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INCORPORATION OF PASSIVE WING FOLDING IN FLAPPING WING MINIATURE AIR VEHICLES

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ABSTRACT

Flapping wing motion produces positive lift in the down stroke and negative lift in the upstroke under zero forward velocity. Large birds frequently exhibit flight behavior where their wings are folded during the upstroke, thus lowering the air resistance as the wing is moved upwards. The result is reduced magnitude of negative lift produced during the upstroke, relative to the positive lift produced in the down stroke, where the wings are unfolded and the area is increased. We expect that by incorporating this style of upstroke wing folding into miniature air vehicle (MAV) platforms, beneficial flight properties would arise. Specifically, a portion of the wings' overall lift will be generated by upstroke folding and downstroke unfolding, even at zero forward velocity. Such a capability will reduce the reliance on aerodynamic lift produced due to the forward motion of the MAV. This in turn would reduce the minimum flight-sustaining forward velocity and thus enhance MAV maneuverability by allowing for a reduced turning radius.

Incorporating wing folding into a miniature air vehicle platform presents a unique challenge due to strict weight constraints present at small sizes. Using actuators to accomplish folding actively is not feasible due to the added weight of the actuators and the need for an on-board control system to synchronize the folding with the wing flapping motion. Therefore, the folding motion must be accomplished passively, since this is currently the only viable option in miniature MAVs. We have developed a passive, spatially distributed, one-way folding mechanism. This mechanism has been incorporated into a flying MAV testbed, and has successfully shown that the flapping wing MAV with folding wings is capable of flying at reduced forward velocity, while maintaining the payload carrying capacity.

1 INTRODUCTION

The field of radio controlled air vehicles has made great progress in recent years, and one major area of interest has been the miniaturization of such fliers. Miniature air vehicles (MAVs) will allow a new set of missions to be completed that would be difficult or impossible for a larger-sized flier. Military applications involving flight in crowded urban environments are a major source of motivation for size reductions. In addition, law enforcement, scientific research, search and rescue, mapping, and many others could benefit from the development of MAVs.

There are currently three primary styles of MAV flight. Fixed wing uses airplane style flight, rotary wing uses helicopter style flight, and ornithopter uses bird or insect style flight. The use of flapping wings is becoming increasingly popular in MAV applications. Flapping wing MAVs (also called ornithopters) are expected to present several advantages over conventional MAVs [1-8]. Birds and insects are well-known for their high degree of maneuverability and quiet flights. Hence, flapping wing MAVs are also expected to be quiet because of low frequency operation, which is useful for surveillance applications. Flapping wing MAVs can fly at very low forward speed, making them well suited for obstacle avoidance in indoor operations. Fixed wing fliers are more useful for missions requiring extended loitering times and longer mission ranges, but are not very good at navigating tight urban or indoor environments due to higher flight speeds. Rotary wing fliers are great for hovering and indoor maneuvers, but generate significant noise and consume much higher energy. Ornithopters potentially could provide a useful compromise between the two styles of flight, allowing for a highly versatile and maneuverable flight platform.

A number of researchers have created flapping mechanisms and in some cases used these mechanisms in MAVs to realize flapping wing flight. In each of these works, the primary focus is on the design of the wings and the

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mechanism kinematics. In the following paragraphs, representative works will be listed and described.

Madangopal et al. [1,2] drew inspiration from insect and bird flight to develop a four-bar flapping wing mechanism. The model was characterized with a kinematic model as well as a rigid-body dynamic model. A proposed quasi-steady aerodynamic model of the wings was presented as well. By using tension springs in the flapping mechanism, the load variation seen by the motor was reduced. This resulted in a more power efficient system. A MAV prototype was successfully created and flown.

Galinski and Zbikowski [3] sought to design a flapping wing mechanism, and were focused on the material challenges associated with the production of wings. Two coupled four-bar linkages were used to generate figure-of-eight motion, based on inspiration from insect hovering flight. Aerodynamic loading on the wings was predicted based on the kinematics of the wings. An approach for the wing and mechanism manufacture was presented. Instead of creating a lightweight mechanism for flight, they focused their efforts on creation of a successful test rig that could demonstrate the wing motion properly.

Cox et al. [4] described piezoelectrically actuated mechanisms and wings, based on the musculoskeletal structures found in insects. By harnessing the natural tendency of such elastic systems to store and release energy rapidly, very simple and small flapping devices can be created with high frequency wing motions. They tested a five-bar linkage design, as well as two four-bar linkages. A wing design was proposed that passively achieves the proper relationship between wing translation and rotation to enhance flight efficiency and to draw inspiration from nature. No successful test flights were presented.

Banala and Agrawal [5] developed a mechanism using both a five-bar and a four-bar linkage in concert to mimic insect figure-of-eight motion. The degrees of freedom that were present in the wing included out-of-stroke plane motion, as well as twist angles that vary with time. These degrees of freedom are important parts of flight in the small insect flight regime. The wing-tip path as well as the twist angle were optimized based on data collected from the flight of hawk moths. The mechanism prototype was manufactured and tested at three different speeds.

