# Senior Design Group #5:

# Enhanced Agility of MAV's Using Adaptive Structures

# Final Report


**Due:** April 12, 2011

**Client:** Dr. Benjamin Dickinson

**Advisor:** Dr. William Oates

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**Executive Summary**

Research in adaptive structures is a very cutting edge and mostly undiscovered field at this point. Adaptive structures or smart materials can be used for a variety of applications including; CPU's, avionics, and consumer products. Smart materials are defined as a material that will significantly change one or more of its properties when exposed to external stimuli(2). The materials include, but are not limited to piezoelectric, dielectric elastomers, and shape memory alloys.

The Air Force Research Laboratory (AFRL) at Eglin Air Force base has contracted senior design group five in order to test whether or not the flight characteristics of a Micro Aerial Vehicle (MAV) can be changed by using adaptive structures. In the past our client, Dr. Benjamin Dickinson, has done research using a basic elliptical frame with a dielectric elastomer placed on top. This experiment concluded that the delay time for stall was increased at higher angles of attack and also that the lift coefficients increased compared to the base line. See figure 1 (page5).

The initial testing has proven that there is a basis for furthering this research. The AFRL has contracted the group to continue Dr. Dickinson's research. The main component of this project is the testing of a new electrode placement and its resulting change in flight characteristics. In order to record these results the group has scheduled time at the University of Florida's Research and Engineering Education Facility (REEF) located outside of Eglin Air Force base. Here the concept designs will be tested for lift and drag coefficients, as well as rolling moments. Although stress and fatigue testing need to be done before the prototype can be used in the field, the client is more focused on the limitations of this application.

Along with electrode variation the group must also design a suitable connection system for the testing equipment at the REEF facility. This design must prevent all arcing to the measuring device. These designs will be done with Wildfire's Pro Engineering software. The specific dimensions for the wing and test platforms will be used to ensure compatibility. Due to low forces of lift no FEA will be done on the wing components themselves. Also the project advisor Dr. William Oates specified that the FEA on the smart material has already been done and not pertinent for the project.

**Motivation**

The applications for low Reynolds number (less than 10^5) micro aerial vehicles (MAV's) are essentially limitless. They can be used for surveillance, surveying, reconnaissance, and many other objectives. There is a lack of knowledge into the behavior of these vehicles due to their size and air speed. In order for the field to advance, better designs that will result in more stable and agile flight are necessary to increase the dependability of these vehicles. The use of smart materials is perfect for an application such as this in that they do not require the use of mechanisms to function, and may be able to replace current control systems and the weight associated with them. In order for MAV's to prove themselves useful in the field, steps must be taken towards improving their performance.

**Justification/Background**

The client of this project is Dr. Benjamin Dickinson, a materials researcher for Eglin Air Force base. MAV's are still very much in the developmental stages and much is to be learned about their flight characteristics. The MAV itself will need to be agile and durable enough to navigate various obstacles and the inherent forces therein. The flight environment should be able to range from high heat conditions such as deserts to dark cold wet conditions such as caves. This project calls for the implementation of adaptive structures in order to improve flight characteristics.

Even though the field is very new there have been a number of innovations and papers published. Many studies that have already been done are modeled after natural phenomena such as avian and insect flight. Many of these solutions have worked but are strictly limited to unfixed "flapping" flight, which can be a nuisance while trying to fly through places with low clearance. Others have tried to meet the challenge by using adaptive structures to change the wing geometry resulting in increased performance. Another problem that must be solved is managing the deformation in the way that the polymer does not lose its elasticity which all membranes are subject to when put under fluctuating stresses. This can either be done by finding a material that hinders this behavior, or by implementing a quick inexpensive way to change the material out between flights.

Last year a design group used an electrically actuated elastomer in order to deform the wing geometry in an advantageous way. In theory applying an electric potential across this membrane will cause the membrane to deform in a convex fashion. The results of this experiment in this instance were less than desirable do to an improper placing of the membrane. The client, Dr. Dickinson, has done further work using a basic elliptical frame with a dielectric elastomer used for the top surface. By changing the geometry of the wing Dr. Dickinson was able to produce an increase in the lift coefficient of around 30% at low speeds (See figure 1).

