and thrust value for each frequency. Additionally, other numbers such as the average frequency over the run (due to the controller, the frequency is not held completely constant), current draw, and minimums/maximums are either saved automatically into a data structure or graphically displayed and saved as JPEGs at the user's discretion. Any important calculated values that are warranted for manipulation are then exported to Microsoft Excel along with a comment that typically would describe the current study. The data was then manipulated in Excel to extract more graphs and analysis.

Visual Inspection

For as many comparison tests that exist to define differences between geometries, one that demonstrated to be most reliable was a simple "eye test". The level of acceptable accuracy expected within this study, especially for nominally identical wings, far exceeds what one might get if two visually incomparable wings are run. Meaning that if wings have a tendency to display inconsistent batten widths from wing to wing, carbon fiber that has strayed or bled away from the structure, or uncontrollable dimensions such as varying strip widths created within the manufacturing process, the scatter associated with the gathered data will be too great. Figure 2-10 indicates how a wing might appear if a hand lay-up method is taken. As mentioned in Chapter 1, if minor disparities are to be measured, then every detail throughout the procedure of measuring average thrust would require scrutiny.

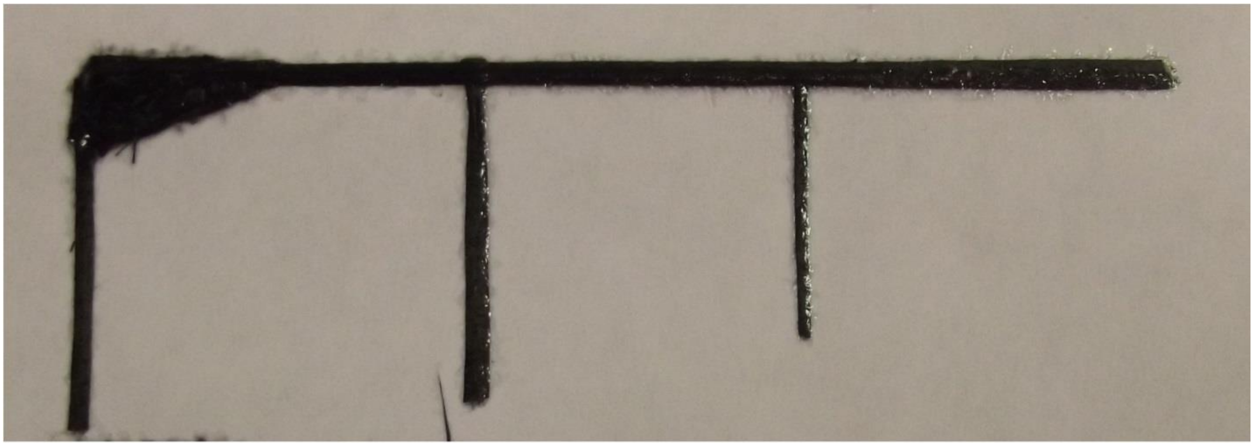


Figure 2-10. Image of a wing manufactured by a hand lay-up method having considerable visual inconsistencies such as the battens differing in width, the LE is a function of span, and the triangular section has smashed out beyond the desired dimensions. Photo courtesy of Jason Rue.

In the figure, the battens have different widths, the triangular attachment point is not distinct, and the leading edge increases in width toward the tip. In trying to reduce scatter within the data and adjusting manufacturing techniques to keep the necessary meticulousness, the eye test was the first hurdle to overcome.

CHAPTER 3
MANUFACTURING

The wings take advantage of passive wing deformation, much like hummingbirds or insects, as described by Wu [33]. The wing compliance and LE stiffness have positive aerodynamic effects and, while using passive deformation, can simplify kinematic actuation while reducing parts and weight. Having wings that are repeatable and robust are essential to any further developments in this area.

Wings created in this paper can be divided into constituents, frame and the membrane. This chapter outlines several ways to produce the wing frames, each evolving to enrich the latter. The material used for the membrane remained a constant throughout the entire experimental program and originated with Wu. An extremely thin (14 microns) nylon based film by Honeywell, called CAPRAN® 1200 Matte, is used for the membrane, although according to their specification sheet, general uses consist of thermal lamination for book cover applications [42]. This material has a relatively high tensile strength at rupture (234-276 MPa) and puncture strength (925 g) while being very lightweight. In comparison, another material previously used at the University of Florida with a similar elongation, Mylar® has an ultimate tensile strength of 200 MPa (Machine Direction)/234 MPa (Transverse Direction) [43].

Also crucial in the wing's makeup is how the frame is attached to the membrane. Initially, a spray adhesive by 3M named Super 77 was used, but the glue remained tacky long after it was applied. McIntire performed peel tests on an Instron machine with several different adhesives [34]. He found that a thin cyanoacrylate (CA) adhesive held much tighter as it had a more brittle bond. Even after numerous additional trials during that inquiry, no better option was found. The first three processes in this paper use CA while the fourth manufacturing process introduces a solution to frequent problems, such as membrane delamination, an adhesive transfer tape from 3M. In addition to the 3M 9471LE Transfer Tape, a few future and ongoing projects are also described in Chapter 5 to improve the bond between these surfaces.

The wings used by McIntire weigh roughly 0.12 g to 0.22 g so new methodologies were designed to keep the wings in a similar range, not only for consistency but to not overload the motor.

For each progression involving prepreg carbon/epoxy detailed in this chapter, regardless of how pressure is applied during the curing cycle, a manufacturer's recommended two hour controlled temperature profile is used and was detailed in Figure 3-1. As for the carbon fiber itself, a ~35% toughened epoxy resin unidirectional carbon prepreg was purchased from The Composite Store (http://www.cstsales.com). The fiber and the AR250 Series Resin originated from Aldila Composite Materials. The woven bidirectional carbon epoxy prepreg (AX-5160) cut for the triangular sections was from Axiom Materials (http://axiommaterials.com).

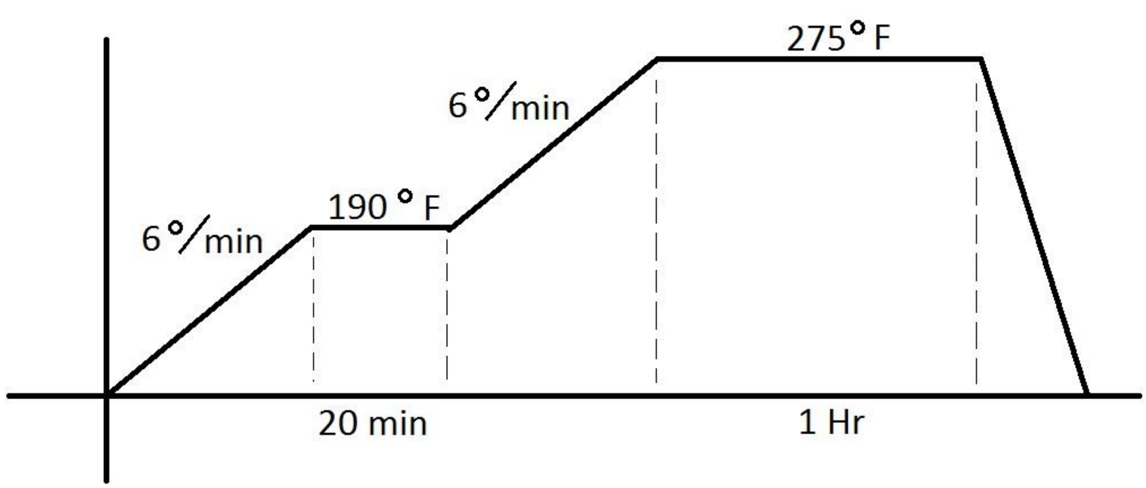


Figure 3-1. Manufacturer's recommended oven configuration to cure ~35% resin carbon fiber taking roughly two hours. These steps were programmed into the oven and followed exactly.

Hand Lay-Up Process

The first step to creating a high-fidelity experimental process was to improve a commonly used method for wing assembly, as Nguyen [6], Wu [33] , and McIntire [34] performed, which entails a hand lay-up technique where carbon fiber strips are delicately laid on a flat plate in a certain pattern and cured in a vacuum bag within an oven. Bidirectional carbon fiber made up the triangular attachment area whereas the unidirectional composes the rest of the frame. The main advantage to this process was that it was done entirely in-house and was easily customizable.

Process One

Stages involved with this route are critical as the hand lay-up serves almost as an art form. Once a certain design had been set, a thin outline of the features was printed and glued to a flat plate with Super 77, being careful to keep the surface as pristine as possible. The surface was covered by a very thin (0.0254 mm, 0.001 in) thermally stable release film called D7000 (http://www.decomp.com/) to prevent the carbon fiber from sticking. Cautiously, 6 mm by 12 mm triangles were cut by hand from the bidirectional prepreg and narrow, roughly 0.8 – 1.0 mm, strips were trimmed from a larger sheet of unidirectional prepreg. The triangular area was then laid in three layers with a leading edge sandwiched in between, which was composed of one to three layers depending on the desired stiffness. A single carbon fiber layer made up each other support batten.

After the entire frame was sufficiently oriented and aligned with the printed pattern, another piece of release film was taped on top to help secure the carbon fiber and keep it from sticking to the vacuum bag. The whole plate was then placed into a sealed vacuum bag, compressed by 30 in Hg to insure proper consolidation, and positioned in the oven.

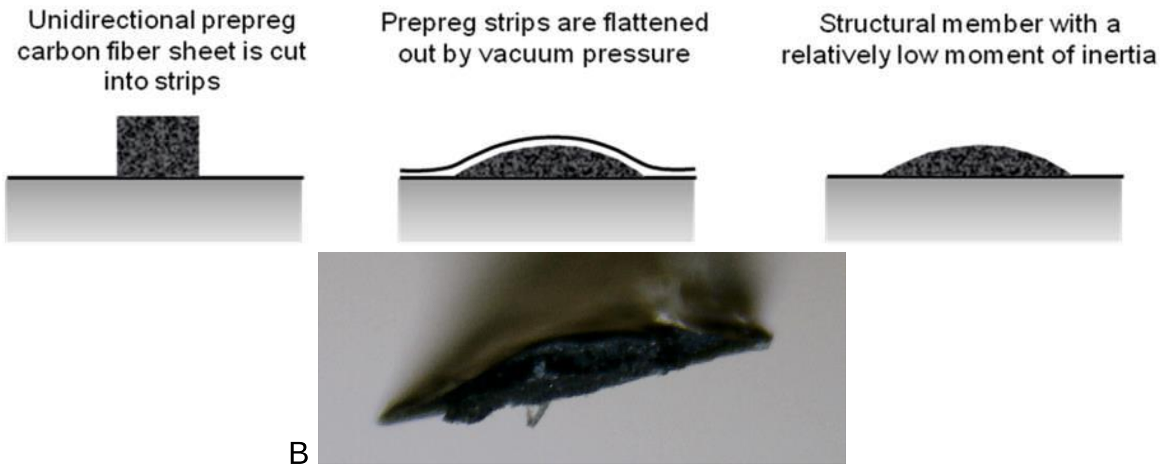
Once the cycle was complete, the wings were delicately removed from the flat plate and prepared for the gluing process. Each wing was held with tweezers while CA was meticulously spread over the carbon fiber. If too much glue was placed on the surface, the excess would spread out onto the CAPRAN® and change the membrane properties. On the other hand, if an insufficient amount is dabbed onto the carbon fiber, delamination would almost certainly occur during testing. Again, the advantages are listed below.

- Done completely in-house
- Method easily altered for new wings

Issues

This process is routine and typically used but holds many uncertainties and concerns. Obstacles include the loss of the cross sectional shape as it generally flattens out under pressure losing stiffness, along with the point that it is also fairly difficult to keep the fibers aligned, or cut the strips with consistent accuracy. Figure 3-2 illustrates the matter of losing the defined rectangular shape of the cross sectional area thus reducing the moment of inertia.

Since Wu found that the leading edge stiffness and minimizing weight play a large role in thrust production, one can immediately make a generalized statement that the wings laid up by hand are not optimal for thrust production and are less efficient. For a certain level of thrust production, these wings also weigh more than they should due to that fact, as the carbon fiber could be utilized more efficiently.

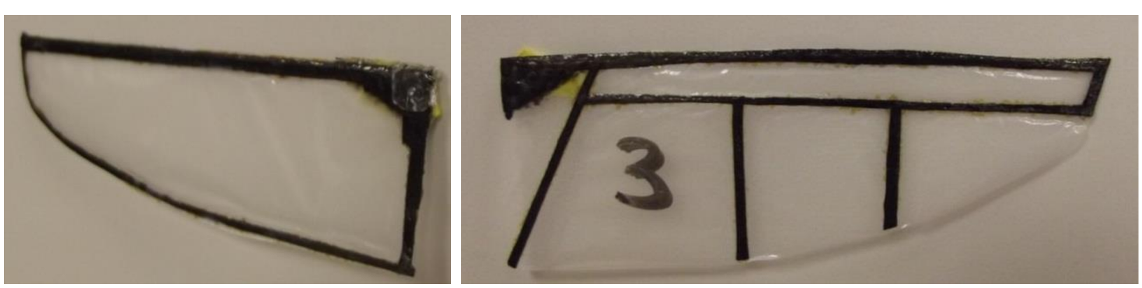


A

B

Figure 3-2. Problem of carbon fiber on a flat plate loosing structural stiffness. A) Diagram description courtesy of AFOSR Flapping Proposal. B) Actual picture of the cross section of a three layer carbon fiber LE. Photo courtesy of Jason Rue.

Therein lays another predicament with the struggle of commanding the battens to a definite position as very little restrains the carbon fiber while it cures. In Figure 3-3, two pictures explain this point. The battens are off kilter, the LE developed a bow, and the triangular area is by no means distinct. These wings fail the visual eye test and could not possibly be reproduced. For optimization to produce reliable results and to improve upon average thrust production, the wings must be repeatable. The thrust values obtained through experimentation must be trusted with little variation.



A B

Figure 3-3. Typical deviations in carbon fiber from the hand lay-up process. A) Overflowing triangular area and uneven widths. B) Curved LE and imprecise angles. Photos courtesy of Jason Rue.

Each wing, when it is glued to the CAPRAN®, was then cut by hand to the desired curve. This is difficult to mimic and can be a major drawback since lift is generally proportional to the wing area. A summary of the deficiencies include:

- Hand-cut prepreg carbon/epoxy
- Loss of cross sectional area
- Difficult to keep fibers aligned
- Many human components to process
- CA bond and shelf life

Teflon® Mold Method

To correct several of these issues, a CNC milled Teflon® (PTFE) mold was created. The mold was resistant to sticking, held the carbon fiber in place during the curing cycle, and kept the cross sectional shape intact. As an alternative to the vacuum bag, a silicone mat with a temperature range of -50°F to 500°F, well within the oven profile, was layered to apply pressure, and then was clamped down bounded by two 6.35 mm (0.25 in) aluminum plates. The specific plate thickness was to deter warping when the screws were tightened.