Conn et al. [6] analyzed the flight of insects and presented guidelines for the simplification of flapping mechanisms. Several candidate MAV drive mechanisms were classified in terms of the level of constraint they impose. A flapping mechanism using a novel parallel crank-rocker was selected to recreate insect wing motions. The parallel crank-rocker mechanism has flapping and pitching degrees of freedom, unconstrained output motion, and adjustable wing angle of attack. The goals of the mechanism were to provide stability and maneuverability. A prototype was manufactured and aerodynamic tests were performed.

Tantanawat and Kota [7] described a means of improving efficiency in terms of input power for rigid and compliant mechanisms. An analysis of a four-bar mechanism is presented to investigate power consumption. It is shown that by storing elastic energy in a compliant mechanism, the power requirements for such a mechanism can be reduced below that of a non-compliant mechanism. Their work does not present a detailed design, however.

Zdunich et al. [8] developed and tested the Mentor, a flapping wing MAV capable of hovering and forward flight. The development of the wings and the unsteady airfoil analysis used to analyze the aerodynamics are presented. Two successful prototypes are flown, and an on-board control system is used to stabilize flight.

Billingsley et al. conducted an experiment to measure the influence of folding on thrust and lift generation [9]. A Park Hawk 2 ornithopter was fitted with a one-way passive compliant mechanism along the wing spar. By testing the ornithopter with the folding wings on a load cell, the lift and thrust production was studied and compared to the non-folding wings. It was shown that lift is increased by using a folding wing, and thrust is decreased. However, this style of wing folding did not lead to a successful flight.

Our goal is to create a successfully flying flapping wing MAV that incorporates folding wings for improved lift production at zero forward velocity. This in turn is expected to enable slower forward flight during operation, and therefore improve maneuverability. We created a version that utilizes passive wing folding, as well as a version without wing folding. The two flight platforms' design characteristics will be summarized and discussed in this paper. Finally, different variants of the folding wing concepts will be examined to determine the best direction for future research.

2 DEVELOPMENT OF A BASELINE FLAPPING WING MAV

2.1 Overview:

Before developing a folding wing design, we developed a flapping wing MAV with non-folding wings. By showing that this MAV is an effective flier, we developed a baseline from which to try new wing concepts that incorporate wing folding. Due to the difficulty in accurately modeling the quasi-steady aerodynamics encountered by a highly compliant wing, we have adopted an experiment-based approach to assess forces acting on the wing.

Our MAV consists of five primary subsystems. These are the wings, the drive mechanism, the body, the tail, and the actuators and electronics. The primary areas of research interest were the wings and the drive mechanism, whereas the other subsystems provided a functioning flight platform on which to evaluate the effectiveness of these two primary systems.

The body of the MAV was constructed from foam and carbon fiber rods, for minimum weight. The tail was mounted to the rear of the body, and has left and right steering control, much like a rudder in an airplane.

The desire to keep the weight as light as possible led us to use the lightest functional electronic components available on the market. A brushless motor was used as the source of the rotary motion, due to sufficient efficiency and acceptable weight. The motor was paired with the lightest matching remote control receiver, tail servo, speed controller, and battery cell.

By establishing that the drive mechanism, the body and tail, and the electronics were all suitable for sustained flight using non-folding wings, we established a starting point to begin parametric study of new wing concepts.

2.2 Drive Mechanism Design:

Based on the weight, size, and functionality constraints, we determined that a compliant mechanism would be highly suitable for realizing the drive mechanism. This is because a compliant mechanism minimizes losses due to friction and is easy to manufacture since it consolidates many parts into a single part. Figure 1 shows the mechanism concept. Flexural members were incorporated into the mechanism to provide for compliance in the structure to facilitate motion. The two wing supports each are attached to the rocker in the central connection point in the top center, and hinge at the two outer connection points at the top left and right, respectively. This creates a flexion in the compliant frame as the flapping reaches the highest and lowest point of the cycle. By introducing this flexibility into the design, a restoring spring force is released into the mechanism at the two points where the maximum torque is needed from the motor.

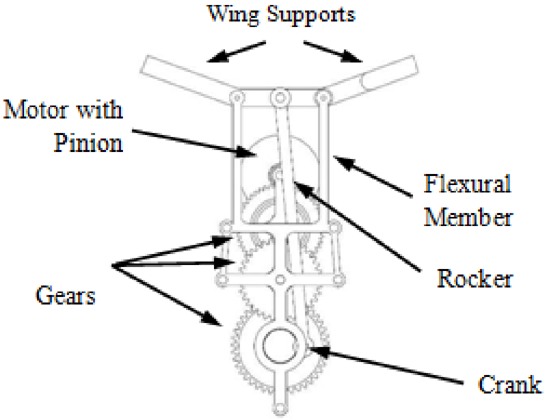

Figure 1. Compliant mechanism concept.

