Fabrication and Analysis of Small Flapping Wings

Rue, Jason; Chang, Kelvin; Ifju, Peter; Haftka, Raphael; Schmitz, Tony; McIntire, Justin; Tyler, Chris; Ganguly, Vasishta; Chaudhuri, Anirban

ABSTRACT

Flapping winged micro air vehicles (MAVs) have been of interest due to their unique flying characteristics. Wing design is an essential aspect of making a robust flapping device. The more popular approach to obtaining an optimized wing is to completely mimic natural species. Rather, our study is only inspired by these biological flyers, suggesting that the optimum design for an active one degree of freedom flapping motion may differ. Error reduction is crucial to the experimental optimization approach, building confidence that variations in thrust are attributed to wing topology. To allow for consistency among replicate wings, the fabrication process must be controlled and accurate along with data acquisition and experimental setup. Digital image correlation and slow motion photography was used to find subtle differences and gain more knowledge of the physics behind flapping. Hovering MAVs serve as the primary application of the optimized wing.

INTRODUCTION

Ever since human powered flight was discovered, fixed and rotary wing aircraft have been prominently used in designs. After smaller unmanned aerial vehicles and micro air vehicles (MAVs) were introduced, these continued to be on the forefront of thought, although a new track started to develop: flapping wings. Fixed and rotary wings, especially at the small scale level, introduce numerous problems that flapping solves. Stability issues along with no hovering or slow flight capabilities plague fixed wing aircraft while rotary wings have relatively low efficiency and a high noise signature. Flapping wing micro air vehicles (FWMAVs) have the ability to hover or have forward flight, require a short or vertical takeoff, and have high maneuverability, all advantages over the others. These properties also are ideal for indoor applications. In addition, a FWMAV can be easily disguised and, with optimization, has the potential, shown from nature, to have a superior efficiency. For these reasons, flapping is worth acknowledging as a potential propulsion source.

The more popular approach to obtaining an optimized wing is to completely mimic natural species [1]. Rather, our study is only inspired by these biological flyers, suggesting that the optimum design for an active one degree of freedom flapping motion may differ. The wing starts with a basic quarter-ellipse planform, similar to a hummingbird sized wing. Furthermore, unidirectional carbon fiber battens make up unique structural patterns while a bidirectional triangular portion acts as the attachment point to the flapping mechanism. The carbon fiber strips are cut with a custom multi-bladed hand tool which creates repeatable and predictable sized battens. Then the arrangement is laid into a CNC Teflon mold and allowed to cure in an oven under pressure. A 14 micrometer nylon based membrane created by Honeywell, called Capran, is connected to the structural using cyanoacrylate glue. The batten arrangements are created in such a way that the wing follows an active one degree of freedom (DOF) movement but has a structural passive second DOF.

In terms of testing, a custom single DOF flapping mechanism is fastened to an ATI Nano17, a six-axis force/torque sensor, to record thrust and lift values. A set of Point Grey Research Flea2 2.0 MP cameras, combined with Computar's 12-36 mm F2.8 C-mount lenses, divided into upper and lower pairs allows for digital image correlation (DIC). DIC is utilized to look closely at the flapping cycle and to notice changes in the deformation.

This study will mainly focus on thrust production since a high offset for weight is necessary in hovering flight. The results from this work will generate a large, well-documented data-base (i.e. 100s of wings) of experimental results that can be used by numerical modelers for validation purposes, as well as establish an efficient methodology to parameterize topologies to streamline future modeling efforts [2]. As for future work and advancements once the data-base is complete, a standalone hovering FWMAV can be manufactured.

EXPERIMENTAL SET UP

A challenging problem comes when a robust flapper mechanism is needed for testing purposes. Not only does this device need to withstand months of testing so that wings can be compared but the flapping motion must be symmetric, the wings need to detach without difficulty, it must work appropriately with the ATI Nano17 force/torque sensor, and be easily repaired. Figure 1 shows the flapping device used at two different angles. A few details make it quite robust including two separate circular bearings which lessen available slop while having tighter tolerances to reduce binding and create a more symmetric response. The attachment point of the wing is characterized by a friction fit canal which holds the wing in place by a screw. This drastically reduced the time it takes to change out wings and the damage done to the wing itself as opposed to other methods. Also, all parts are made from aluminum on a precision CNC machine for accurate results.