Process Two

The phases involved with this process started with a 3 mm thick sheet of PTFE. Via Dr. Tony Schmitz's graduate student Chris Tyler, Figure 3-4 depicts a 1 mm diameter, four-fluted square endmill bit on a three axis milling machine (Haas TM-1) cutting the sheet. This design was custom and could be redone simply by altering the CAD model.

These Teflon® molds could be milled in a relatively quick period of time and allowed for several consecutive carbon fiber curing cycles as they were reusable.

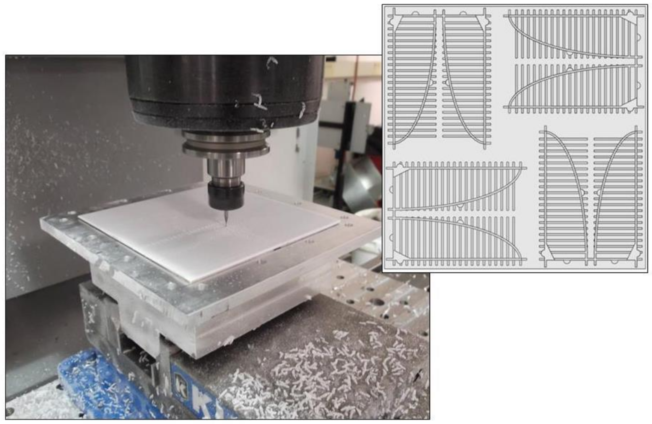


Figure 3-4. A CNC mill cutting the Teflon® mold shown in the upper right. Picture courtesy of Chris Tyler, graduate student of Dr. Tony Schmitz.

Once the mold was shipped to the University of Florida, carbon fiber strips were cut similar to the previous method. One large difference was the construction of a custom multi-bladed *strip cutter* (Figure 3-5). Instead of continuing past efforts to struggle with consistency, this device allows up to eight strips to be cut at one time while each having a very dependable width of 0.8 mm. The quantity of strips could be controlled by placing a certain number of razor blades within the apparatus.

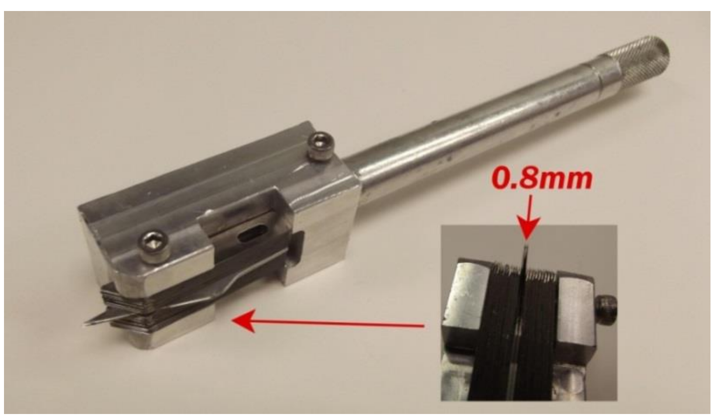
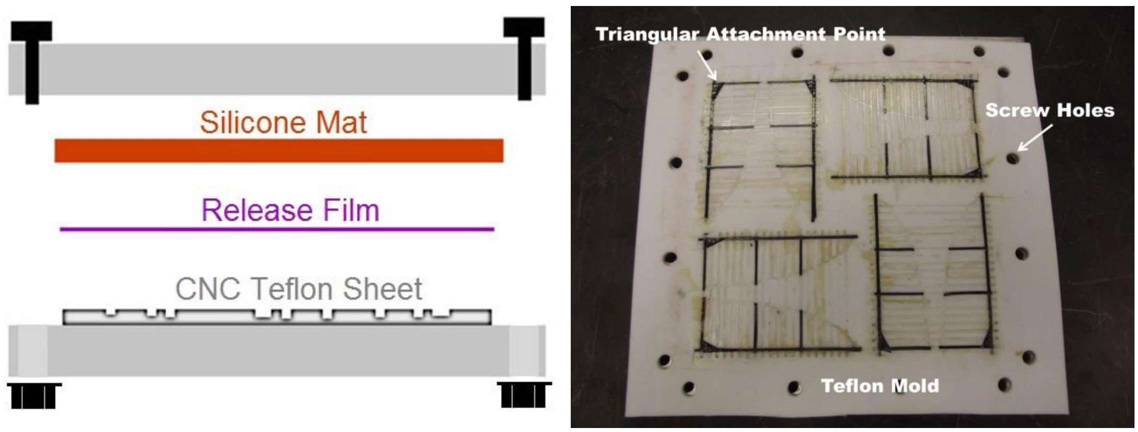


Figure 3-5. Custom strip cutter created to not only cut carbon fiber strips consistently but cut multiple at a time, becoming more efficient and saving time. Photo courtesy of Jason Rue.

Strips would then be skillfully positioned into the mold, like Figure 3-6B indicates, and then sandwiched with release film and a 40A durometer silicone mat (1.5875 mm, 0.0625 in) between two aluminum plates. Figure 3-6A encompasses a cross sectional drawing of how the layers are assembled. It is noteworthy to mention that initial Teflon® sheets were permanently coupled to aluminum plates post milling. Subsequently, large shipping costs and warping led to a detached sheet that extended out to the border where the screws held the sheet in place during the curing process. This halted many of the warping issues and allowed only the PTFE to be shipped from the UNCC campus to UF, drastically reducing costs.



A B

Figure 3-6. The Teflon® Mold in two views. A) An exploded view of the aluminum sandwich structure. B) Photo of post cure mold. Photo courtesy of Jason Rue.

After the curing cycle in the oven, the wings were carefully removed from the mold, attached to CAPRAN® with CA, and cut out by hand. As can be seen below, the frames are considerably improved and compare well with the hand lay-up frames. Figure 3-7A illustrates the advances made as the carbon fiber strips hold an even width, are much straighter, and the triangular section is much more defined. The second picture lays duplicate wings side by side, matching better than previously possible with the methods demonstrated by those at the University of Florida. A rehash of the advantages follows the figure.

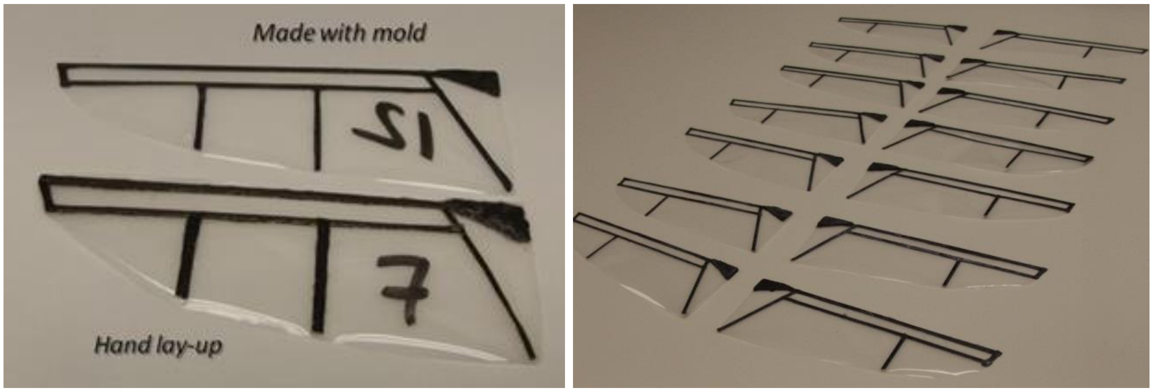
A  B

Figure 3-7. A quick visual comparison regarding the wings from the hand lay-up and mold processes. A) Comparison between two carbon fiber frames created with the hand lay-up and mold methods. Visually, one can see the improvement brought by the mold process. B) A series of carbon fiber frames that meet the visual test and show promising repeatability. Photos courtesy of Jason Rue.

- Much more consistent strips
- Was able to keep the cross sectional shape better
- No vacuum bag saved material and time
- Reusable molds

Issues

Some issues still remained, especially those with uneven pressure distribution, warping, thermal expansion, and mold depth. Many times the resulting specimen contained batten cross sections that lacked repeatability. The result of a shallow mold channel or too much carbon fiber was a “muffin” top that accumulated above the mold and is shown in Figure 3-8A. Here a leading edge was cured, cut, surrounded by epoxy, and polished so that an approximately 150x photo could be taken. If the mold channel was too deep or a deficient amount of carbon fiber was placed into the groove, a recess consistent with the pressure distribution formed causing air bubbles and less contact area when the top surface was glued to CAPRAN®. A side experiment was performed to find the mold’s correct depth. As a result, various layers of carbon fiber were correlated to particular mold depths, although some variation still existed.

One downfall of the strip cutter was that the blades needed to be positioned precisely or when the tool was pressed down to the material, a few blades pierced further than the others. Occasionally this would even cause a blade to not penetrate the carbon fiber and an entire strip would be skipped. Also, the carbon fiber would, at times, bunch up or move slightly as the cutter moved through it. As mentioned above, this led to having extra or too little fiber in the mold. One solution could have been to just fix the carbon fiber sheets down to the cutting table or establish a pretension.

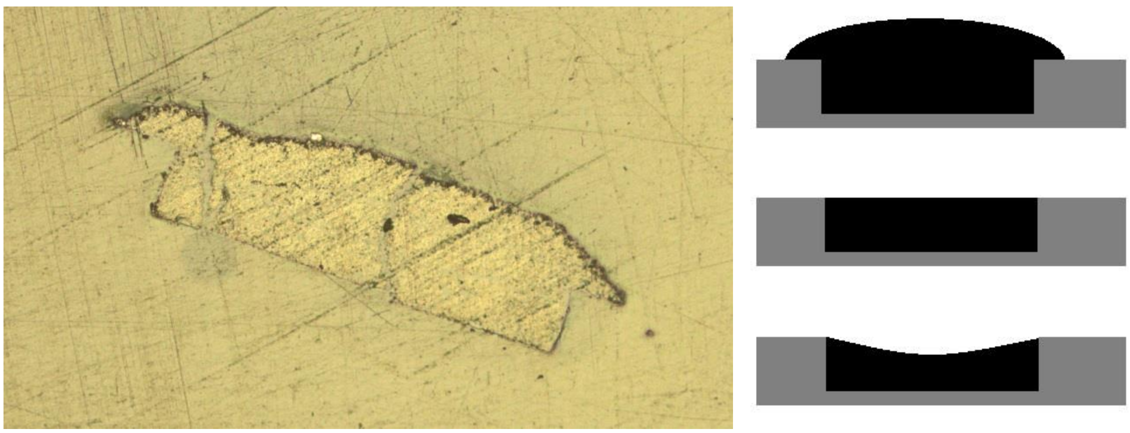
A  B

Figure 3-8. One problem with the Teflon® mold process was the difficultly of syncing the mold depth and amount of carbon fiber correctly so that a rectangular cross section was formed. A) Zoomed in view (approx. 150x) of the LE's cross sectional shape post cure. B) Looking at cross sectional shape variations. Photo courtesy of Jason Rue.

An irregular pressure distribution would also occur if screws on the periphery were tightened incorrectly. If a poor compression transpired by screws that were under torqued, a lack of carbon fiber consolidation would ruin the frame. The screws would also present a dilemma if one side of the mold was squeezed stronger than the other.

Plate warping became a nuisance and led to the change from thinner aluminum to the 6.35 mm (0.25 in) plates. Originally, the Teflon® mold spread only up to the screw holes, leaving a sizable gap between the outer portions of the plates when sandwiched. A bowing ensued and managed to form an added reason for unbalanced pressure.

Thermal expansion was deemed an explanation to the occasional buckling as it continued to appear. While still mainly in the mold under the post cure phase, the carbon fiber would lift up. Figure 3-9, provides a look at this phenomenon and hints to the question of whether the carbon fiber cured properly. When this happened the structural integrity seemed to stay intact and the LE flattened once out of the mold.

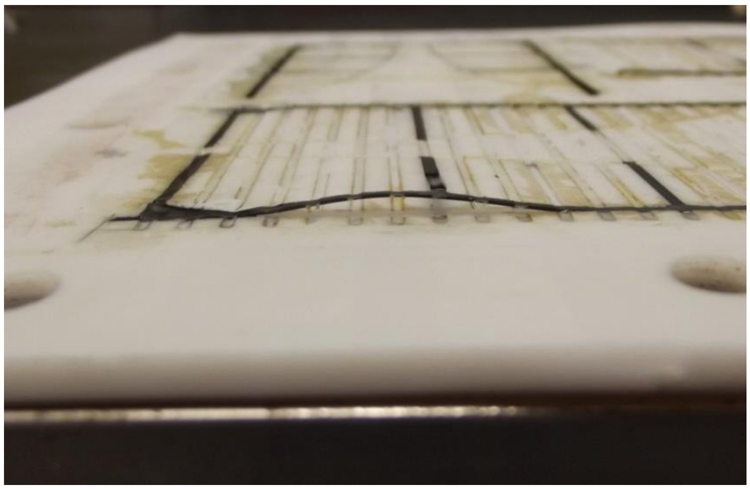


Figure 3-9. Buckling possibly due to pressure distribution or thermal expansion. Photo courtesy of Jason Rue.

As the molds run through multiple curing cycles, excess epoxy from the prepreg builds up and leaves residue. In Figure 3-9, a discoloration reveals evidence of this point. After extended applications, the carbon fiber gains a tendency to adhere to the mold making it impossible to remove, thus only working for so long.

Weak joints, caused by the sudden merge of a flexible one layer batten and either the LE or the triangular attachment area, in many cases, nullifies the wing before data can be taken. Figure 3-10 gives a glimpse of an incident where the root batten completely detached. Extra epoxy also frequently extends from the frame and must be cleaned off.

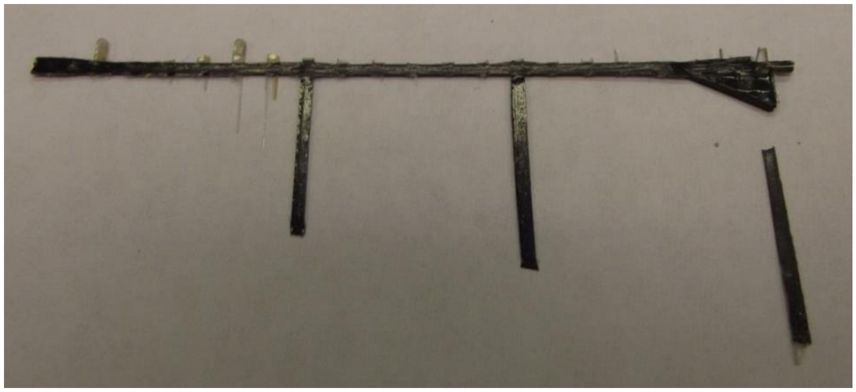


Figure 3-10. Example of cured carbon fiber frame where breaks occurred along weak joints. Photo courtesy of Jason Rue.