Due to the use of compliance as a functional characteristic, the system can be modeled as a pseudo-rigid body planar mechanism. The compliant members were modeled as rigid links with torsion springs at anchoring joints. The rotational stiffness of the spring was calculated according to Eq. (1). The sensitivity analysis showed that the influence of the rotational stiffness change on the sought reaction forces is very minor – change of k_{rot} by 10% changed the reaction forces by less than 1%. A constant rotary motion Ω was applied on the motor shaft.

$$k_{rot} = 3\,E\,I\,/\,l \ \text{[N m / rad]} \qquad (1)$$

where:

k_{rot} – Rotational Stiffness
E – Young's Modulus
I – Moment of Inertia
l – Beam Length

We describe a systematic approach for designing drive mechanism using kinematic modeling and finite element analysis in [11]. We scaled the design described in [11] to account for the higher wing area being investigated in this paper. Figure 2 shows the final design.

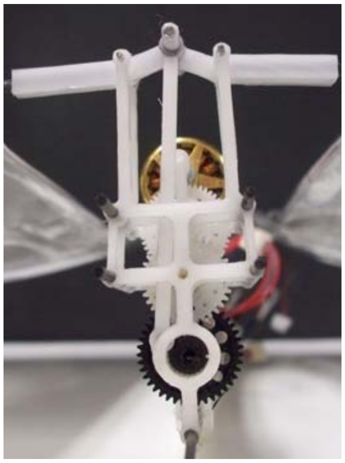

Figure 2. Compliant flapping mechanism.

The drive mechanism proved to be a good design. It was very crashworthy, and was able to withstand many impacts without major damage. The simple modular construction allowed any damaged parts to be easily replaced.

2.3 Wing Design:

Wing design depends on a number of factors that interact and affect overall aerodynamic performance. The general principle of operation is that during the flap cycle, the wing creates a rounded airfoil shape, which creates lift when air passes over, due to a beneficial pressure gradient that is created. With changes in the stiffness of the wing, the airfoil shape created during flapping is altered, thus affecting aerodynamic performance. Experimental results indicated that the chord-wise stiffness of the wings plays an important role in determining the relationship between lift and thrust production. By creating stiffer wings, the lift is increased, however thrust is reduced. Since a certain balance of lift and thrust is required to sustain flight, several wing versions were tested to find a design that would perform successfully. The three versions of the wing that were tested are shown in Figure 3. Each uses solid carbon fiber rods to provide stiffness to the Mylar foil wings. The first design derives its stiffness primarily from the leading edge spar, which is located along the flat bottom edge shown in the figure. The second design has a stiffener at a 30 degree angle with respect to the leading edge, and the third design has a stiffener at a 60 degree angle.

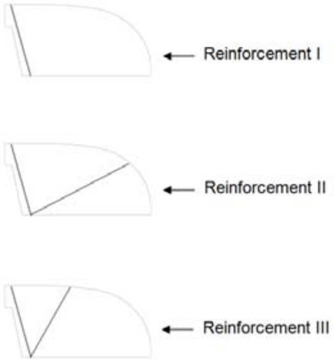

Figure 3. Wing design concepts.

Each of the three designs was tested using the load cell illustrated in Figure 4, to determine the configuration that provides the most favorable performance attributes.

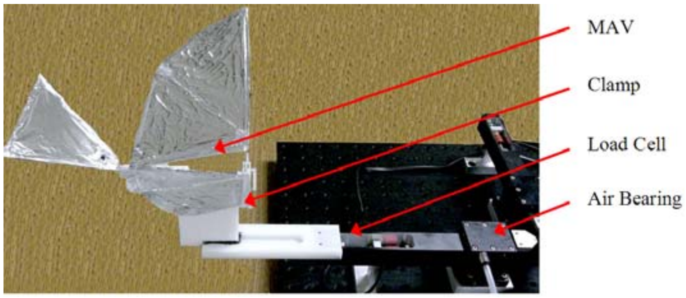

Figure 4. Load cell used to evaluate lift and thrust performance of MAV concepts**.**

The results of the thrust test are shown in Figure 5. It can be seen that the first design which has smallest stiffness provides the least amount of thrust. The second and third reinforcement are both superior in generating thrust, with the third design providing marginally more thrust than the second reinforcement. Despite this result, the second reinforcement design was chosen since it caused the flapping frequency to be reduced by roughly 0.5 Hz. Since one of the goals of the flapping wing platform was to minimize the noise generated in flight, a slower flapping rate would help to accomplish this goal.