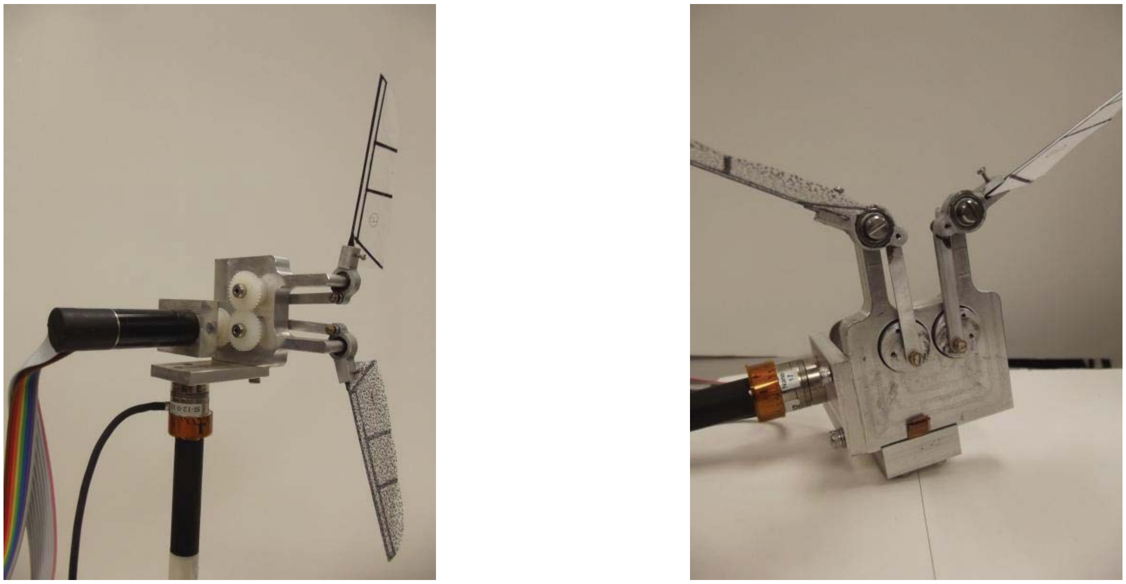

Fig. 1 Current flapping device shown from two separate angles. The left gives an easy view at how the motor, gears, and sensor tie together when mounted and ready for testing. The right illustrates the opposite side of the flapping device and a closer look at the screw-in attachment point for the wings.

The construction on the flapper was such that the wings move in approximately ± 33° from the mid-plane. A quick study was done to show that the preconceived thought that increasing the flap angle would ultimately raise the average thrust value obtained through post-processing. Indeed, shown in figure 2, for the same wing and setup, the thrust curve is elevated by increasing the flap angle.

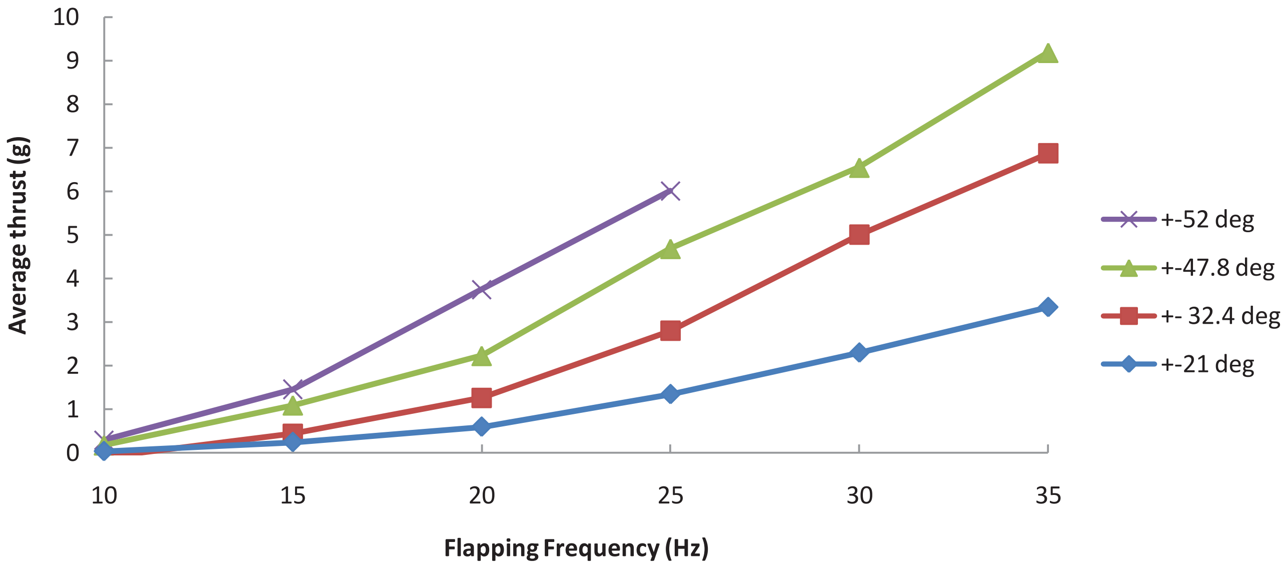

Fig. 2 Shows a graph relating different flap angles (angle from midplane) to the average thrust produced. This clearly shows the relationship between an increased flap angle and more produced thrust.