A few alternatives of the mold design occurred in conjunction with the aforementioned, including a Teflon® sheet that did not stretch to the border of the aluminum plate and one with thinner aluminum plates with fewer screws, both of which established warping concerns. For any mold where the Teflon® stopped short of the outside edge, the PTFE was adhered to the aluminum plate. Assorted solutions to help stop the sheet from moving were attempted including: a double sided carpet tape that stuck well although partially melted, the CA or Super 77 that was not strong enough to last through the oven cycle, and a 30-min Epoxy that ended with mixed results. Any thick adhesive commonly dried with lumps, worsening the pressure distribution. These were ultimately discarded and replaced without a fastener and a larger sheet fixed in place by the through screws for reusability and costs. Because any plates slimmer than 6.35 mm (0.25 in) bent when the screws were tightened and molds with fewer than four screws per side held lower pressure on the carbon fiber, all styles incorporating these features were rejected. One design where a thicker Teflon® mold was placed into a vacuum bag to apply pressure had decent results but had trouble pressing into the crevices of the mold and curing correctly. Ultimately, a list of the issues is listed below in bullets.

- Uneven pressure distribution
- Warping
- Thermal expansion
- Buckling of cured fibers
- Mold Depth
- Cutting prepreg carbon/epoxy consistently
- Epoxy build up on molds
- Weak joints on frame
- Travel time between universities
- Cross section repeatability
- A new design took an entirely new mold
- CA bond and shelf life

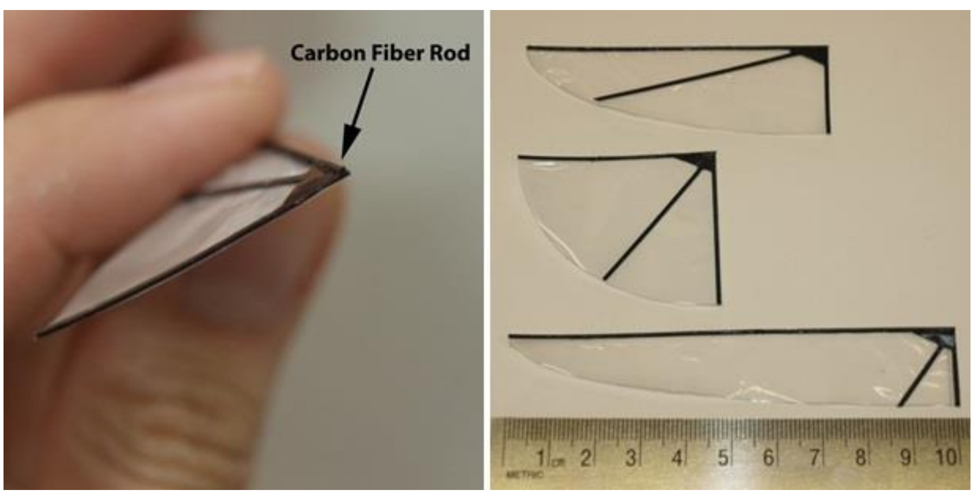
Plastic Frame

Ultimately, cost and precision needs drove the study to the current method. Instead of molds, the author switched to a 250 μm sheet of Delrin (acetal resin) plastic [44] which was CNC milled into the shape of the desired frame and fitted with a commercially available 0.5 mm (0.02 in) diameter Graphlite [45] carbon fiber circular rod. The rod slid into a 0.2 mm trench on the LE for stiffness created by a 0.4 mm endmill. One huge advantage to this procedure was that they could be machined in less than two minutes per wing as opposed to the hours necessary with carbon fiber. Strong stiffness and adequate fatigue properties were the reason behind acetal resin. This was a much more cost effective manufacturing process, given that the core study calls to test hundreds of wings. It also incorporated less human error, benefitting from machine precision batten placement and thickness. Adding CNC precision throughout the wing provides repeatability and keeps craftsmanship as a priority. The wing area has an effect on the thrust output, so to maximize repeatability and to further development; faint marks were printed onto the CAPRAN® as cutting guides before it was adhered to the frame. An ink jet printer was utilized so that heat did not affect the material properties of the membrane.

Process Three

Following the design being drawn in a CAD program, the Delrin frame was milled at the University of North Carolina at Charlotte and shipped to the University of Florida. There, the author, to keep a solid bond between the frame and rod, applied rubber toughened cyanoacrylate glue to the LE and attached the rod. This CA was sought after due to its added strength from the thin CA used to bond the membrane. The frame was then adhered with CA to CAPRAN® like previous wings. The weight of the wings compares well with the previous carbon fiber wings, ranging from approximately 0.1 to 0.25 grams per wing. Several plastic frame wings, laid out in Figure 3-11, justify the CNC mill as each wing manifests fine detail. Stiffness wise, this process is far more controllable than any other especially with the pre-cured carbon fiber rods. For a closer look, Figure 3-12 displays three photos that demonstrate the precise nature of the CNC milled wings along with a cross sectional view at the tip of a wing.

A



B

Figure 3-11. Completed plastic frame wings with the carbon fiber rod, frame, and CAPRAN® already combined. A) 0.5 mm circular carbon fiber rod glued to LE. B) Size and shape example of completed wings shown with a metric [cm] scale. Photos courtesy of Kelvin Chang.

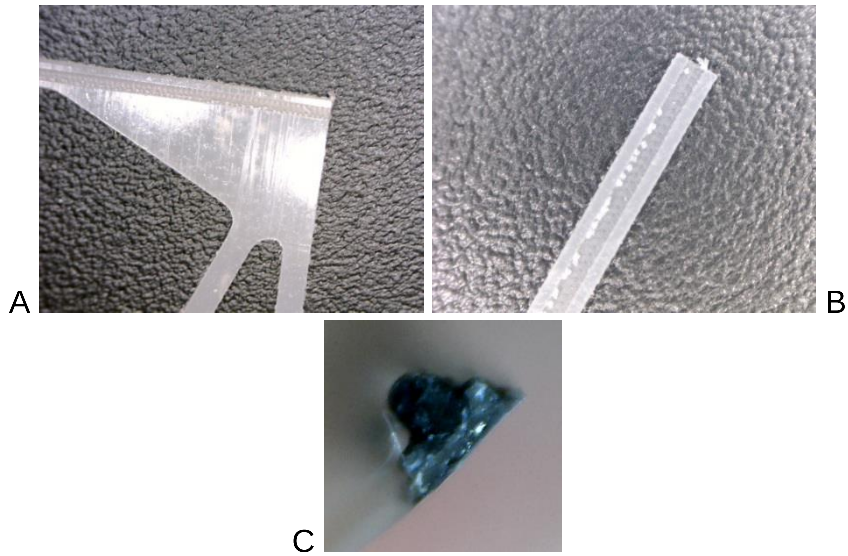


Figure 3-12. Zoomed view of the plastic frame. A) Close up of the triangular section. B) LE trough that shows the detail that can be manufactured. C) Cross section with the rod attached to the frame. Photos courtesy of Jason Rue.

White Delrin was used in some of the wings to help with DIC measurements. Figure 3-13 arranges three photos, each covering the process. The same mill used previously sculpts the wing while the other photos give an example of a frame before and after the rod is adhered to the LE.

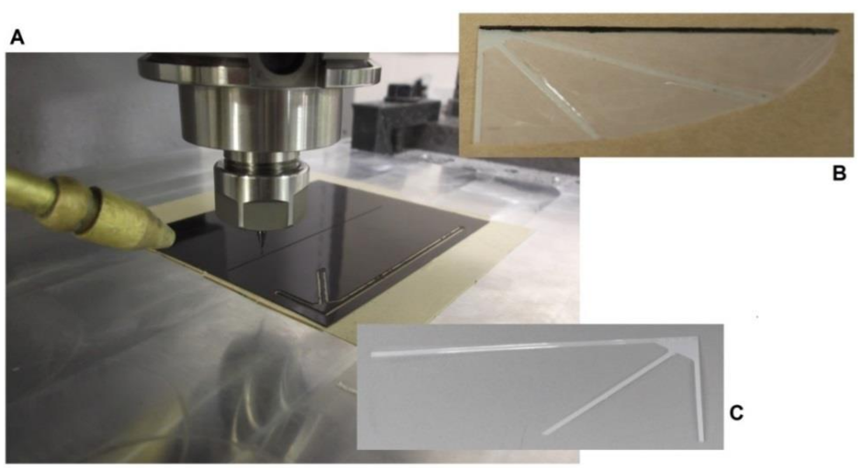


Figure 3-13. A figure with the steps of the process from milling to the plastic white frame to the finalized wing. A) The mill carves out the acetal resin. B) White Delrin frame with carbon fiber rod attached. Even though the rod is black, the black LE is mainly due to the rubber toughened CA. C) White Delrin frame. Picture A courtesy of Chris Tyler, graduate student of Dr. Tony Schmitz. Photo B-C courtesy of Jason Rue.

- Cost effective
- Dramatically less time to create wing
- LE has commercial repeatability
- Color allowed for better DIC measurements
- Less human error
- More consistent wing area

Issues

Almost all parts of this wing are machine controlled except for attaching the carbon fiber rod to the LE and the frame to the CAPRAN®. The amount of glue build up is difficult to control by hand and can lead to slight weight differences between wings. The manufacturing process also created a few residual stresses within the frame, leading to slight warping and a curvature to a fraction of the wings. Multiple problems arose when the CA would reach the end of its shelf life as it thickened and lost effectiveness. The existing problems are listed as follows.

- Fastening the rod to the LE
- Attaching the plastic frame to CAPRAN® as it comes off frequently
- Travel time between universities
- Residual stresses from manufacturing which cause slight warping
- CA bond and shelf life

Transfer Tape Technique

Adhering CAPRAN® to the plastic frame became problematic quite frequently during testing periods and work was done to find new techniques to attach the membrane with new adhesives and vacuum pressure or compression. By far, this seemed to be the most pressing issue with wing development. This led to more human interaction and repeated attempts to reglue the bond. Additional testing and curing time was also a small concern. A few options of acrylic or rubber based adhesives with high shear and initial tack that typically occupy the back of permanent stickers stood as the primary materials. The potential here was to virtually peel and stick the frame onto the

CAPRAN®, removing weight from excess glue and human error along with speeding the procedure. A solution was a 58 micron 3M High-strength double sided Acrylic Adhesive [46] typically used for plastic nameplates, graphic overlays, or attaching identification material to lightly oily surfaces. This removed the thin CA from production and while substituting a durable, long lasting, and time saving material.

Process Four

All initial steps were barrowed from the plastic frame process including the CNC milled frame and circular carbon fiber rod. A change occurred next as the frame needed to be adhered to the membrane. The frame was positioned onto the one inch wide transfer tape carefully to make sure the whole area made contact. Once settled in place, a piece of white computer paper (cut to size) sandwiched the frame with the tape backing. Pressure was applied along the edges of the frame with a finger until the tape could be peeled away completely from the backing. At this point, the frame could be loosened as well and pushed onto the CAPRAN®. The wing was pressed down to remove any gaps and was then cut out similarly to prior procedures. While a custom press applied the needed compression required for this step, vacuum pressure could also strengthen the bond and reduce voids, although was found to be lengthy and less effective. A few of the advantages are bulleted below.

- Two year shelf life
- Extremely smooth and consistent
- High initial adhesion
- No need for glue to dry

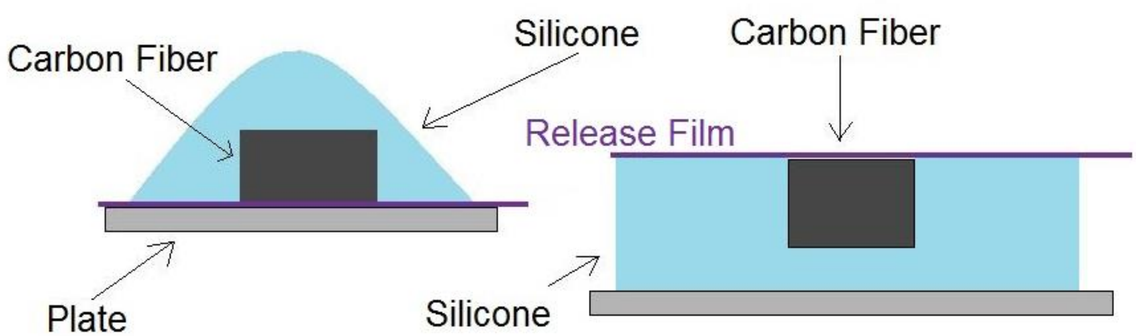
Issues

Even with being a sound material and procedure, a few issues still existed. Obviously the carbon fiber rod was still glued on with rubber toughened CA and the plastic frame had to be created at UNCC as well as the stresses in the frame. Opposed to the widely available thin CA, the 3M transfer tape cannot be purchased in small quantities. Lastly, the tape sticks immediately and has a strength that is not conducive to fixing an ill place frame. Attention was needed to appropriately position the frame to the CAPRAN®.

- Fastening the rod to the LE
- Travel time between universities
- Residual stresses from manufacturing which cause slight warping
- Sticks immediately and allows no play
- Not available in small quantities

Other Attempts

As previously described, a few manufacturing processes have been developed to help diminish scatter and spawn superior results, although, not every attempt worked. Before the Teflon® CNC milled molds were created, Dragon Skin® High Performance Silicone Rubber (http://www.smooth-on.com) was used as a surrounding to help keep the carbon fiber's cross sectional shape as pictured in Figure 3-14. This effort was unsuccessful since the silicone lacked the strength to hold the carbon fiber in place.



A B

Figure 3-14. Effort to use silicone rubber to keep the carbon fiber's cross sectional shape. A) After laid on a flat plate, the silicone rubber was poured on top of the carbon fiber. B) The silicone rubber was treated as a female mold.

Apart from changing the depth of the mold, different durometer silicone mats, specifically a super soft 10A and 20A with varying thicknesses, were used to apply pressure with the hope of varying the penetration and pressure distribution within the Teflon® mold channel. This would also exhibit failure and added more variables to validate. The softer material generally spread outward and into the groves as planned although was not solid enough to apply a high pressure. If the mats were clamped differently and not allowed to expand outward, it might have been possible to administer the correct level of pressure.

The LE thickness was shown to hold importance due to the increased moment of inertia. As a result, thicker plastic LEs were constructed but were identified as being too heavy. Most overloaded the controller and refused to run.

In the attempt to choose a new material for the frame, a few other routes were tested. The thought behind switching was mainly due to accuracy but also to decrease dramatically the manufacturing time. Isotropic materials such as aluminum, titanium, and ABS plastic, as well as a milled 0-90° bidirectional cured carbon fiber plate were machined. The wings were either too soft or not stiff enough for this application, although it led to the composite plastic/carbon fiber method currently adopted.