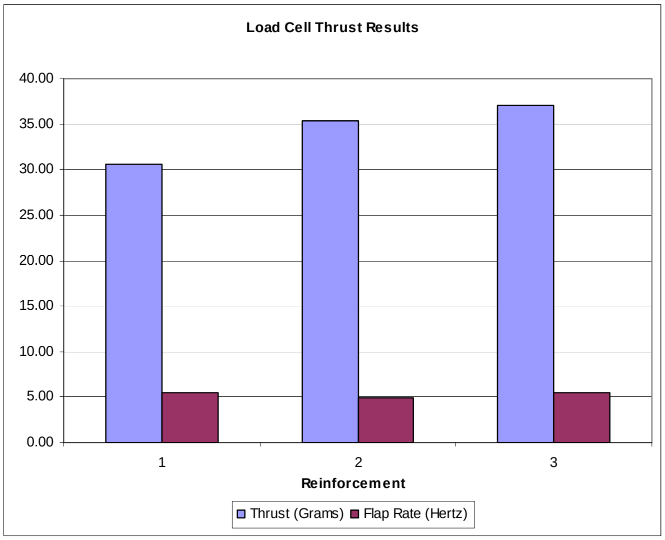

Figure 5. Load cell results – Thrust and frequency with varied reinforcement type.

Once wing design was selected, several versions were constructed with varying wing area to investigate the relationship between wing area and thrust performance, as well as the impact on flapping frequency and subsequent noise generated. Figure 6 summarizes the results of the load cell testing. The plot shows the average thrust generation, as well as the amplitude of the peaks. The corresponding flapping frequency is shown for each of the wing areas tested. In addition to thrust testing, similar testing was performed on wings of varying size to determine the lift generated as a function of wing size. The results of the lift testing are summarized in Figure 7. It can be seen in the plot that there is nearly zero net lift generated during the flapping motion, regardless of wing area. This result is to be expected, since the wing area is the same during the upstroke and down stroke. Therefore, the thrust generated during the wing beat is of greater importance, since it is this force which propels the vehicle forward, creates airflow over the wings, and causes aerodynamic lift to make flight possible. Based on the results of testing, a wing area of 691.7 cm^2 was chosen, with a wing span of 57.2 cm. This point provided a good balance between thrust and flapping frequency, and was well-aligned with our previously determined design goals.

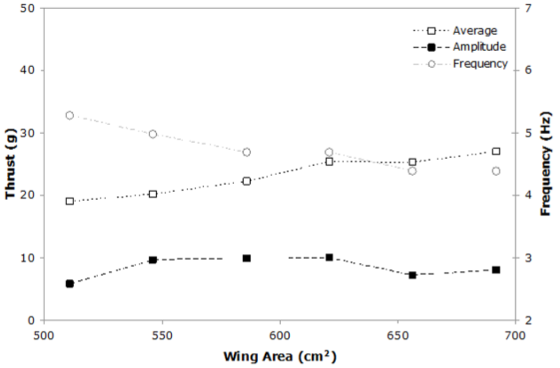

Figure 6. Load cell results – Thrust and frequency with varied wing area.

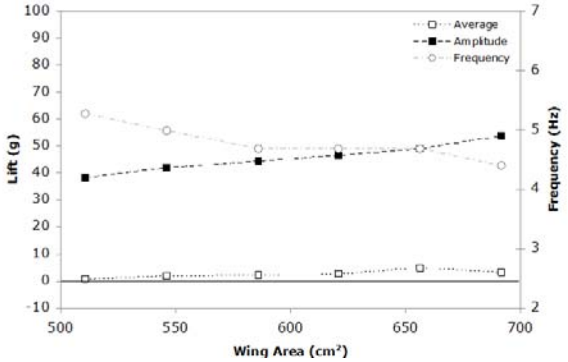

Figure 7. Load cell results – Lift and frequency with varied wing area.

2.4 Non-Folding Wing Test Results:

An MAV was constructed with wings utilizing a stiffener at a 30 degree angle, and with an area of 691.7 cm^2. The weight distribution of the MAV is shown in Table 1.

Table 1: Weight Breakdown

Part/Modules	**Weight [g]**
Drive Mechanism	6.40
Body	2.10
Wings	1.10
Nose	0.5
Electronic Components	9.20
Battery	7.10
Others (glue, tape, connectors, etc.)	4.80
Total	**35.00**

The primary purpose of this MAV with non-folding wings was to establish a suitable test platform on which to test new wing designs that incorporate various forms of wing folding. The main performance specifications are listed in Table 2.

Table 2: Performance Specifications

Overall Weight	35.0 g
Payload Capability	12.0 g
Flapping Frequency	5 Hz
Wing Area	691.7 cm^2
Wing Span	57.2 cm
Flight Duration on single charge of battery	8 min
Flight Velocity	3.75 m/s

Flight testing was successful, with the MAV capable of sustained flight. To begin flight, the MAV was hand launched at full throttle. The pilot provided radio control using a commercial over the counter radio intended for use with a remote control airplane. Altitude was controlled by varying the rate of flapping. After climbing up to a certain height the MAV could be operated with a lower frequency and hold it's altitude level. It was sometimes possible due to additional lift from the wind conditions to flap the wings at about 1Hz with the MAV still climbing. The tail was angled left and right to provide rudder-like steering control. By gradually dropping altitude and cutting throttle at the proper moment, gentle landings were performed with no damage to the vehicle.