COEFFICIENT OF VARIATION

A repeatable experimental procedure and setup is essential to assuring that variations in the thrust are the result of changes in the batten configuration of different wings. It is important to identify the proportion of the total variation that is due to error. The three sources identified to contribute to this error include fabrication, data acquisition, and experimental interaction/setup. A systematic approach that involves eliminating the presence of certain sources of error allows for a better understanding of those that are left to permeate. This approach assumes that two of the same wing, absent of errors, will provide the same average thrust value when analyzed. Separate investigations have allowed for the identification of these sources of error, guiding efforts in reducing them. Multiple trials of these studies are used to obtain a coefficient of variation (COV), and assist in providing more confidence in the data. The resulting COV is used to compare across these studies to gather a better understanding of the contributions Table I. The wing experiments have been dissected to show the way sources of error have been exposed, creating a better understanding of the contributions from each Fig 3.

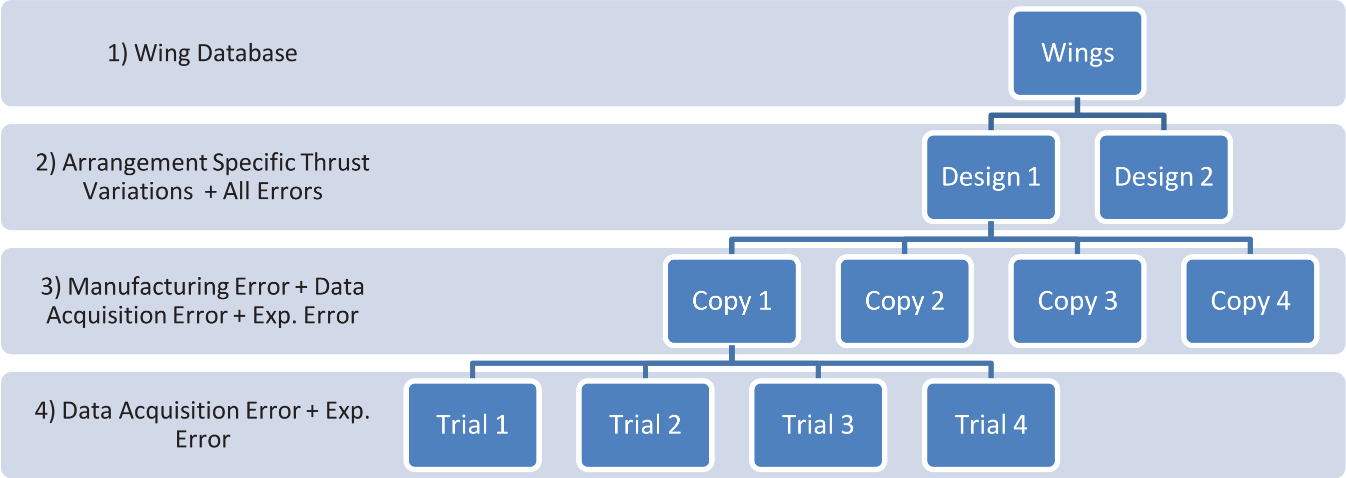

Fig. 3 The thought process for investigating the sources of error is illustrated, where each stage exhibits different sources of error.

Table I

Distinguishing Errors

Source of Error	Stages to compare	
Manufacturing	Stage 3	Stage 4(Taking wing off between trials)
Data Acquisition	Stage 4(Without taking wing off between trials)	No variation
Experimental	Stage 4(Taking wing off between trials)	Stage 4 (Without taking wing off between trials)

The second stage comprises designs that differ in batten arrangement, while stage 3 consists of manufactured copies of one design. Testing in the 3rd stage would have all three sources of error described before, lacking variation due to batten arrangement. The fourth stage tests a copy multiple times, taking the wing off and attaching it back on to the flapping mechanism before proceeding with the next trial. The experimental error's presence depends on whether the flapping mechanism was physically disturbed between trials. The procedure for stage 4 includes removing the wing between trials.