Each method had advantages, although many had a slew of shortcomings. The hand lay-up process became archaic and quickly fell behind in terms of reliability, although wings by this method could be erected in house with ease. The Teflon® mold worked well but struggled to deliver the needed precision. Delrin plastic frames with an inserted carbon fiber rod evolved into the best method to date.

CHAPTER 4
EVALUATION OF TECHNIQUES

Again, to touch on the goal of this paper, a past manufacturing approach was to be made repeatable and reliable so that small variations in thrust production between wings could be concluded as a definitive gain or loss. If the thrust measurements of a single design recorded in recurring attempts are too scattered, then optimization and further experiments would prove to be very difficult. This is based on the idea that a certain frame design should result in the same thrust production every time it is produced. Even though the flapping process is highly dynamic and controller driven, it is an assumption that constant thrust production is plausible. To determine how the manufacturing procedures related with respect to average thrust production, duplicate frames were created with each method described in Chapter 3 to ascertain whether the scatter in the data was reduced. The wing replicates (separate copies of the same nominally equal design) would then show if a tested result could be trusted. Ideally, every duplicate would yield the same result. As duplicates were produced, attention was also focused to identifying how weight differences propagated throughout the batch.

Two-Design Assessment

In this paper, two frame designs were fashioned with four manufacturing styles: a hand lay-up, a Teflon® mold sandwiched by aluminum plates, a CNC milled plastic frame, and a new membrane attachment method using transfer tape. Plain frame drawings, seen in Figure 4-1, describe both designs: one characterized as having parallel battens and one with a radial pattern. As mentioned in Chapter 2, a 75 mm x 25 mm wing was tested throughout this study. A group of patterns were chosen since they had been used in the past with success without major deformation, delamination issues, or inadequate thrust and these two were randomly taken from that selection.

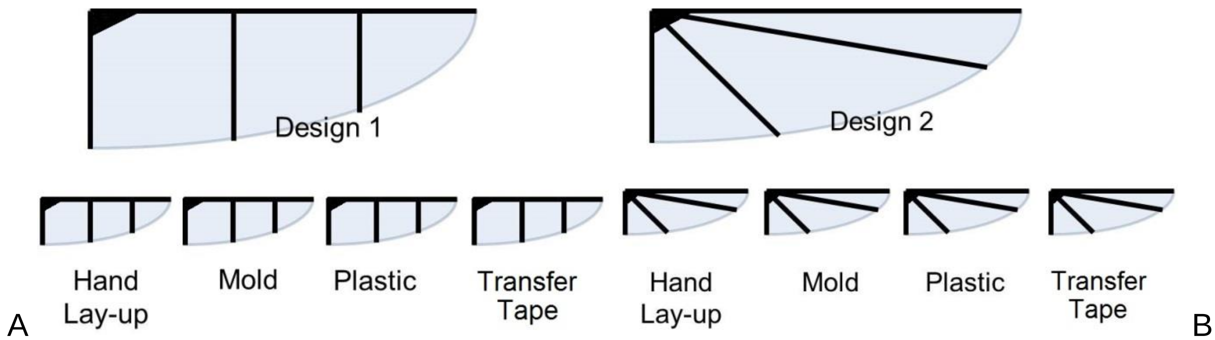


Figure 4-1. Shown are the two designs chosen for the validation process. Although created in the past, these were randomly chosen from a group of wings that had decent test results. A) Design 1, described as having parallel battens. B) Design 2, defined as radial battens.

To further understand the scope incorporated within this study and to visually show explanations regarding data collection, Figure 4-2 illustrates the hierarchy breakdown for *one* design and the total quantity associated to each level. For every manufacturing type, ten duplicates of a single design were assembled, leading to eighty pairs in total, with each comprising of ten trials.

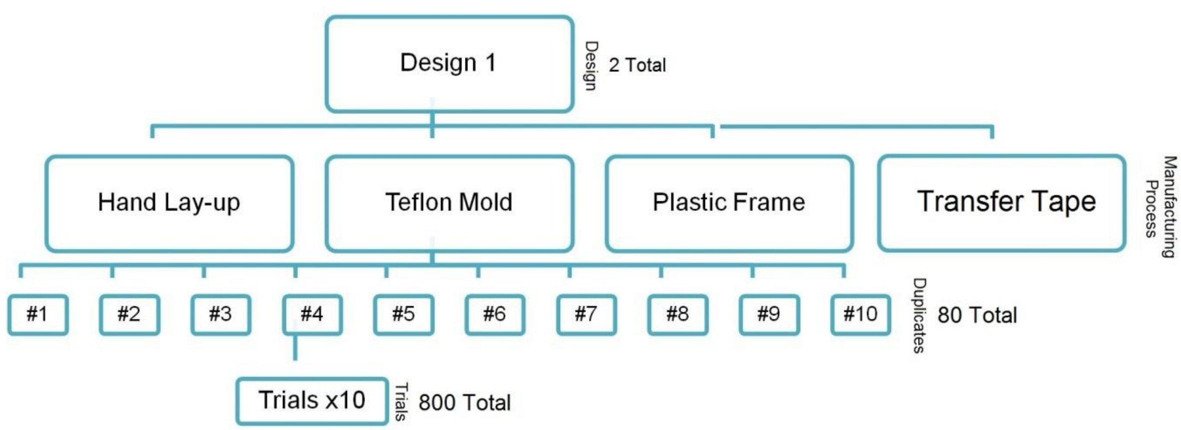
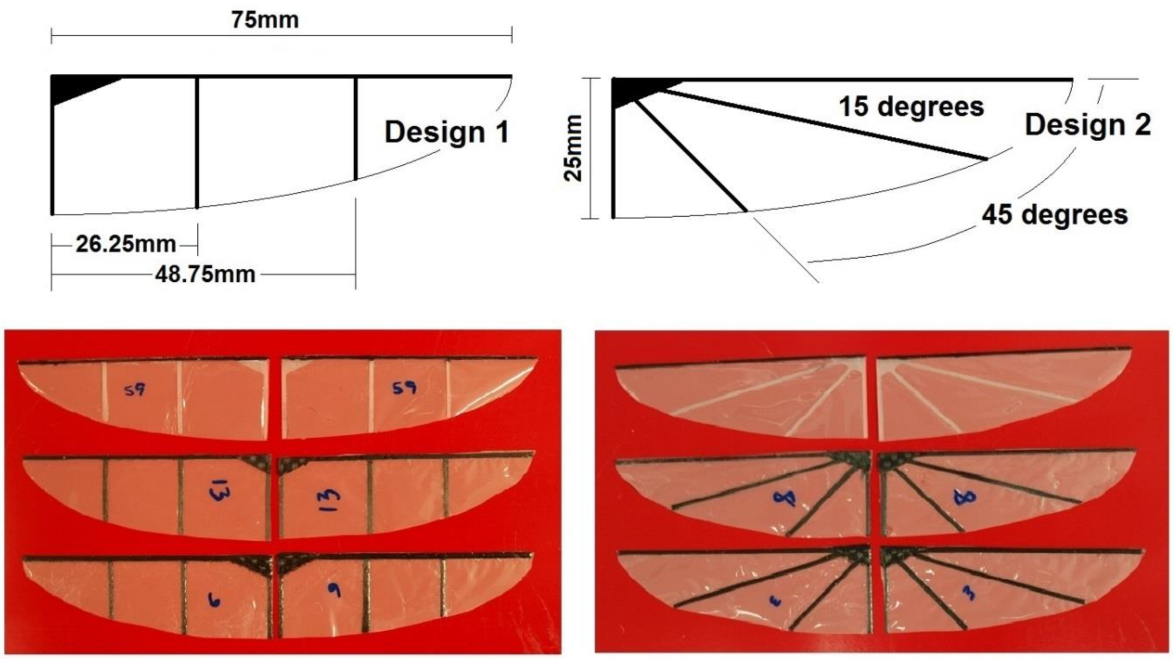


Figure 4-2. Hierarchy breakdown of the experiment explaining a total of 80 duplicates were constructed with 800 runs.

The specific dimensions for both designs are arranged in Figure 4-3 followed by samples from each manufacturing technique. Three layers of carbon fiber made up the

LE in both the hand lay-up and Teflon® mold versions while the same 0.5 mm (0.02 in) diameter carbon fiber rod was inserted onto the plastic frame. All other battens were a single layer of carbon fiber for wing support. Any thicker battens inside the wing would have generally made the wing heavier without adding structure stiffness.

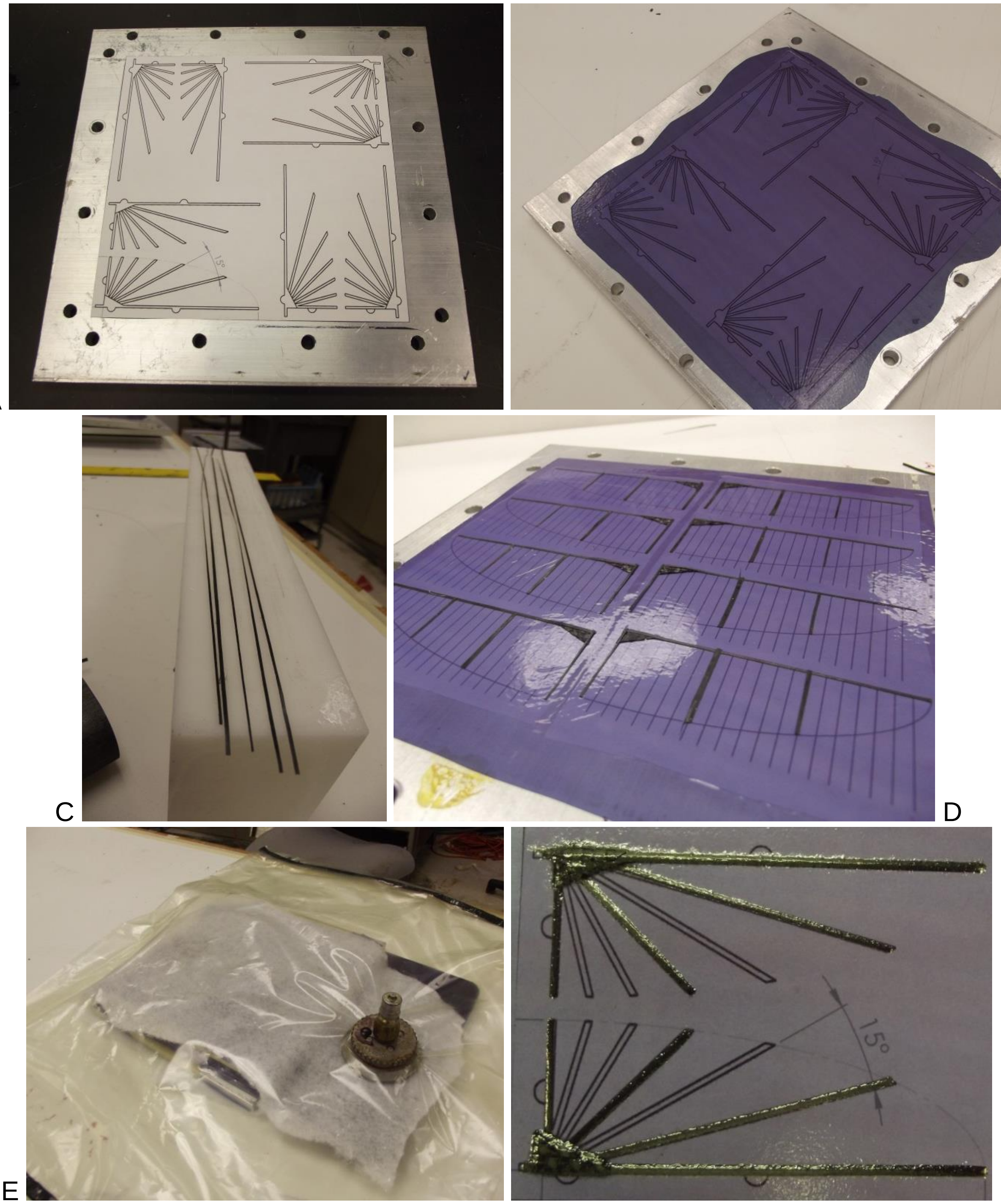


A B

Figure 4-3. Dimensions, layout, and various examples of the processes for the two design confirmation. For brevity, the transfer tape technique was excluded due to looking exactly like the plastic frame. A) Dimensions for Design 1 along with a look at examples of the three manufacturing systems. B) Measurements for Design 2 accompanied by a similar view of the three methods. Photos courtesy of Jason Rue.

Hand Lay-up Process

The hand lay-up process taken from past graduate studies at the University of Florida is pictured in Figure 4-4, where the radial design was printed, glued to a flat plate, and coated with release film. This marks the beginning step within the process and continues to include cutting the carbon fiber, placing it on a flat plate, and vacuum bagging the end product.



A B C D E F

Figure 4-4. A look at the flat plate and hand lay-up procedure. A) A flat plate with Design 2 printed on paper and glued to the surface. B) The pattern with release film on top. C) Hand-cut prepreg carbon/epoxy strips. D) Parallel batten wings laid-up before curing cycle. E) Flat plate placed into a vacuum bag. F) Radial batten wings post cure before they are removed from the flat plate. Photos courtesy of Jason Rue.

Next, the carbon fiber was cut by hand with a single blade, laid out with great detail, and cured under pressure in a vacuum bag during a heating cycle. Once the oven cycle completed, the frames were carefully removed from the aluminum flat plate (Figure 4-5) and glued to CAPRAN®. The problem of unreliable strip width remains and serves as a reinforcement of the need for superior methods.

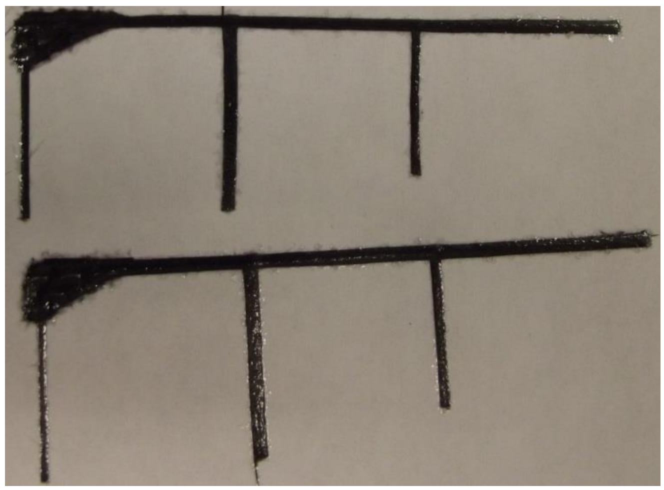


Figure 4-5. A close up of Design 1 post cure. Photo courtesy of Jason Rue.

To stay constant with this execution, the outline of the wing was cut with scissors however no guide kept the area absolute.