During flight testing, it was determined that it is possible to maintain flight in wind speeds of up to 6mph. In outdoor flight, the ceiling is roughly 50 feet, at which point further gains become very difficult due to greater wind variability. In indoor flight, the maximum altitude was generally limited by the height of the ceiling.

Payload testing showed that up to 12 grams can be successfully carried by the MAV, while still maintaining its functionality. Depending on the payload weight, the center of mass of the MAV is altered, so positioning of the payload is important to maintaining the desired flight behavior. The payload capacity was sufficient to permit some useful payloads to be carried, and in one test flight, a 7.2 gram camera and transmitter setup was used to send live images to the ground station in real time during flight [10].

Video of the flight tests can be seen online for each of the versions of the MAVs created by the Advanced Manufacturing Laboratory [10].

3 ENABLING WING FOLDING BY COMPLIANT LEADING EDGE

3.1 Design Options:

In designing the folding wing concept, we identified three goals that we wanted to accomplish. First, we wanted to create a MAV with a slower forward velocity and better zero velocity lift characteristics. Next, we wanted the folding wing joint to be as light as possible, thereby maximizing the weight available for lifting a payload. Finally, we wanted to ensure that the wing flapping was symmetric, for stability and controllability of the MAV.

There were three primary design categories that were considered for incorporating compliance into the wings.

The first design concept considered was the use of a polyoxymethylene plastic (Delrin) hinge designed to limit the motion of the wings to a desired angular range. This concept is shown in Figure 8 and was tested at three ranges of angular motion.

$\theta_1 = 0^\circ$ to -15°
$\theta_2 = 0^\circ$ to -25°
$\theta_3 = 0^\circ$ to -35°

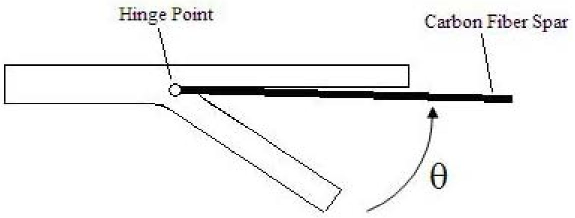

Figure 8. Solid hinge folding wing concept.

In this concept, the outboard portion of the wing spar, located to the right, is able to swivel around a brass pin mounted in the Delrin housing. Since there is no spring or resistance in this pinned joint, the wing is free to move to wherever the inertial and aerodynamic loads push it. Therefore, by designing the swivel housing to have a hard stop at the zero degrees position, downstroke wing folding can be prevented. By selecting the lower angle of the swivel housing, the amount of upstroke bending can be varied to any value that is desired. In Figure 9, the wing is shown at the zero degrees position, which shows downstroke non-folding in the swivel joint.

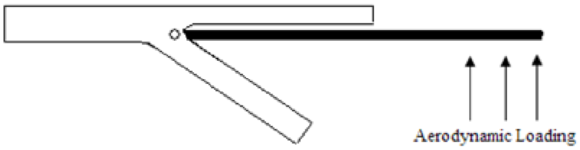

Figure 9. Solid hinge non-folding during downstroke.

The inertial and aerodynamic forces on the wing are all that are needed to maintain this wing position throughout the downstroke. In Figure 10, the wing is shown during the upstroke, with the inertial and aerodynamic loading causing the wing to fold downwards.

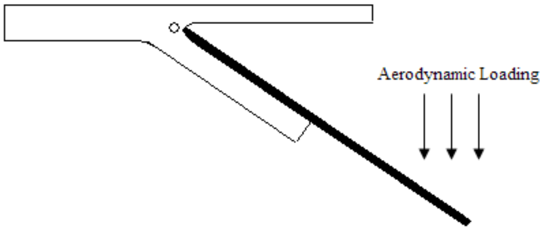

Figure 10. Solid hinge upstroke folding.

A photograph of this design concept is shown in Figure 11. The wing is at its maximum folding angle, which is what the wing looks like during the upstroke when aerodynamic and inertial loads are pushing it downwards.

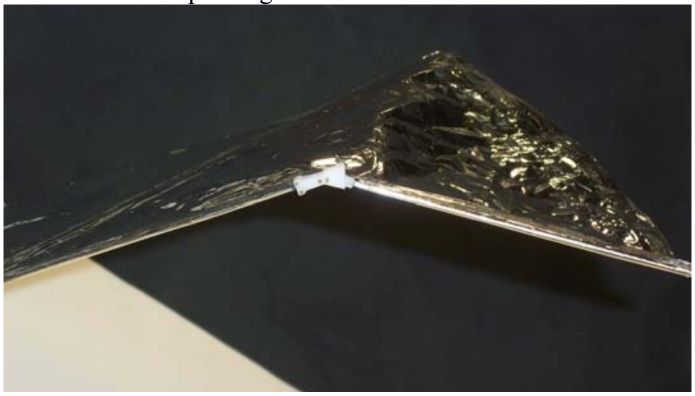

Figure 11. Solid hinge wing folding during upstroke.