MANUFACTURING

One investigation that focuses on this error entails analyzing different wings with identical plans of fabrication. Therefore, a batch of wings would be made using the same process, producing visually similar wings that possess manufacturing errors.

The first attempts at producing wings involved a hand-layup, where a printed guide helped in batten arrangement. The wings were prepared with thin 0.8mm strips of pre-impregnated unidirectional carbon fiber which were cut using a typical single blade razor guided by a ruler. Once laid on a board, the wings were vacuum bagged and cured under 30 PSI pressure in an oven. A test of 10 of these wings helps illustrate the variation in average thrust Fig 4. Error contributions from all three sources (manufacturing/data acquisition/experimental) are present.

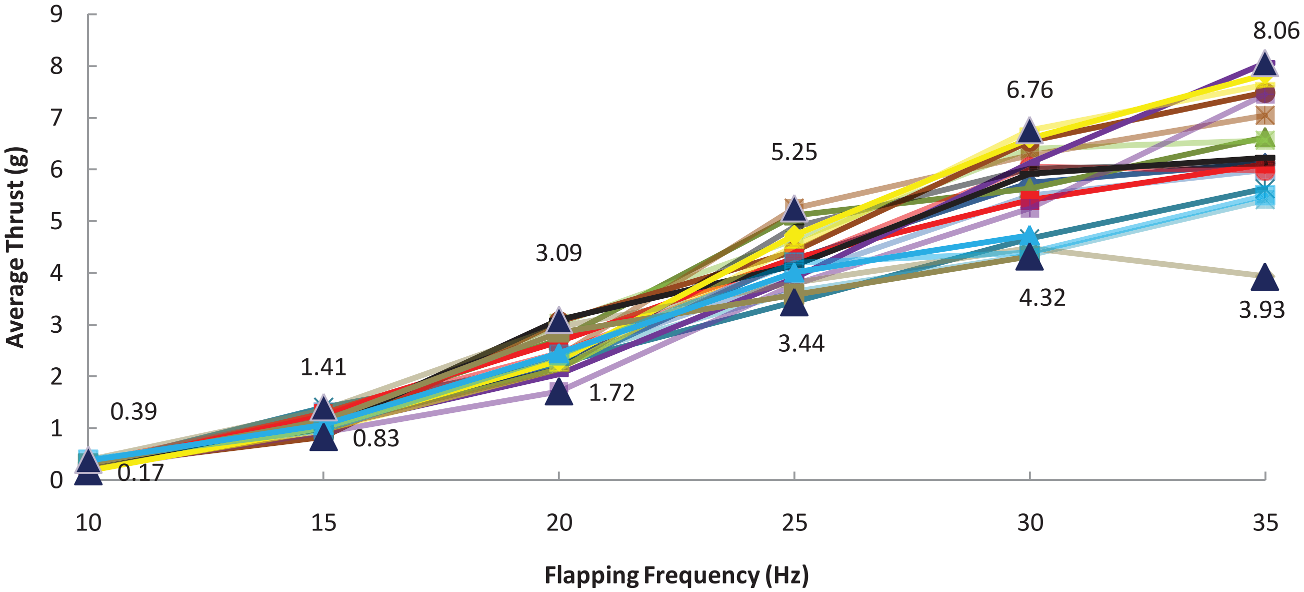

Fig. 4 A study of 10 different wings with two trials for each wing. The wings are hand laid up in a similar fashion with the same batten arrangement. For clarity, the maximum and minimum values are displayed. Even though trials of the same wing are comparable, over the 10 wing span, the thrust varies by as much as 50%.

The figure explains a study of ten different wings where each was given two trials to gather a better understanding of the variation in average thrust production. The highest and lowest numbers of observed at each frequency are provided. It is apparent that there is more scatter at the higher frequencies which can be due to more than just the manufacturing error.

One part of the manufacturing error that was visually observable was the inconsistency in the batten thickness. This was the result of using calipers and visual inspection in assuring batten thickness. Therefore, a tool was devised to assist in creating more even strips. Made from aluminum, the razor blade holder firmly grasps multiple standard razor blades at the distance of the thickness desired for the strips, exhibiting the proper geometry to be held by a CNC machine for further function.

Another improvement came in the form of more accurate batten arrangement and geometry. Using a CNC Teflon mold, the square cross section of the pre-impregnated carbon fiber was sustained while each batten is placed more accurately/precise. The wing frames assume a more visually precise geometry and benefits from an external pressure applied during the curing process which is supplied by sandwiching the mold tightly between two aluminum plates. The variation in thrust is less with these manufacturing techniques implemented and can be seen in Fig 5.