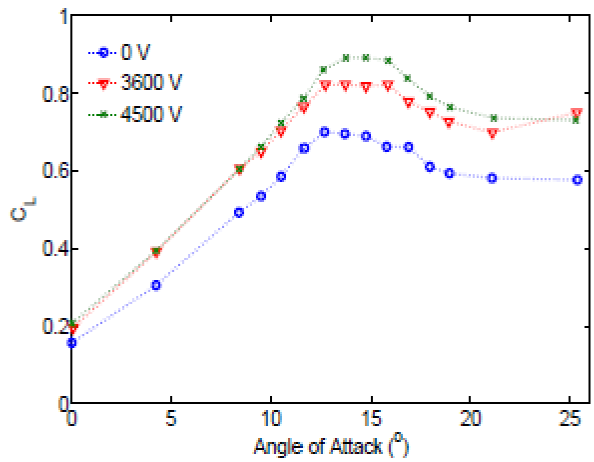



**Figure 1- Lift Coefficient vs. Angle of Attack for wind speeds of 6 m/s. (Dickinson/ Oates)**

Figure 1 shows that the greater the applied voltage to the membrane the larger the gain in lift. The figure below shows the wings deformation at the peak lift coefficient for (a) 0 Volts and (b) 4500 Volts.

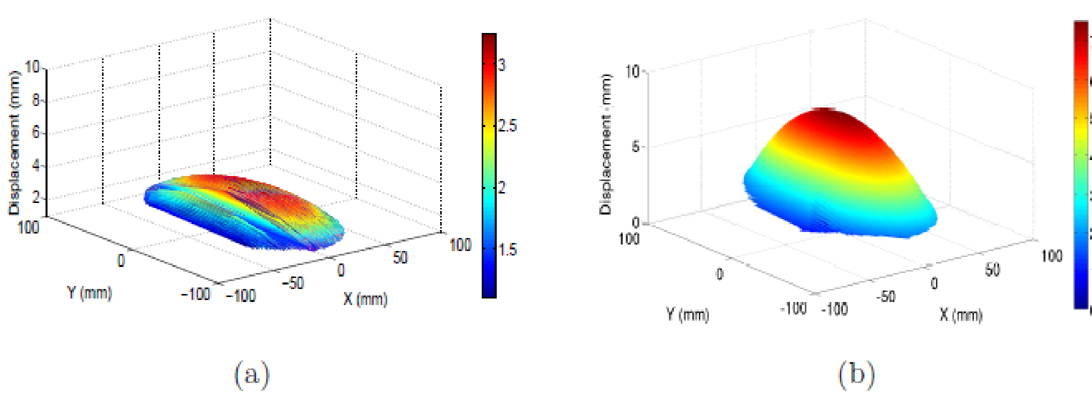



**Figure 2- Shows the deformation of the wing membrane at the peak $C_L$ for (a) O V and (b) 4500 V.(Dickinson/Oates)**

There are a variety of adaptive materials that can be used for this project. Placing no limitations on the power source normally leaves the design very open ended, but the client has specified that a dielectric elastomer is to be used to continue the work that has been done earlier.

**Objective**

Enhance the aerodynamic properties of fixed wing MAVs at low air speeds (5-10 m/s)using a dielectric elastomer. The ultimate goal of the project is to prove that adaptive structures integrated into an airfoil are a viable way to improve or change the flight characteristics of MAVs. The enhancement of MAV's can be, but is not limited to , increased lift coefficient, better flow attachment, or decreased stall speeds. This will be done by varying the electrode geometries of the elastomer. It is the intention of this group to provide empirical results if these enhancements with a budget of two thousand dollars.

**Overall Concept Design**

The design for this project is a simple one. The design consists of one, major, non moving part. The frame for the wing is a simple ellipse with major and minor axis equal to twenty centimeters and ten centimeters respectively. A pre-stretched segment of VHB tape will be placed on the top side of the frame. Either side of the tape will be covered in carbon grease. This grease acts as an electrode and can be varied so that desirable flight characteristics can be changed. Once a voltage is applied across the electrodes the tape will deform. Figures one and two below show the basic concept of the elastomer without a voltage and flow applied (figure 3) and with a voltage applied (figure 4).