Teflon® Mold Method

Two Teflon® molds were carefully crafted for this study and included dimensioning from Figure 4-3. The carbon fiber strips were now carved out with the custom multi-bladed strip cutter. Figure 4-6 displays a picture of the Teflon® mold procedure that includes the mold, the carbon fiber once they are meticulously placed in position, the clamped sandwich structure, the post cured wings, and one example where that was removed and prepared for the CAPRAN®.

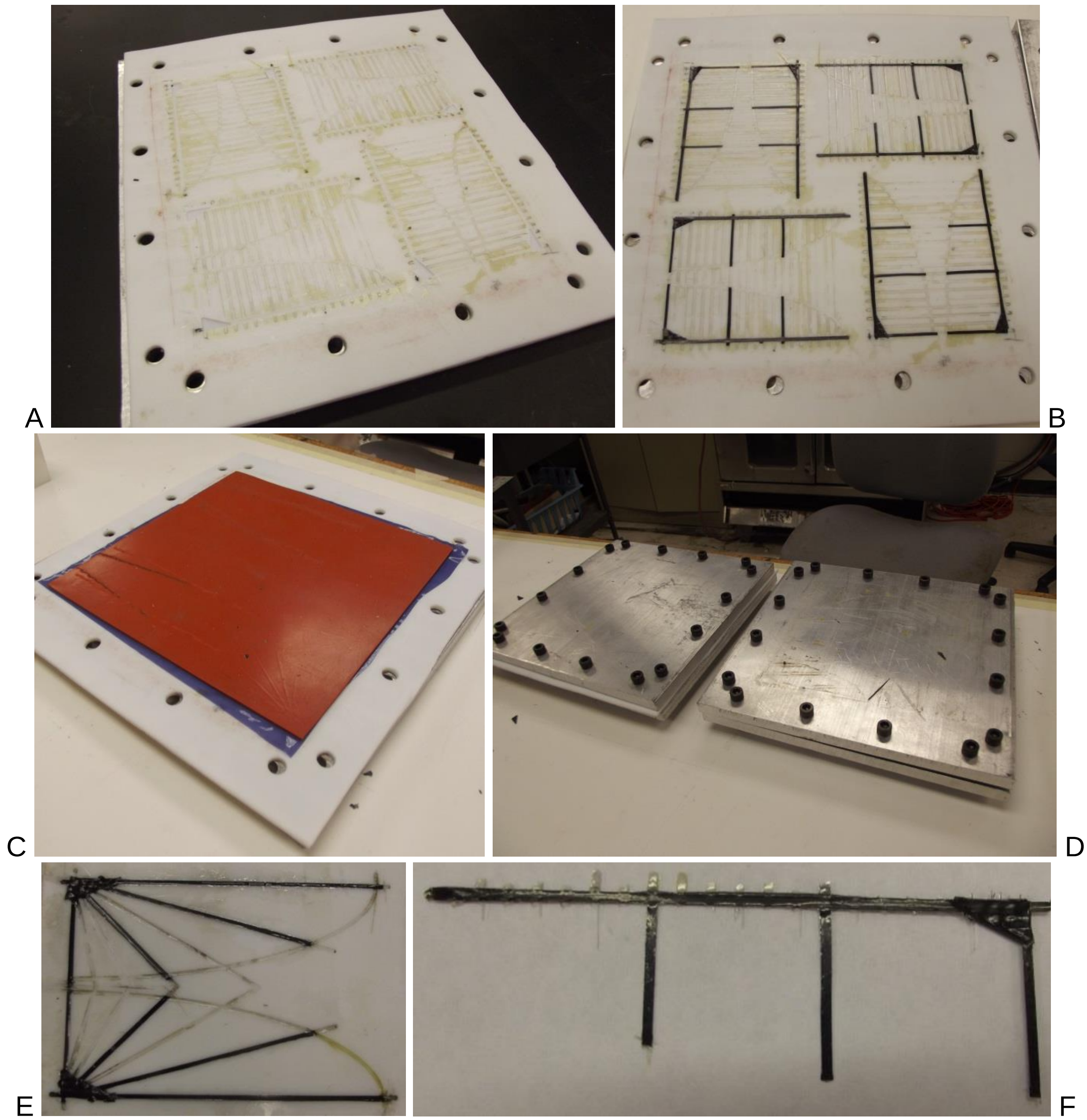


Figure 4-6. A glance at the Teflon® mold process. A) Design 1 mold. B) The pre-cured Design 1 Teflon® mold. C) Mold with the silicone mat and release film placed on top. D) Two molds clamped and ready for the oven. E) View of the Teflon® mold wings after the curing process (Design 2). F) Design 1 post-cure out of the mold. Photos courtesy of Jason Rue.

Even with the author having practice in making hundreds of wings with the hand lay-up method and a keen eye, the mold delivers a more repeatable product every time.

Plastic Frame

Delrin plastic frames were milled with precision at a constant thickness. After the frames were received, the commercial rod was added to the LE with rubber toughened CA. That combination was then put on CAPRAN® that had been printed on previously with outlines. Figure 4-7 depicts the milled frame and final product against a red background so that details of the white plastic can be seen easily.

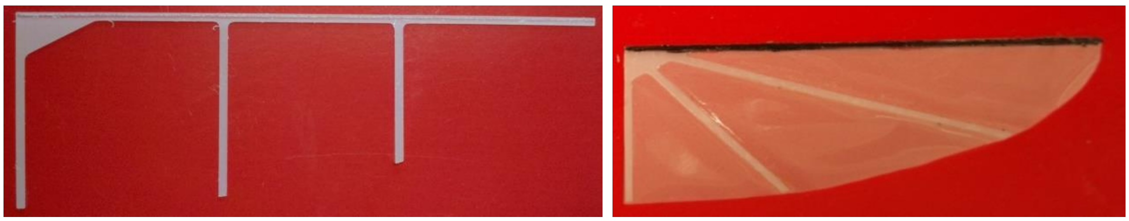
A  B

Figure 4-7. Plastic frame with the LE carbon fiber rod attached. A) White CNC milled Delrin plastic frame. B) Final wing with the carbon fiber rod glued to the LE and the frame to CAPRAN®. Photos courtesy of Jason Rue.

Transfer Tape Technique

The time saving technique solved a problem that had plagued some wings throughout testing. During the flapping experiments with wings where the transfer tape was utilized, not a single wing developed delamination. This point all but neglected human interaction during the trial testing. The tape thickness also was far more consistent than the layers of thin CA applied to the frame. Figure 4-8 lays out the steps taken to adhere the 3M transfer tape to the plastic frame.

A few supplies were examined as potential materials for the step in Figure 4-8E including vacuum bag plastic and paper. Paper was chosen for its cost, reliability, and ease to use. Figure 4-8F portrays the wing once the backing was removed. Once the frame is carefully peeled off, the plastic remains with a consistent layer of adhesive and can be pressed down onto the CAPRAN®.

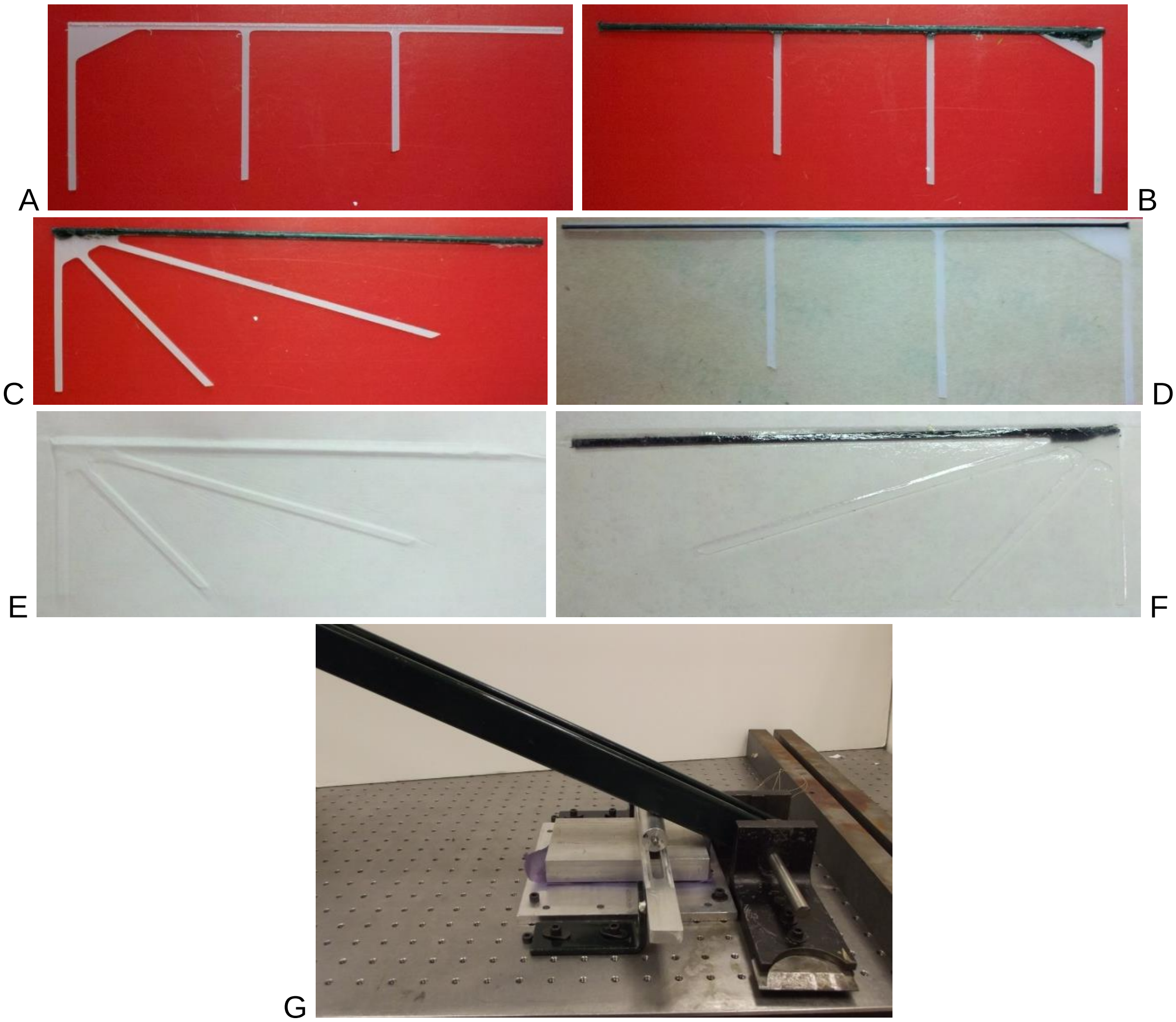


Figure 4-8. Steps involved with applying the transfer tape. A) The same plastic CNC milled frame used in the previous step. B) The plastic frame with a carbon fiber rod attached with rubber toughened CA. C) An example of the radial design. D) The frame is placed onto the one inch wide transfer tape. E) A piece of white computer paper sandwiches the frame with the tape backing. F) The backing is removed to display the frame with a complete layer of transfer tape attached. G) Custom jig designed to apply high pressure to the frame/CAPRAN® and to remove air gaps between the two. Photos courtesy of Jason Rue.

Results

After all the manufacturing processes, eighty pairs of wings were ready for testing. Individual wings were weighted on a Gemini-20 Portable Milligram Scale and then mounted on the flapping mechanism, going through ten consecutive trials. Each trial consisted of the flapping frequencies of 20, 25, and 30 Hz. The average thrust production in each of the ten trials was then combined to give a single measured value linked to that particular wing pair. Below explains the comparisons between the eight (two designs, four manufacturing methods) categories in areas of interest (*weight* and *thrust production*). The trends show an ideal situation for both variables as they decrease in variation and validate the work accomplished to update manufacturing.

A few parameters were graphed in the evaluation including histograms of the actual values and the coefficient of variation, which is defined as followed.

$$Coefficient\ of\ Variation, CV \equiv \frac{Standard\ Deviation}{Average}$$

Histogram bins were arbitrary chosen to split the minimum and maximum into ten equal groups while the CV was sought after to normalize the data and compensate for a changing mean. As seen in the comparisons, the designs finished with similar trends although very different paths. This leads to the conclusion that many of the measurements could be design specific.

Weight Comparison

Eighty wing pairs completed for this test were broken into the respective groups, either by design or process. For the weight assessment, the 160 individual wings were weighed and tabulated. For each of the eight groups, the coefficient of variation was calculated (Figure 4-9).

As the production methods developed, the values dropped and added confidence that the more refined wings were more consistent. First off, the radial batten design CV dropped by ~20% or more for each process, for a total of 60.7%. The parallel batten wings had a similar reduction, but totaled 88%.

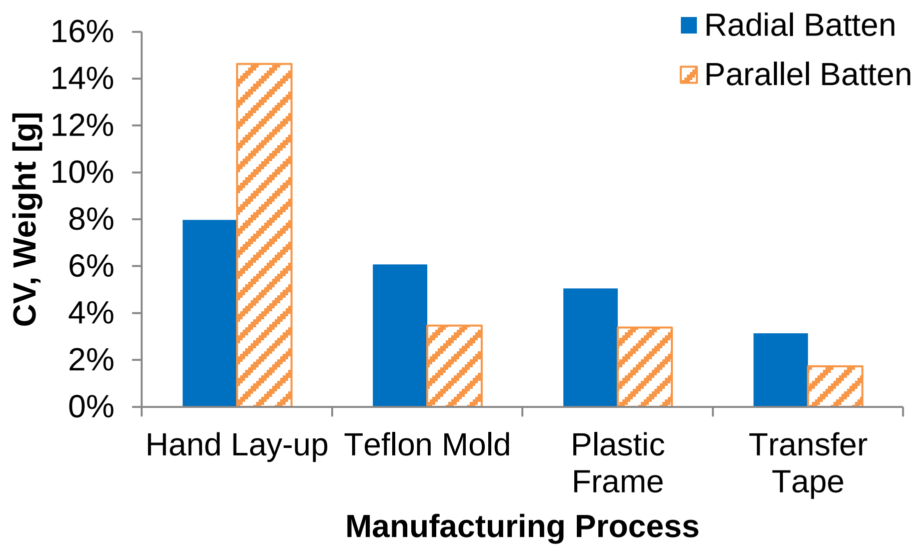


Figure 4-9. For the ten pairs (20 total) of wings in each category, this illustrates the CV of the weight in grams. Each method improves this measure, making the duplicate wings much more consistent.

As a look at the actual weight distribution, eight combined histograms are located below with the same horizontal axis. The weight bins range from 0.126 g to 0.199 g. Figure 4-10, encompassing the four radial batten types, shows how they became more reliable and less scattered while Figure 4-11 clarifies the four parallel batten types. These reflect how the weight gathered around an average and how the scatter was reduced with each additional approach.

The hand lay-up method had a much more spread out data set, especially with the parallel batten wings. This endorses the work to better the initial manufacturing procedure and states that this method is less desirable for optimization.