The second concept used a flexible Delrin part as the folding member. This concept is shown in Figure 12. The body of the MAV is to the left and the wingtip is to the right in the figure. The carbon fiber rod coming from the MAV body is mounted into the Delrin part shown. Exiting from the right of the Delrin member is another carbon fiber rod that terminates at the wingtip.

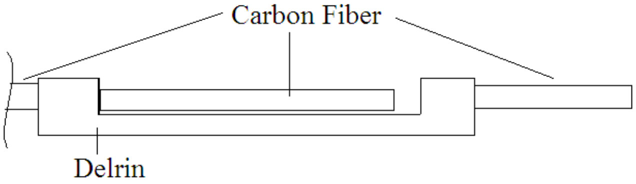

Figure 12. Flexible Delrin hinge concept.

During the upstroke, when folding of the wings is desirable, the only thing that provides bending resistance is the lower thickness of the Delrin part, shown in Figure 13.

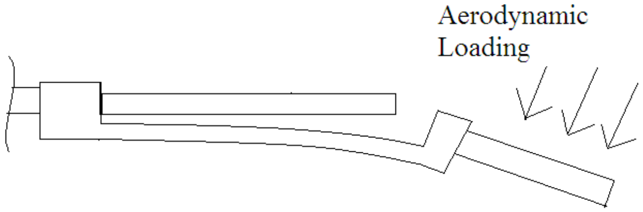

Figure 13. Delrin hinge upstroke folding.

During the downstroke, when wing folding is undesirable, there is bending resistance from the Delrin as well as the central carbon fiber rod, thus preventing wing folding, as shown in Figure 14. This concept was tested at thicknesses of 1.5mm and 1.2mm, where thickness refers to the lower section of Delrin that is directly under the small central carbon fiber rod.

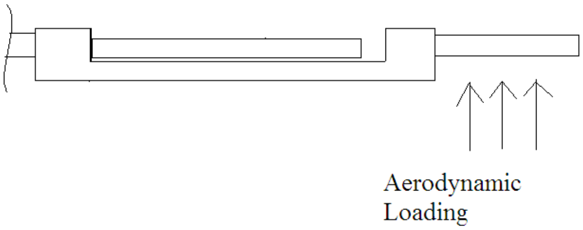

Figure 14. Delrin hinge downstroke non-folding.

This concept has the benefit of distributed bending over the length of the Delrin flexible member instead of being focused sharply at a point along the wing spar. A photograph of the concept during upstroke bending is shown in Figure 15.

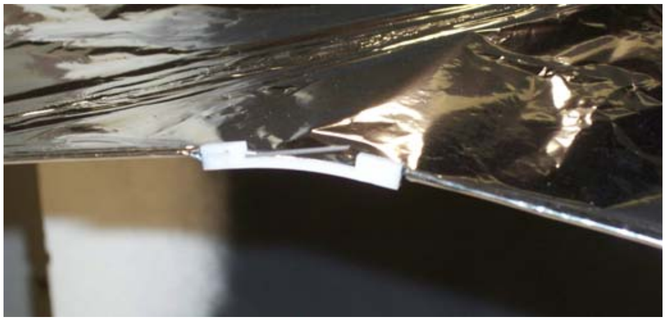

Figure 15. Delrin hinge wing folding during upstroke.

The third concept explored was the use of flexible carbon fiber wing spars with Delrin stops to limit compliance to the upstroke only. This concept is shown in Figure 16.

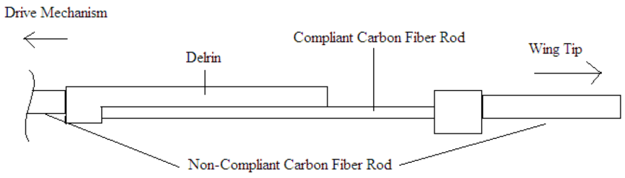

Figure 16. Compliant carbon fiber hinge concept.

A thicker piece of carbon fiber was used for the inboard portion of the wing, shown on the left. This mounts into the large Delrin stop shown in the middle of the figure. There is a smaller diameter carbon fiber spar mounted under the Delrin stop. This smaller diameter compliant carbon fiber spar connects to another smaller Delrin piece where it terminates, shown to the right. The carbon fiber spar emerging from the outboard side of the smaller Delrin piece on the far right is the same larger diameter carbon fiber rod as the large inboard spar on the far left. Since the central carbon fiber spar is of smaller diameter than the inboard and outboard spars, it has less bending resistance. Therefore, during the flapping motion, this spar will be bent more by the aerodynamic and inertial loads of the upstroke, as shown in Figure 17.