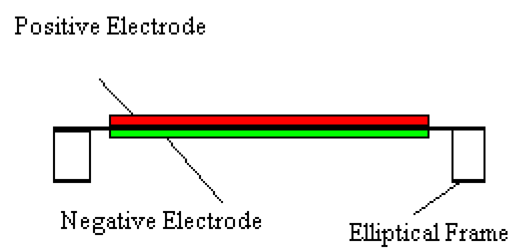



**Figure 3- Basic wing cross section without an applied voltage**

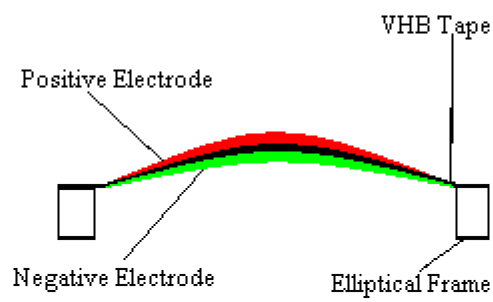



**Figure 4- Basic wing cross section with voltage and flow applied**

## Constraints

The client for this project, Dr. Ben Dickinson has provided a basic wing frame structure for the group to use. Because this project is based on a technology that is characterized by a lack of knowledge and experimental data, the client's main request is to test whether or not dielectric elastomers are a viable material for enhancing the flight characteristics of MAV's. The elastomer specified for use by the client is VHB (Very High Bonding) 4910. This elastomer is very easy to find and cheap, which makes it ideal for this project. The power source used will not exceed 8000 volts in order to ensure safe operation and limit arcing. The group must also design a suitable connector for the testing platform to ensure that the lab equipment does not sustain any damage.

**Materials**

The materials for this project were mostly specified by the client. The dielectric elastomer that is to be used is VHB (Very High Bonding) 4910. This material is relatively cheap and can be bought in bulk. This material also gives one of the most reliable deformations of all materials considered for use. Basing the design on this material meets the specification that the wing must be easily replaceable.

In order for this VHB tape to undergo a deformation it must be subject to an electric field. Unfortunately using a fixed electrode hinders the deformation of the elastomer, and usually results in failure. In order to account for this blow out problem the group has decided that carbon grease will be used as the electrode. Using dielectric carbon grease ensures that the voltage applied is even distributed throughout. A thick even coat of the grease will ensure that the VHB is not exposed upon deformation.

The wing frame itself is made of an Al6061 to prevent deflection while under strain from the elastomer. The connectors must be insulating to prevent arcing to the valuable testing equipment in the lab. Delrin plastic, characterized by its resistivity to deflection and electrical current make it an ideal candidate for these parts.

**<u>Electrode Test Configurations:</u>**

For this project we are focusing on two main implementations of electrode placement on the wing platform, which leads to two test configurations. The first test configuration which we are interested in is placement of the electrodes on the entire surface (top and bottom) of the membrane (Figure 4).

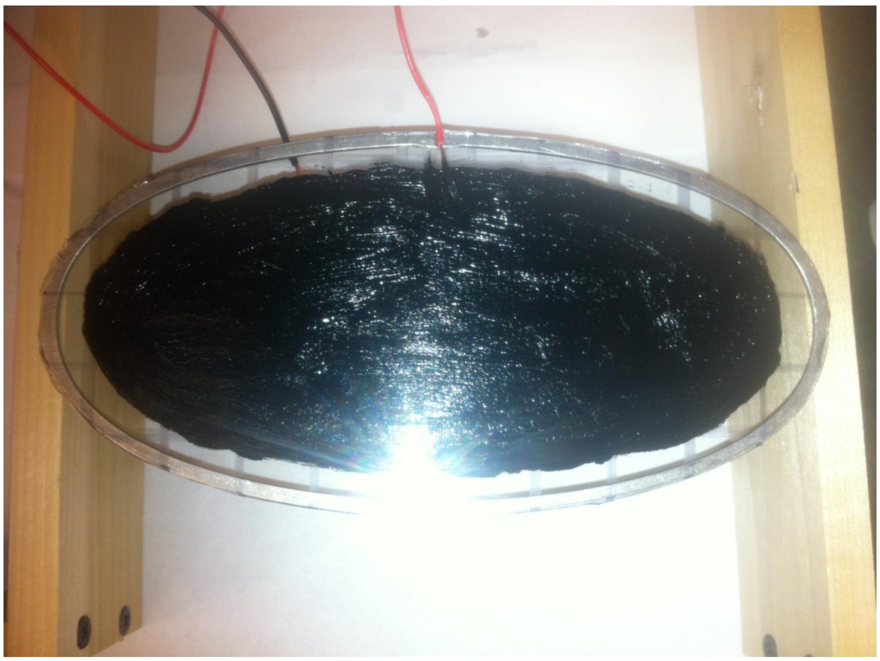


Figure 4- Shows the lift prototype with the electrode covering the entire surface.