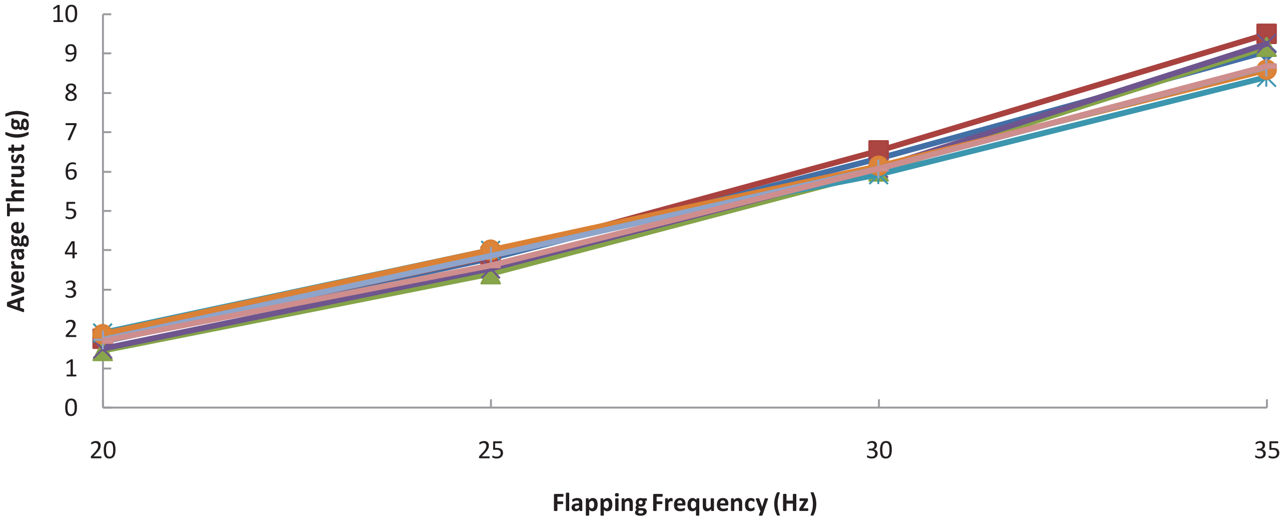

Fig. 5 Frequency versus thrust is compared where new manufacturing techniques are used. Here, four wings with two trials apiece gives a much lower variation with the CNC Teflon mold and custom approach for cutting more accurate carbon fiber strips.

The implementation of a CNC mold and multi-blade hand tool assists in lowering the scatter of average thrust values. This study compares different wings which have the same batten arrangement. Figure 6 shows the clear discrepancy between the hand laid up wings one from a mold.