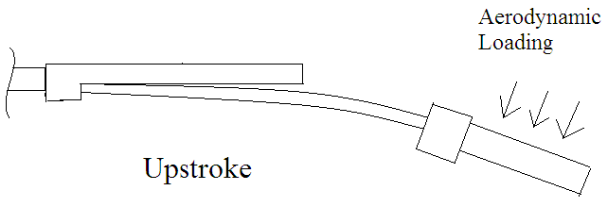

Figure 17. Carbon fiber hinge upstroke folding**.**

However, the shape of the channel in the Delrin stop in the center of the figure only allows for the folding to occur on the upstroke, as shown in the figure. During the downstroke, the Delrin stop resists deflection and adds its stiffness to the stiffness of the smaller central carbon fiber rod, causing the wing to only be able to fold significantly on the upstroke, as shown in Figure 18.

Figure 18. Carbon fiber hinge non-folding during downstroke**.**

This effect can be seen from the bottom view, shown in Figure 19. A benefit of this design is that the wing folding is distributed over the length of the smaller diameter carbon fiber rod.

Figure 19. Bottom view of carbon fiber hinged wing**.**

A photograph of this concept during the upstroke bending is shown in Figure 20. From the picture, it can be seen that the wing bends along the length of the small central carbon fiber spar.

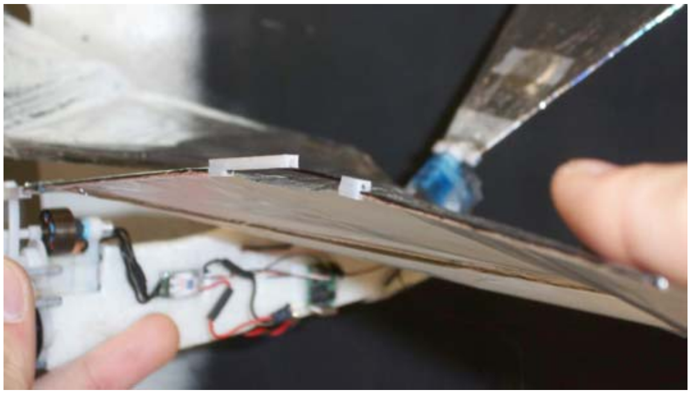

Figure 20. Carbon fiber hinged wing folding during upstroke**.**

3.2 Evaluation and Selection of the Wing Folding Option:

In order to evaluate the folding wing concepts, we used the same load cell setup as with the previous variant of the MAV, to determine lift and thrust properties. Each of the design concepts was tested so that the relationship between folding and aerodynamic forces could be compared. First, the flexible carbon fiber rod design was tested with a 1 mm diameter central spar used as the folding member. Second, the flexible Delrin concept was tested with thicknesses of 1.2mm and 1.5mm in the thin section of the member responsible for the folding. Third, the solid hinge concept was tested at three angular ranges In addition to testing the three angular ranges, the span-wise mounting point along the wing spar was varied at four evenly distributed points moving outwards from the body to the wingtip.

For the plastic hinge concept, the lift results are summarized in Figure 21, and the thrust results are summarized in Figure 22, respectively.

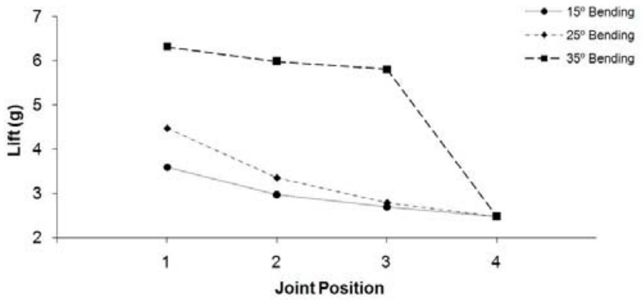

Figure 21. Lift results of solid hinge wings**.**

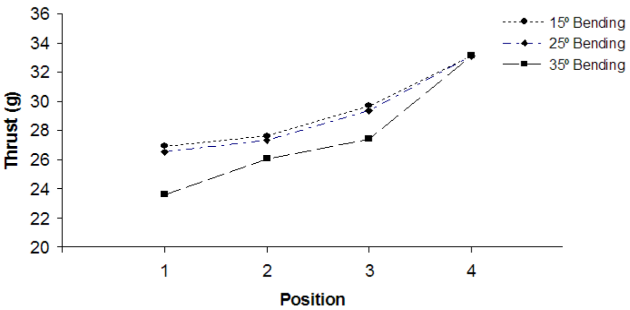

Figure 22. Thrust results of solid hinge wings**.**

Based on the results shown in the plot, a bending angle of 35 degrees at the first (most inboard) mounting point maximizes the desired goals of increased lift and decreased thrust, theoretically allowing for closer to zero forward velocity flight. This result is because the largest possible folding is being used, thus causing maximum reduction in wing area during the upstroke. However, this version of the folding wing MAV was unable to complete a successful test flight. Subsequent analysis using a high-speed camera revealed that during the flapping cycle, the motor was stalling at a few points during the flapping cycle. Therefore, it was determined that the plastic joint design with a hard stop at the compliance limit would be unsuitable for use with this MAV.