The Teflon® mold reduced the number of bins associated to the distribution as expected with consistent wings. Although somewhat repeatable, characterized by these variables, there still exists a necessity for the plastic milled frames. For both designs, the plastic frames, attached by CA or transfer tape, were in reduced clusters and a closer averaged value.

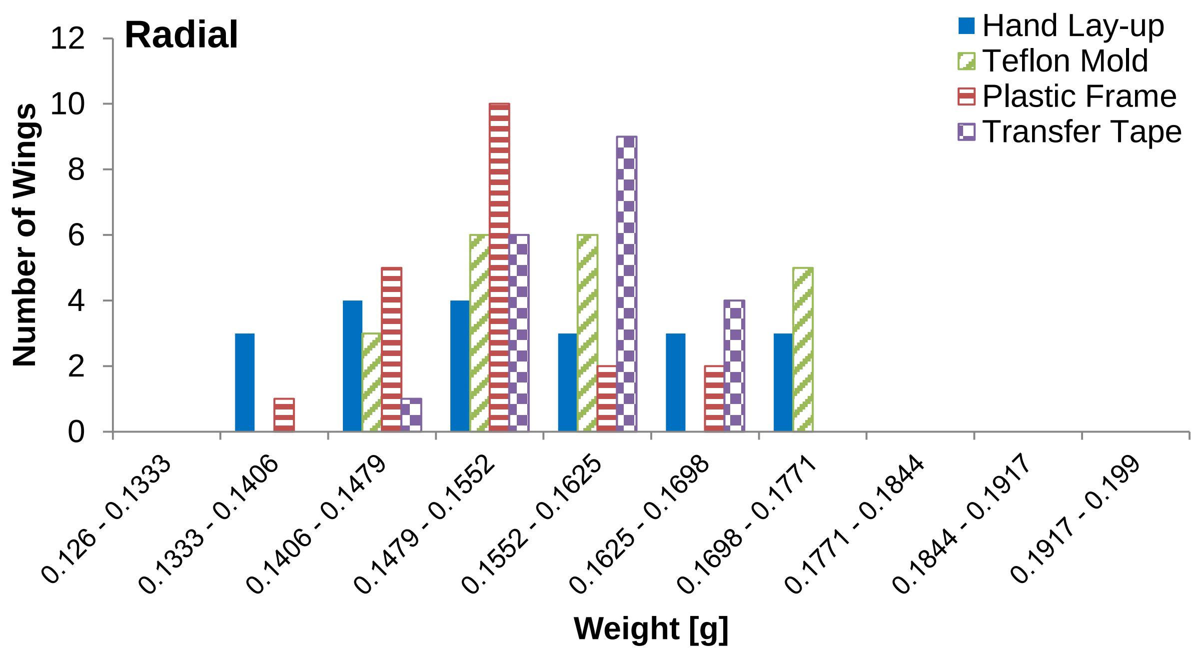


Figure 4-10. Histogram showing a drop in weight variation due to the enhanced processes for the radial batten wings.

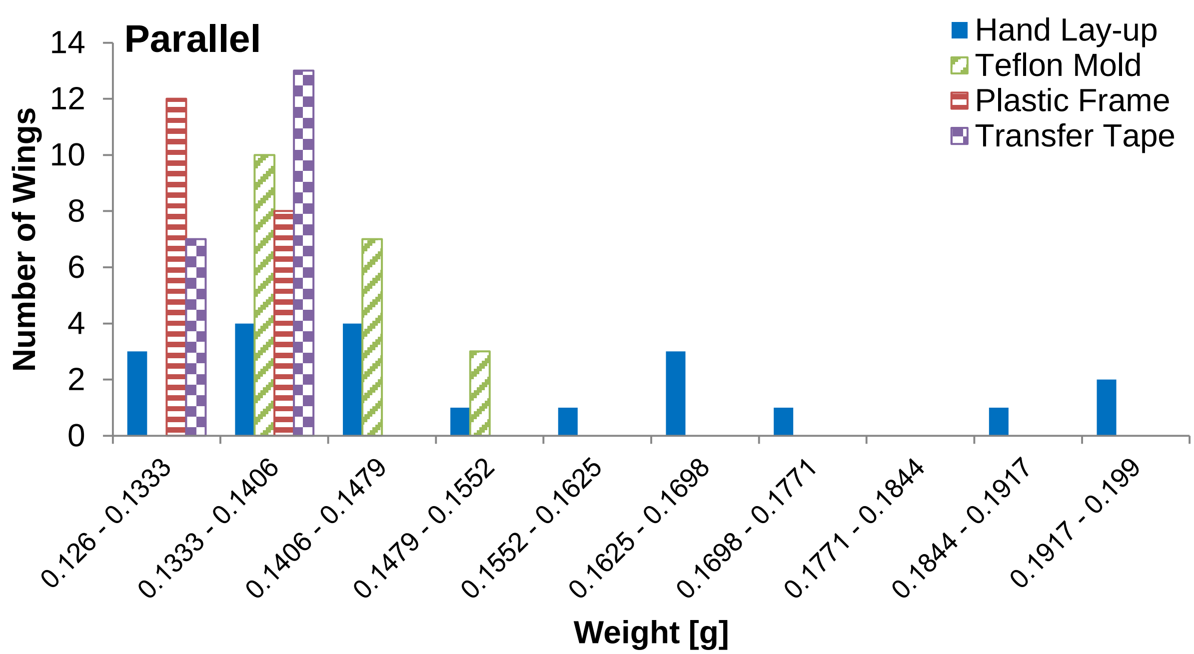


Figure 4-11. Histogram showing a drop in weight variation due to the enhanced processes for the parallel batten wings.

The average weight, in grams, for the eight types of wings is in Table 4-1. The plastic frame wings were found to be roughly 4% lighter for the radial batten style than the carbon fiber frame alternatives although increased again when the transfer tape was used. Here, the reduction in CV was enough to offset the slight gain in weight for the fourth procedure. For the parallel batten wings, an improvement of approximately 7% and 14% was found from the Teflon® mold and hand lay-up methods respectfully. In a similar trend as the radial batten wings, the weight increased marginally with the transfer tape.

Table 4-1. Average weight of the 160 individual wings.

Manufacturing Process	Radial Batten	Parallel Batten
Hand Lay-up	0.155	0.153
Teflon® Mold	0.158	0.142
Plastic Frame	0.150	0.132
Transfer Tape	0.157	0.135

With continuous reductions in weight, the wings created by the multiple manufacturing methods become more efficient, taken that similar thrust values are measured. The large changes in standard deviation demonstrated the need for the new approaches.

Average Thrust Comparison

This section expands upon the main reason behind this paper. The experiments of prior UF graduate students using carbon fiber and a hand lay-up have been shown to be problematic, especially with dependability. Average thrust production was measured for each pair of wings, and, much like the weight, the CV was examined as well. The thrust data in this section was measured at 30 Hz. Throughout many of the studies, the 30 Hz mark was focused on to fit within the constraints of the flapping mechanism and to produce a level of thrust that could counteract the weight of a standalone hovering device. The duplicate wing CV values are obtained in Figure 4-12, where a 43%, 56%, and 24% reduction occurred for the radial batten manufacturing progresses. The parallel batten wings saw a 46% and 76% dip for each of the initial two steps. The transfer tape process added an unfavorable 9% at that step from 2.52% to 2.74%. Since the testing was done with a finite population of ten wings, the loss was taken as negligible and the values treated as equivalent.

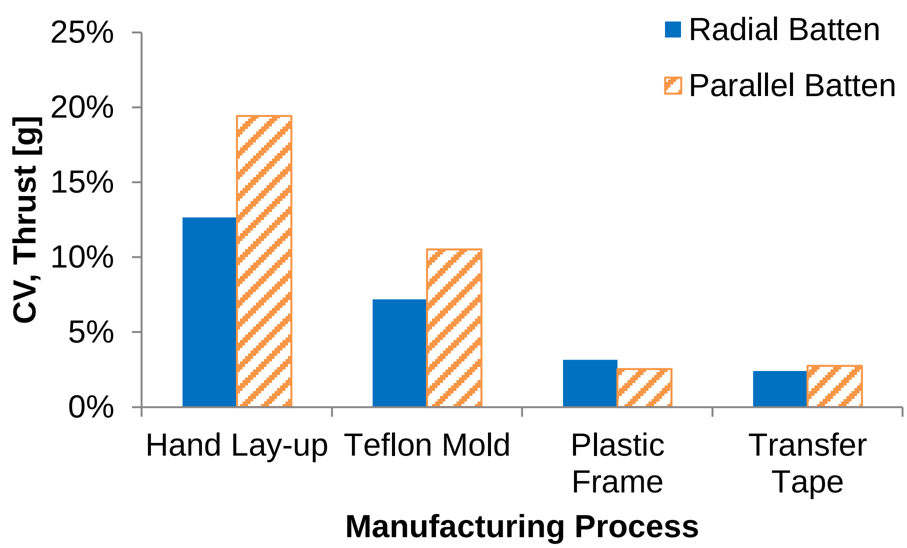


Figure 4-12. For the ten wings in each category, this illustrates the CV of thrust in grams. For each batten structure, the upgraded manufacturing technique lowers this statistic, allowing for more reliability.

Altogether, the radial batten wings saw a decline in CV of 81.1% from the hand lay-up to the plastic frames adhered with transfer tape. In being even more pronounced, the parallel batten ones noticed a staggering 86% drop.

Small variations from wing to wing could not be regularly differentiated with the hand lay-up process. If the plastic frames are considered in the future, significantly more assurance would be held that, based on thrust production, one wing design was superior or inferior over another.

An effort was made to try and quantify the uncertainty throughout the process based on thrust production from flapping wings while being in hover mode. A concurrent study of 67 designs with the plastic wing frames was conducted to determine how the uncertainty would split between the manufacturing variability and testing errors. Uncertainty brought by manufacturing was mostly due to machine tolerance and human error while the testing uncertainty was present from sensor and testing conditions. Multiple wings with geometrically nominal designs were compared to extract manufacturing uncertainty while the testing uncertainty was quantified by looking at repeated trials. By using surrogates and an optimization algorithm called Efficient Global Optimization, Anirban Chaudhuri, graduate student of Dr. Raphael Haftka, was able to use 33 designs for a final analysis. His work was described in [47] and concluded a conservative testing uncertainty of 3.55% along with a conservative manufacturing uncertainty of 3.15%. Since ten trials of a wing are customary, the testing uncertainty is reduced to 1.12%. The *total* uncertainty was calculated to be 3.34%, a number acceptable to start any further optimization as it was lower than an initial 5% goal. This value is slightly higher than the 2.4% or 2.7% given in the last part of Figure 4-12 due to having a limited number of samples for the calculation and being conservative in nature. Even though there is a slight discrepancy, there is a strong belief that the testing uncertainty is much lower than the manufacturing error. Through the optimization, Chaudhuri was able to increase the maximum thrust output within the study by 7% to 11.9 g at 30 Hz. This value exceeds the error and can be trusted as a true improvement.

Aside from the differences in CV, the scatter of actual thrust values is described within the eight gathered histograms below (four radial and four parallel). The thrust bins extend from 3.85 g to 8.01 g and was gathered at 30 Hz.

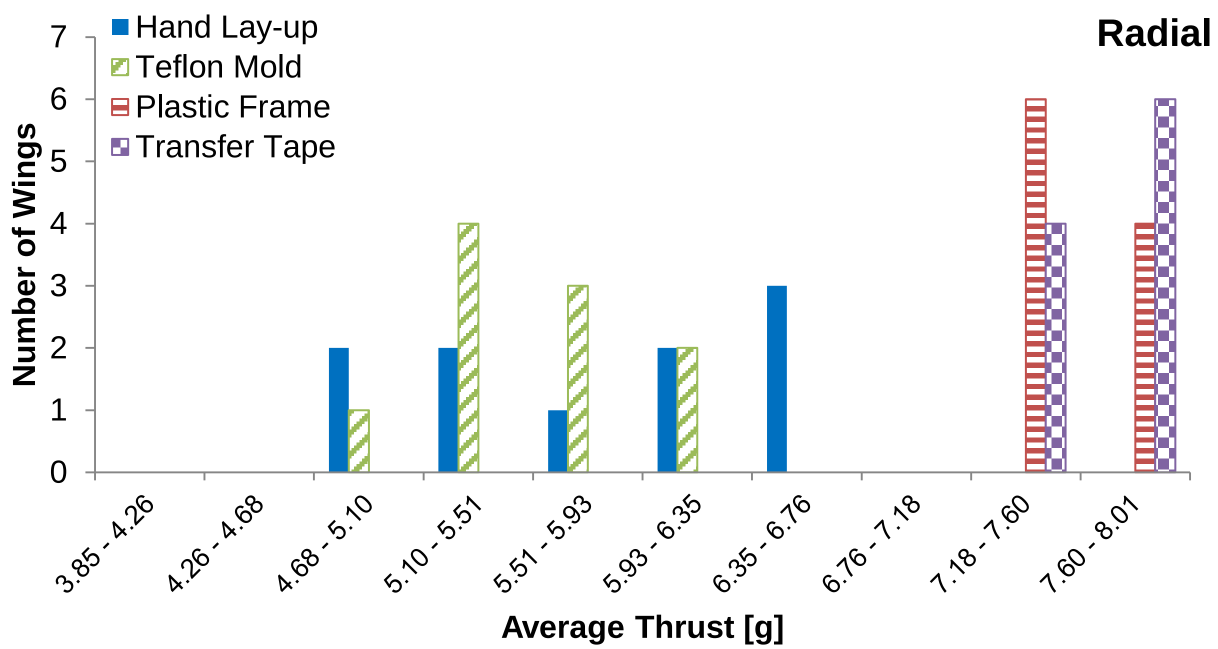


Figure 4-13. Histogram showing the drop in thrust variation due to the enhanced processes. The increase in thrust for the plastic frames is quite visible here as the plastic frame/transfer tape bars are dramatically shifted to the right.

Even though two designs were investigated, the aforementioned range is considerably larger than a tolerable breadth. Much like the case of weight, the thrust values see a substantial range for the hand lay-up procedure. This does not lend itself well to optimization where an average thrust value must be trusted. The Teflon® mold helped, again, in the two design cases by contracting and centralizing the values.

The red (plastic frame) and purple (transfer tape) color outlines an even further subtraction, being in only 2-3 bins. Ultimately, these amounts should be as close as possible to instill faith in the thrust production. For all four categories, the radial batten wings seem to be confined to fewer bins. It may be the case that the topology is suited to flap in this range and is more stable than the parallel batten wings. Since the parallel batten wings embodied a parallel trend in the weight description, a possibility persists that the frame geometry could be correlated to the performance.