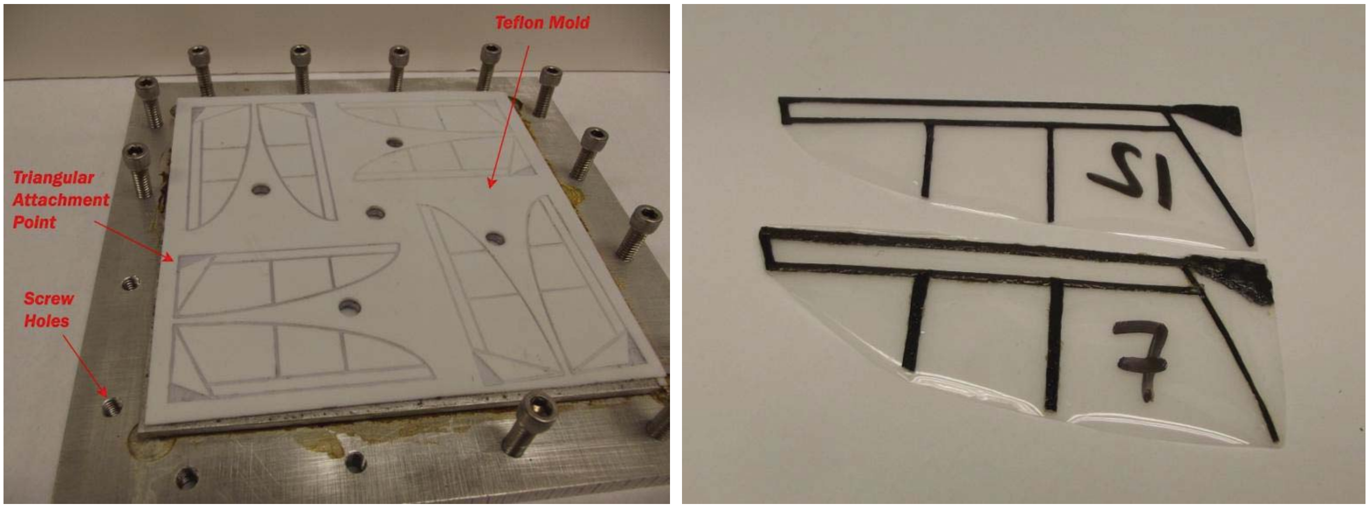

Fig. 6 On the left, the CNC Teflon mold shows how it can properly hold the carbon fiber in place during the curing process. The photograph on the right shows the difference in the hand laid up method (bottom) and the CNC Teflon mold method (top). Visually, the difference is unprecedented, for the prior strips were uneven and not well defined.

To extract the manufacturing error in the average thrust reading, several copies of the same design were tested. This focuses on the error introduced from creating multiple wings from the same mold and eliminates the variations from numerous batten arrangements. When this error is compared to separate trials of a single copy, a manufacturing error can be seen Table I.

DATA AQUISITION

The method in which data is collected from the force sensor plays a role in the error produced when obtaining the average thrust. The sampling rate and batch size transferred are parameters that define an acquisition, and are controllable from the software standpoint. Trials detailing the variation in the coefficient of variation (COV) with respect to the sampling rate and batch size (dump) were investigated.

In attempts to extract the error due to data acquisition, there still exists miscellaneous sources of error that cannot be differentiated or excluded. Therefore, the case detailed in table I for obtaining the data acquisition error includes other unavoidable errors such as variations in the environment and small physical disturbances such as vibrations in the table. To properly observe the contribution of the data acquisition to the overall COV, it is necessary to compare stage 4 (without taking wing off between trials) with a similar set of trials free of any data acquisition error. This, unfortunately, is not within our capability.

The variation in the COV is displayed for different acquisition setups. It is noticeable that increases in the sampling rate generally yield a lower COV. For the case of a 60k sampling rate and 20k data dump rate, the COV is slightly higher than the 30k-10k case which means that computer the used may have converged due to its computing limitations. Since the overall database of wings will focus around 30 Hz, at least a 30k-10k data acquisition method will be used for any testing.

In every trial run, data was gathered for a certain testing time. A cause for consideration was that a longer testing time may assist with reduction of noise by adding data to the average. For this reason, a study was developed to investigate the effect of longer acquisition time on COV, ranging from 10 to 120 seconds where the average was not greatly improved. Even with a shorter time, enough flapping cycles had past to get an accurate average. A longer testing time does though increase the time required for the experiment and shows no correlation to lowering the COV.

EXPERIEMENTAL INTERACTION/PROCEDURE

One aspect that creates error stems from interaction with the flapping mechanism when removing and replacing the wing. It is important to take into consideration forms of variation that can develop, including modifications to the wing position on the flapper mounting point and load biases from forces exerted by the operator. This contribution was isolated by comparing a set of trials, where the wings were not disturbed between trials, with one that had the wing taken off and replaced between trials Table I.

Tests of a single wing was used to assure an absence of manufacturing errors, while careful considerations were made to not expose the flapping mechanism to loads above those used to replace the wing. The wing used for this investigation was tested with the parameters of 10,000 samples per second and a 3000 sample dump. Tests present different error contributions from the experimental interaction at depending on frequency. The largest difference seen was 1.74%, while the smallest is 0.20% Fig 7.

The motor controller’s parameters were also explored to inspect the possibility that they might be a source of error. The motor’s acceleration and deceleration settings were varied to check for variation in the COV Fig 7. A wing with identical batten arrangement was used for this study, though its average thrust production is below the previous studies. This expresses the presence of manufacturing error as discussed previously.