The load cell thrust testing for the flexible carbon fiber concept and the two versions of the flexible Delrin concepts are shown in Figure 23. For context, the non-folding wing is shown as wing configuration one, and has the best thrust properties relative to the folding wings. In Figure 24, the lift under zero forward velocity is shown for each of the wing concepts. We have included the non-folding wing data included for comparison.

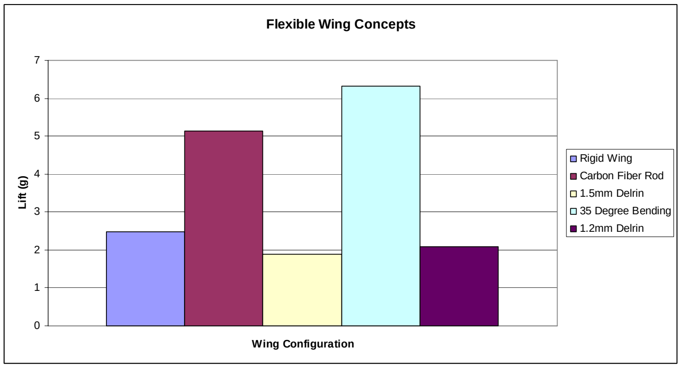

Figure 23. Lift results for spatially distributed folding wing concepts.

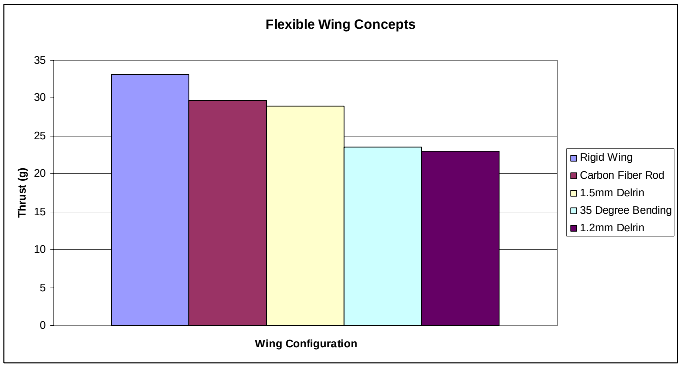

Figure 24. Thrust results for spatially distributed folding wing concepts.

During flight testing, all three concepts were tested to determine flight effectiveness. The flexible Delrin concept and the solid hinge bending concepts proved ineffective at supporting flight. For the flexible Delrin concept, unintended flexibility in the downstroke caused the desired beneficial aerodynamic effects to cancel out resulting in failure to stay airborne. The folding wing variant of the MAV that used a carbon fiber compliance mechanism to achieve the desired wing motions was the most successful concept. The distributed bending created by using the elasticity of the thin carbon fiber rod helped to smooth the increase in torque load on the motor, due to the inertial accelerative forces generated from the folding motions. The thrust decrease was the lowest of all the concepts tested, with a reduction of just over 3 grams. The lift increase was second greatest behind the solid joint bending, with an improvement of 2.67 grams.

The flexible carbon fiber rod turned out to be the best solution for folding wings due to its high flexibility and light structure. It was able to successfully support flight, and provided a good balance between upstroke compliance and downstroke stiffness. Based on our test results, we selected the flexible carbon fiber design for wing folding.

3.3 Folding Wing Test Results:

Test flights with the flexible carbon fiber wings indicated a drop in forward velocity of almost 30%, and a drop in climb rate of 50%, relative to the non-folding wing concept discussed in section 2.4. When equipped with the folding wings, the payload capacity was found to be 10.0g, excluding the weight of the battery. Including the extra components used in the construction of the folding wings, the overall weight of the flier was increased to 36.9 grams, an increase of 1.9 grams.

5 CONCLUSIONS

Our folding wing platform demonstrated that it is possible to reduce the forward flight velocity without compromising the overall lift. We plan to redesign the wings to enhance the climb rate and maneuverability in future versions of our MAV.

Another key area of improvement is in the design and construction methods of the wings we employ in both of our MAV variants. Since the wings are handmade by using heat sealing Mylar foil, no two sets of wings can be made exactly the same. Therefore an area of interest for us is to explore methods for improving the repeatability of the construction such that a more systematic method of study can be undertaken.

We also plan to make the wings more effective in lift and thrust generation by undertaking an aerodynamic study. Key areas of interest will be the addition of more degrees of freedom in terms of flexibility and stiffness strategies, and the corresponding effects on aerodynamic forces generated in flight. Hopefully by more faithfully imitating the wing motions and morphing that are exhibited in nature by birds and other fliers, our MAV wings can be improved in terms of their efficiency and force output.

We are also interested in enabling autopilot based MAV flight in the near future. Since a flapping wing MAV experiences fairly large vertical oscillations corresponding to the wing beat frequency, this presents a unique challenge. As part of this research, a number of novel weight-saving methods will be employed such as in-mold assembly and flexible printed circuit board design to consolidate parts, ease the assembly process, and reduce weight.

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