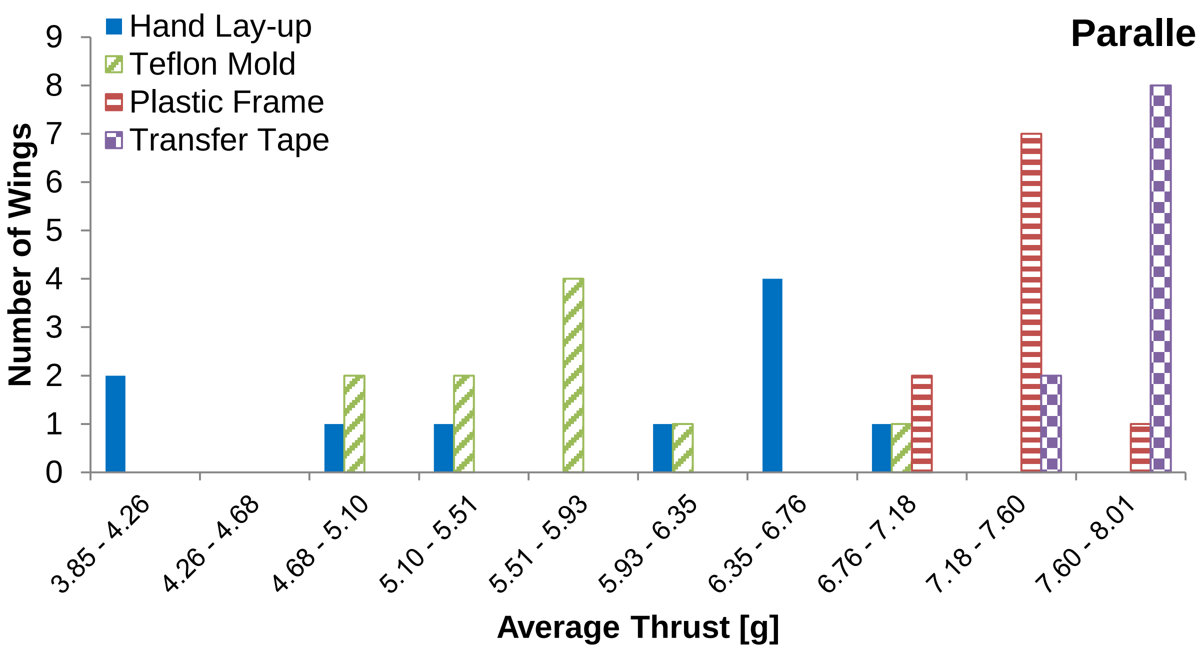


Figure 4-14. For the parallel batten wings, the thrust production for the hand lay-up wings is rather scattered and pulls together with the Teflon® mold. The plastic wings decrease in the number of bins and shift to the right.

For a view of the larger picture, Figure 4-15 and Figure 4-16 break up the data into the two design sets. The graphs give all eighty wings and the results of the thrust measurements for frequencies of 20, 25, and 30 Hz. Based on the four colors and the stages shown in A through D, the thrust advantage and diminished variations are clear. Each step distinctly illustrates a reduction in scatter of the ten wings given on each graph. Visually, the comparison of the hand lay-up versus the transfer tape is undeniably profound. These figures create the purpose of this experiment by themselves and speak the importance of manufacturing procedures. Stage E in both figures combines the averages from each into an overall assessment where it can be seen clearly that the plastic frame and transfer tape wings produce higher thrust than the previous two.

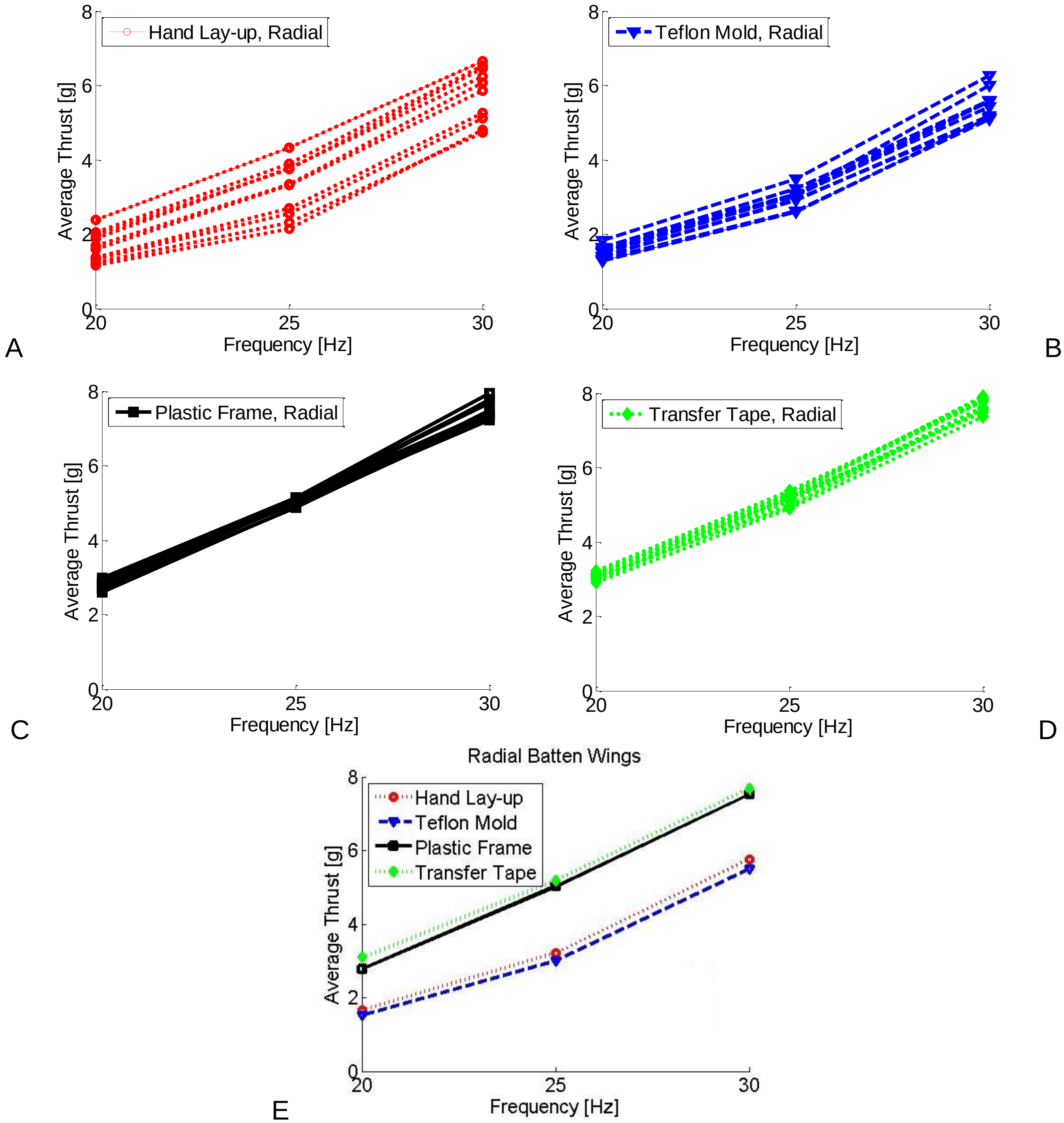


Figure 4-15. Graph of the 40 Radial Batten wings presenting how the variation decreases with each new method. A) Hand Lay-up. B) Teflon® Mold. C) Plastic Frame. D) Transfer Tape. E) A single averaged line for each method plotted together.

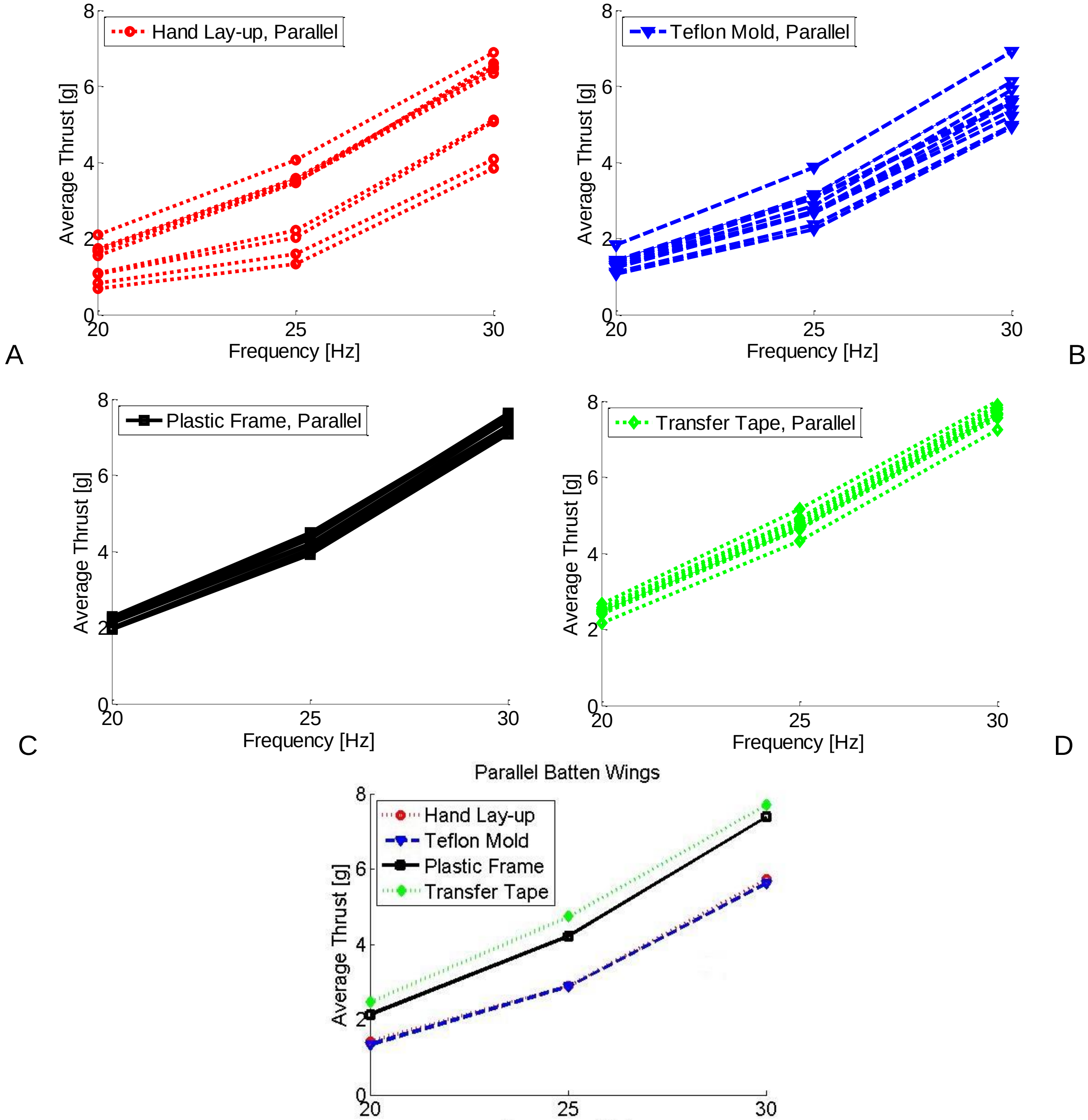


Figure 4-16. Graph of the 40 Parallel Batten wings presenting how the variation shrunk with each new method. A) Hand Lay-up. B) Teflon® Mold. C) Plastic Frame. D) Transfer Tape. E) A single averaged line for each method plotted together.

In terms of thrust force, the plastic frames produced more than the carbon fiber counterparts without question. On average, the radial batten wings gaining roughly 35% while the parallel batten achieved 33%. Exact values are found in Table 4-2. A reason for the increase could be simply that the LE became stiffer with the use of the rod. This is understandable although is a significant achievement since the overall weight lessened as well for the parallel batten. Although this was not an original goal, the successful outcome bred a stronger and more efficient wing.

Table 4-2. Average thrust values at 30 Hz, given in grams, for each of the eight wing groups.

Manufacturing Process	Radial Batten	Parallel Batten
Hand Lay-up	5.77	5.73
Teflon Mold	5.49	5.62
Plastic Frame	7.52	7.37
Transfer Tape	7.68	7.69

A further look into the individual trial CV calculations (different from above) for each of the eighty pairs of wings for 20 Hz, 25 Hz, and 30 Hz proved interesting. These eighty values were formed from the ten trials that each pair was comprised and grouped by manufacturing. For simplicity, the data was averaged in each group and can be seen in Table 4-3. Generally, the CV would decrease as the frequency increased and for each additional manufacturing advance. For the radial design at 30 Hz, the averages held fairly constant between 1.9% and 2.4%. Similarly, the parallel design was around 2.3% for the first two and then dropped to roughly 1.5%. This could be due to the geometry topology differences.

Table 4-3. Average trial thrust CV measurement for all eighty pairs.

Manufacturing Process	20 Hz Ave	25 Hz Ave	30 Hz Ave
Radial			
Hand Lay-up	6.020%	3.047%	1.945%
Teflon® Mold	4.762%	3.347%	2.490%
Plastic Frame	2.793%	2.146%	2.420%
Transfer Tape	1.929%	1.677%	1.960%
Parallel			
Hand Lay-up	7.446%	5.862%	2.332%
Teflon® Mold	6.013%	4.338%	2.351%
Plastic Frame	3.886%	2.484%	1.675%
Transfer Tape	2.959%	1.867%	1.381%

To take a look at the standard deviation data and make sure that the CV values were not skewed due to higher means in the later processes, Table 4-4 shows a decrease for each manufacturing technique. The slight increase for the parallel batten wings put together with transfer tape is rather miniscule and, overall, the procedures acted the way they were intended.

Table 4-4. Standard deviation data for the thrust measurements at 30 Hz.

Manufacturing Process	Radial Batten	Parallel Batten
Hand Lay-up	0.730	1.113
Teflon® Mold	0.395	0.591
Plastic Frame	0.237	0.186
Transfer Tape	0.184	0.211

Conclusions

Over the life of this entire study, the central objective was to acknowledge existing problems with manufacturing or experiment techniques and to provide viable solutions. For additional work and optimization to proceed, stronger confidence was needed in the average thrust production produced by a certain wing design. A check for repeatability was developed, including testing duplicate wings and focusing on how the quantities differed. An element discovered was the fact that several of the quantities seemed to be design specific. This could speak to the precision of the mill, the accumulated errors from data collection, human inaccuracies when materials are glued, or possibly the idea that the geometric configuration does not just play a role in overall stiffness but in performance. The topology of the frame could control how the wing billows under aerodynamic forces, affect how quickly the wing returns to a neutral plane after deformation, and the chordwise twist, an outcome which McIntire found to adjust the thrust production.

After completion, the milled plastic frames proved to deliver less scatter than the other options in both categories of weight and average thrust output. These also contributed a possibility for wings with lower weight, higher thrust, and considerably more reliability. The scatter in the weight and average thrust were convincingly bolstered, adding to the validity and necessity for such a study. The new techniques have brought about an appropriate conversation as to whether the construction of flapping wings, and albeit all small to medium sized carbon fiber *hand* lay-ups, are highly repeatable without extreme attention to detail. The information delivered by this paper offers a discovery to help scholars conceive of innovative manufacturing and hopefully will lead to a better route to the understanding of how different features of a wing link to flight.