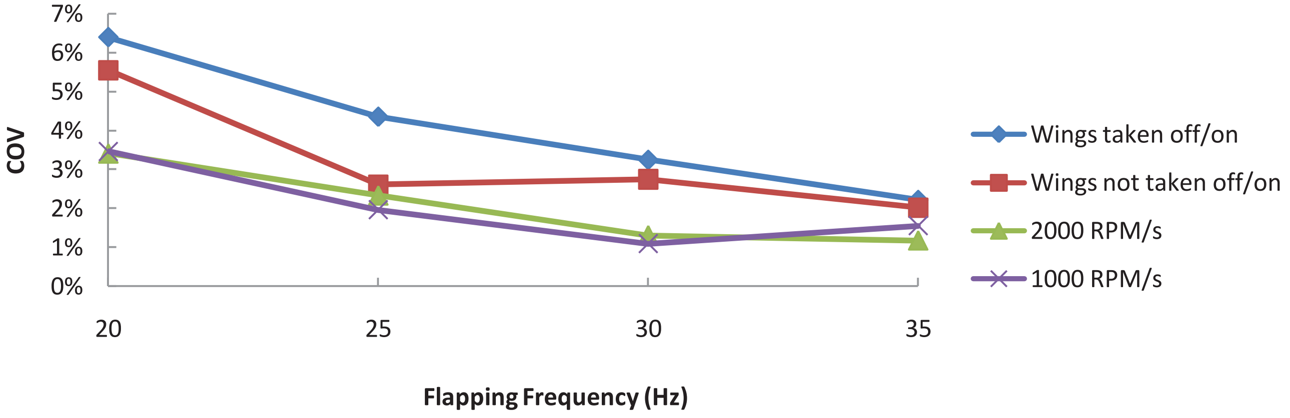

Fig. 7 Studies detailing how the wing’s replacement and motor control affect COV are presented.

FULL FIELD MEASUREMENTS

Digital image correlation is a high-powered tool that when used appropriately, can answer numerous questions about the wing deformation along with capturing and digitizing the rapid motion of a test subject, recording large out of focal plane displacement, reconstructing the flapping motion [3]. A set of Point Grey Research Flea2 2.0 MP cameras and Computar’s 12-36 mm F2.8 C-mount lenses are synchronized with a strobe light to produce a sequence of images of one wing Fig.8. The cameras are set up so that there is a lower and upper pair where each pair is focused and adjusted so that the entire flapping cycle can be seen.

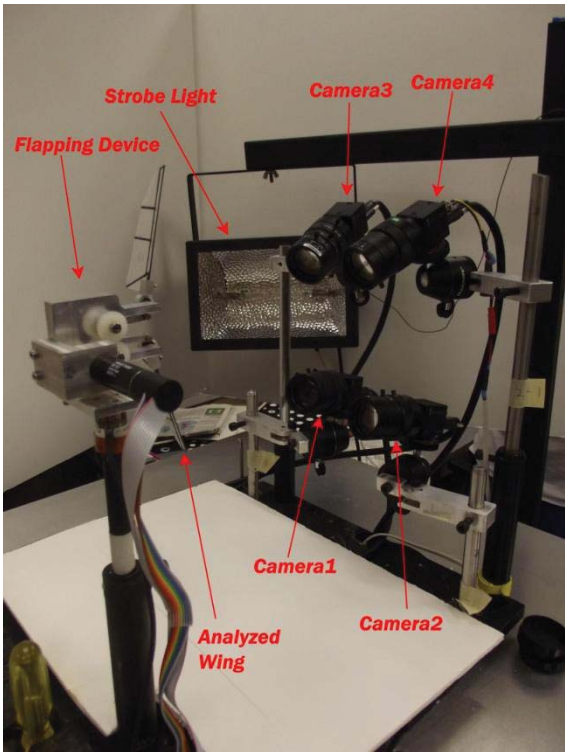

Fig. 8 Depicts the measurement set up including the cameras, a strobe light, and the flapping device.

A program by the name of VIC-3D is able to follow a random speckled black pattern on the wing and, after a calibration, shows the deformations graphically. DIC uses stereo triangulation to digitize a random speckling pattern placed over an object, and thus compute its three-dimensional features. This is followed by a temporal matching process, where the system tracks a subset of the speckling pattern, and minimizes a cross correlation function to compute the un-deformed location of this subset, and thus the displacements [3]. Different approaches have been made to help the program recognize the entire wing and reduce reflections. The speckled pattern, at this point, is being applied by a spray can although a new method of printing straight on to the membrane with a standard printer is being investigated Fig 9.

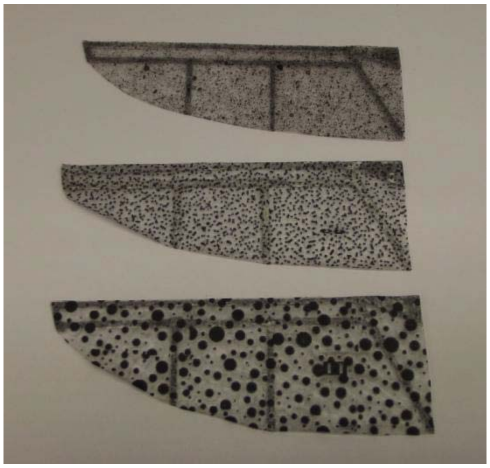

Fig. 9 Three wings with speckle patterns including the spray method (top) and printing method (middle, bottom)

The new method creates more contrast between the white background and black dots, allowing the program to decipher the dots easier and export reliable coordinates to MATLAB Fig. 10.