CHAPTER 5
REVIEW AND FUTURE WORK

As flapping wing technology expands and the advantages are further defined from other propulsion options, more work will be encouraged by the scientific community. In hopes that this paper will generate enthusiasm and build upon the push to understand the physics behind flapping flight, a few major conclusions were established.

- The main goal of this paper was to produce a high fidelity procedure so that synthetic wings could be tested and minuscule variations in thrust production could be decidedly measured as a gain or a loss over another wing. Great strides were taken toward this goal incorporating a flapping mechanism and a manufacturing technique.
- Data collection has been enhanced locally within the lab by coding LabVIEW and MATLAB® correctly to heighten efficiency and productivity. This became pivotal when mass testing was required.
- Monitoring the weight of 160 artificial wings built by separate means demonstrated the erraticism in hand constructed frames. The plastic manufacturing stages accrued nearly 75% less scatter and an average weight savings of 5%.
- Extensive thrust comparisons promoted the importance of this paper when attempting to compare wings. The CV in thrust (at 30 Hz) for the two designs was reduced by over 80% by adjusting how the wings were prepared.
- This method can be adopted by other researchers to help contribute to more reliability and credit to final data. Variability in typical hand lay-up methods have been proven larger and more uncontrollable than originally thought. This paper should at least bring attention to the fact that inconsistencies exist in manufacturing techniques used for flapping wing experiments and provide a viable solution.

Future work entails a continuation to learn the physics behind flapping flight and how certain characteristics can be related to thrust production. Since small flapping wing analysis can be cumbersome and inefficient if lengthy trials of flapping are inevitable before any data is scrutinized, charts or a series of curves could be formulated from experiments to associate relationships and predict thrust production. This particular point is well conceived in Figure 4-2, as for just two designs and four manufacturing techniques, 800 trials were needed. These relationships should be comparing thrust production with certain non-flapping tests. As an example, if a relationship of predetermined curves that correlate wing properties, such as structural stiffness or specific mode shapes, to the average thrust output is organized, the process becomes much simpler for evaluation and leads to an effective intuition. With this method, implementing a simple test could then yield an average thrust value without having to run a more intensive experiment. Also, if a certain thrust should be necessary, the curves would allow for one to realize wing properties before manufacturing occurs.

Given the full range of deformation and frequencies that the wings are exposed to, the natural frequencies and mode shapes could be examined to recognize how the wing's dynamics are correlated to flapping. Presently, vibrational analysis has begun with a Laser Doppler Vibrometer (LDV) to take non-contact measurements. The Polytec scanning vibrometer includes a PSV-I-400 scanning head, a PSV-400 junction box, and a OFV-500 controller module. The wings attached via screws to a Low Dynamic Stiffness (LDS) V201 permanent magnet shaker that sweeps from 1 to 500 Hz. Software analyzes the wing and displays a fast Fourier transform (FFT) with peaks at natural frequencies and an animation of the shapes. Knowing the link of these to thrust production may contribute to how wings are engineered in the future.

Considering there exists a relationship associating stiffness to thrust production, static DIC measurements have started to try and relate deflection to average thrust production. Here, the wings are speckled with black enamel paint and Kevlar string at the tips (Figure 5-1). After a load is applied, two Point Grey Research Flea2 cameras capture photos through Correlated Solution's VIC 2010 software and are processed in VIC-3D to calculate the deflection. Figure 5-1A shows a picture of a wing with the glued on Kevlar strings. Currently, six different measurements are taken including three from the LE string and three from the root string. The three data collections differed by adding various weights (0.3 g, 0.5 g, and 1 g) to the string and photographing the deflection like what can be seen in Figure 5-1B.

One ongoing study called to optimize wings in a three dimensional space, having three variables containing: aspect ratio (AR), an angle (taken from the LE) for the single batten (root batten always there), and percentage that the carbon fiber rod extends down the LE. These variables were chosen exercising the intuition from prior experiments because they correlated strongly to thrust production. Figure 5-2 places the six ARs that were tested (only six for simplicity) plus examples of the other two variables.

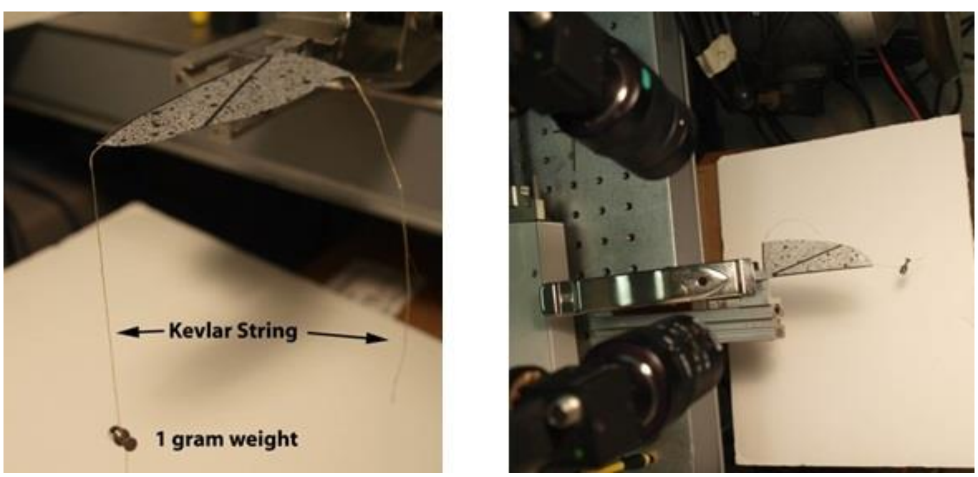
A  B

Figure 5-1. Static deflection DIC. A) Mounted wing with weights hanging from Kevlar string. B) Camera set up for DIC. Photos courtesy of Jason Rue.

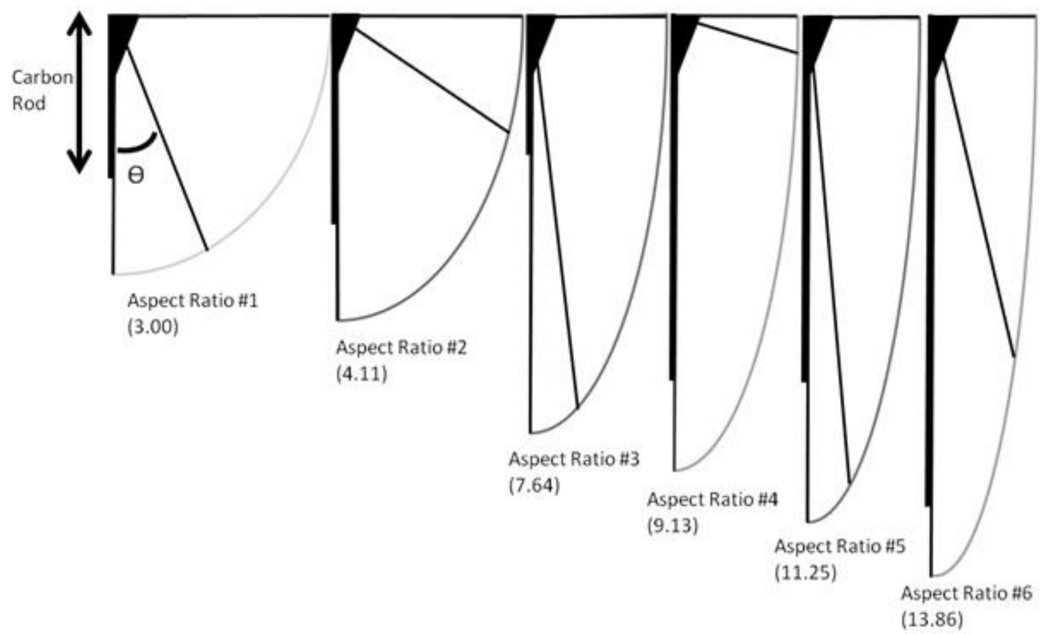


Figure 5-2. Three dimensional space optimization.

Seeding a three dimensional volume with near equally spaced designs, wings were flapped and recorded. Figure 5-3 graphs the elongation percentage of the rod along the LE versus the deflection of the wing tip.

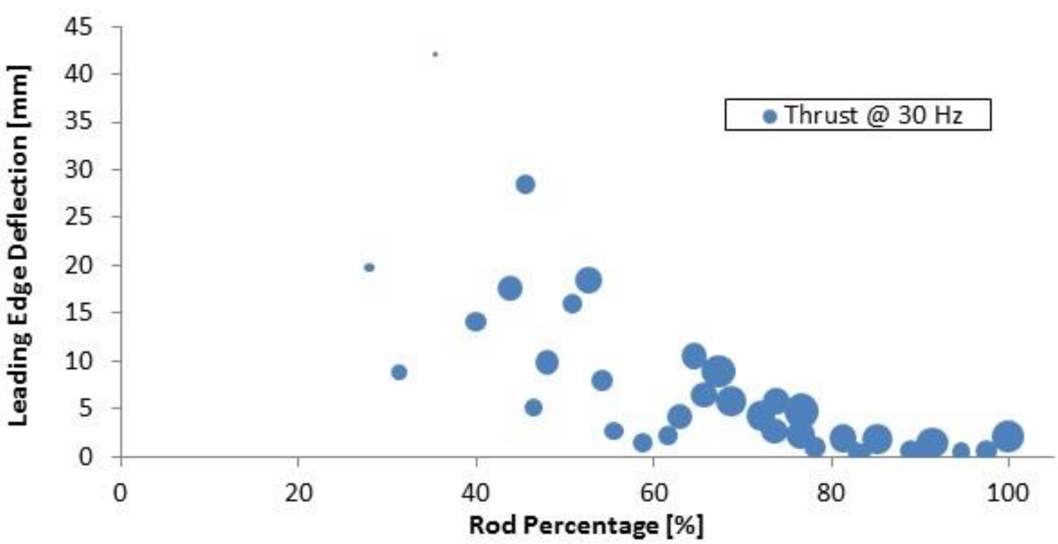


Figure 5-3. A bubble plot presenting static deflection results with a 0.5 gram load obtained for different carbon rod percentages that occupy the plastic LE. The size of the bubbles specifies the amount of thrust obtained for the wings.

The general exponential curve follows expectation, indicating little deflection with wings that have a rod close to 100% of the LE. An interesting behavior of these bubbles is how a few have drifted to the left. This possibly suggests that the single batten has reinforced the LE or the smaller ARs behave stiffer. A real benefit may come from this research trying to correlate certain variables to thrust. Then the space can be expanded to larger ARs and more batten arrangements.

A Nano17 Titanium sensor was newly purchased to help increase resolution of the readings although, due to low overload on the sensor, a new flapping mechanism would need to be modeled and designed in such a way that the sensor is shielded from strong torques or forces. This instrument could allow thrust data to be refined even tighter and for smaller variations to be read.

With the idea of replacing current parts, fabricating a new flapping mechanism could easily enlarge the testing envelope to scrutinize other factors. Besides this change, a new controller and motor combination might permit an increase in flapping symmetry or tolerate heavier wings. Even adjusting the acceleration rates and the PID constants on the current system could concede better results.

Other future experiments could take place to redo inconclusive tests done in the past with insufficient manufacturing approaches.

- Sweep Angle Variations
- Further Recording Time Tests
- Loose CAPRAN® to Produce a “Snap Through Effect”
- Sensor Interaction and how it plays a role
- Wing Mount Stiffness
- Motor Controller and Acceleration
- Long Term Wing Decay
- Varying diameter of carbon fiber rod
- Effectively taper the LE carbon fiber rod

These tests may not lead to any significant knowledge advancements or they could be a breakthrough.

One question remains from the research done thus far about if there is a driving feature in flapping wing thrust production or if a multitude of variables have an effect. Presently, combined overall structural stiffness and geometric topology are two main paths that could be explored.

The research group implemented high speed cameras to look at the wing's kinematics at elevated frequencies which brought insight to perplexities. This technology, should it be found useful, could help drastically in learning about unanticipated occurrences.

Work on new fabrication methods would be beneficial, for the improvement reached in this paper allowed more tests and new possibilities to prosper. Now that wings can be relied upon, science can proceed to fulfill the basic understanding behind flapping flight.

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BIOGRAPHICAL SKETCH

Jason was born to a wonderful family in south Florida. From early on, Jason has strived to continuously apply his abilities and tries to build upon an ever-expanding skillset. From running a small, hobby-driven, business as a teen to attending a world class college to joining a top defense contractor, Jason's experiences give him a vast array of knowledge that will allow for contributions to highly motivated ethical organizations in the future.

Jason started as a teen and an owner of a business, creating wooden pens and pencils from exotic woods. The opportunity taught crucial skills about marketing, accounting, and learning from an early age to keep business records. The pens were sold from California to New York and he was even highlighted by the Penn State Industries' website and catalog.

He continued his diversification as a teen by partaking in multiple varsity sports, playing both, the alto and tenor saxophone, having involvement with numerous community service opportunities, working as a chef in a local café, and keeping a goal of higher education.

Continuing past high school, Jason finished his next step at the University of Florida in 2011 with a Bachelor of Science in aerospace engineering. As a student, Jason was not only on the college's Dean's List and graduated Cum Laude, but kept busy with extracurricular activities. He worked as an undergraduate in the fluid dynamics and wind tunnel labs as an assistant and held a lead position in the annual UAV competitions put on by Cessna, Raytheon, and the AIAA student group. In the competitions, Jason help lead UF to its best finish by maintaining responsibilities such as keeping group deadlines, finding solutions to challenging problems, and strong leadership.

Jason remained persistent through receiving a Master of Science in aerospace engineering in 2013. While accomplishing this feat, he was a teaching assistant for several classes and a research assistant working to further flapping wing technology. Along with using his knowledge and critical thinking skills to further the research objectives set forth within the department, Jason also presented at the 2012 SEM XII International Conference, the 2012 SEM Southeast Graduate Student Symposium, 2013 SEM Symposium, and passed the Fundamentals of Engineering Exam.

In terms of other concentrated areas of interest, Jason would like to continue his education throughout his career experimenting with flight characteristics and analysis of supersonic aircraft, missiles, and other reconnaissance vehicles. His goal would be to elongate the duration of operation, look at stress-strain relations, work on vehicle and product design or development, enhance payload capacities, increase maximum velocities during flight, and to create better maneuverability. Other learning includes specifics about shock analysis, steady and unsteady aerodynamics, finite element analysis, plastic stress-strain nonlinear relations, rotorcraft, and daily launch operations among other subjects of aerodynamics and structural composure.

After graduation, Jason plans to continue his career at Lockheed Martin as a Systems Engineer. He will work to capitalize on technology to increase efficiencies and take market share while addressing crucial issues and providing great products to customers.