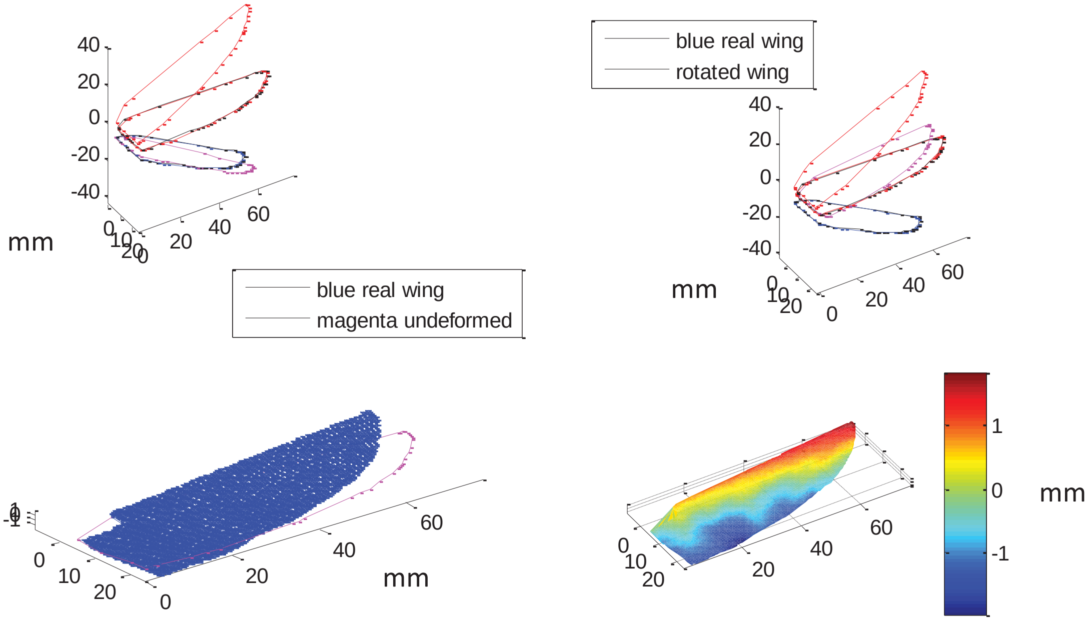

Fig. 10 A MATLAB post-processing graph showing how the DIC measurements are used to see deflections at a certain point in time.

CONCLUSION

Continuing to reduce error and learn more about the physics behind each flap spurs the attention for further trials. Ongoing experiments included looking at how the data was averaged and if that plays a role in error, the sweep angle when attached to the flapper, and if the flapper's mount stiffness affects the sensor. Each test gives insight to where error goes into play and how to help predict it in the future. Table 2 is comprised of the contributions from each error source described previously. Each of these values is calculated approximations from each of the studies.

Table 2

Approximate Error Contributions	
Manufacturing	1.8%
Data Acquisition	1.5%
Experimental	0.8%
TOTAL	4.1%

Manufacturing, data acquisition, and experimental interaction remain the main emphasis for error reduction. Producing a Teflon CNC mold, a custom multi-bladed cutting tool, and an external pressure method during the curing cycle all quicken the manufacturing process and reduce error. Sampling rates also proved to be beneficial in lowering the COV. Once a good understanding of where the error is being propagated is developed, a database of wings can be generated and tested with certainty. Not only can the information help in producing a hovering flapper, but it can assist an ever growing field with knowledge.

REFERENCES

[1] B. Prasetiyo, "Artificial Cambered-Wing for a Beetle-Mimicking Flapper," Journal of Bionic Engineering, Vol. 7, pp. S130-S136, 2010.

[2] P. Ifju, T. Schmitz and R. Haftka, "Expanding the Design Space of Synthetic Flexible Flapping Wings by Advancing Fabrication and Optimization Methodologies," University of Florida AFOSR/RSA Proposal.

[3] P. Wu, "DISSERTATION: EXPERIMENTAL CHARACTERIZATION, DESIGN, ANALYSIS AND OPTIMIZATION OF FLEXIBLE FLAPPING WINGS FOR MICRO AIR VEHICLES," University of Florida, 2010.