The goal of this test configuration is to increase the lift of the wing platform as well as increase the critical angle of attack. This configuration will confirm the results found by Dr. Dickinson and Dr. Oates in the summer of 2010.

The second test configuration we are interested in can be seen below in Figure 5.

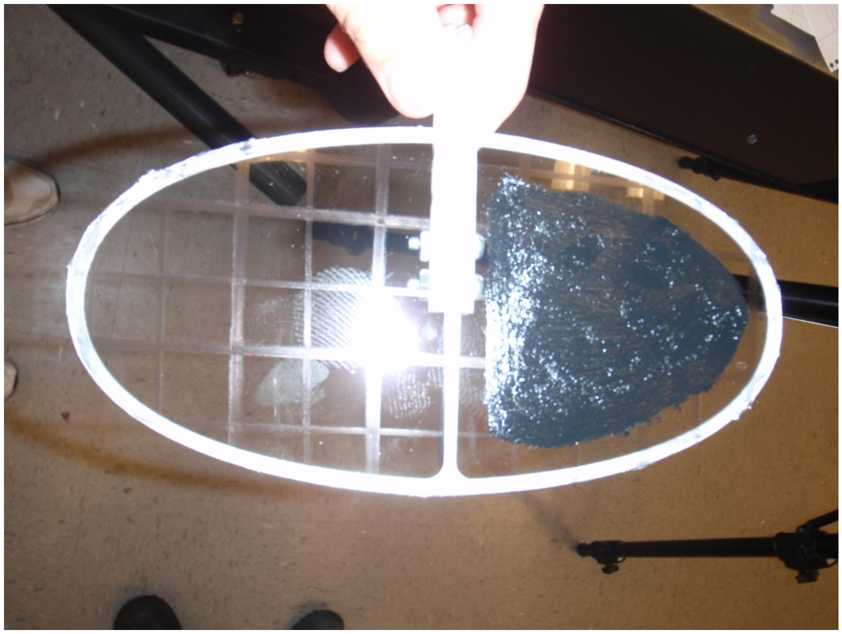


Figure 5- Shows the roll test configuration.

The focus of this configuration is to test the viability of using a dielectric elastomer as a control surface in a MAV. The theory is that when a voltage is applied to the electrodes, it will change the aerodynamic properties of one side of the elliptical wing enough to induce roll. As in the leading edge configuration, the thickness of the electrode, as well as the applied voltage will be varied in order to optimize the desired result.

**Experimental Equipment**

Figure 6- REEF Low Speed Wind Tunnel

Figure 6 shows the low speed wind tunnel at the REEF testing facilities. This tunnel is specifically designed for low Reynolds number testing. The test section is one meter squared and it is capable of reaching wind speeds in excess of 20 meters per second.

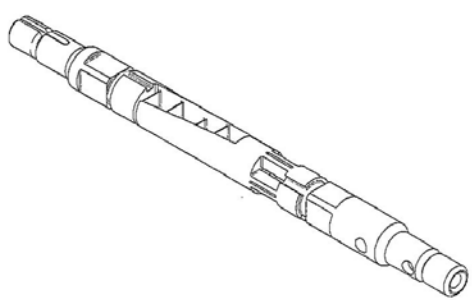


Figure 7- Sting balance

Figure 7 shows the sting balance used to acquire data. This sting balance has tolerances up to ten pounds of force in six degrees of freedom. This piece of equipment is able to measure vertical, horizontal, and axial forces, as well as pitch, yaw, and rolling moments.  It takes these measurements and converts them to a digital signal.

**Figure 8- Movable test platform**

Figure 8 shows the support platform that is connected to the sting. This platform uses two linear motors controlled via lab view in order to change the angle of attack of the wing while keeping the wing in the center of the free steam.

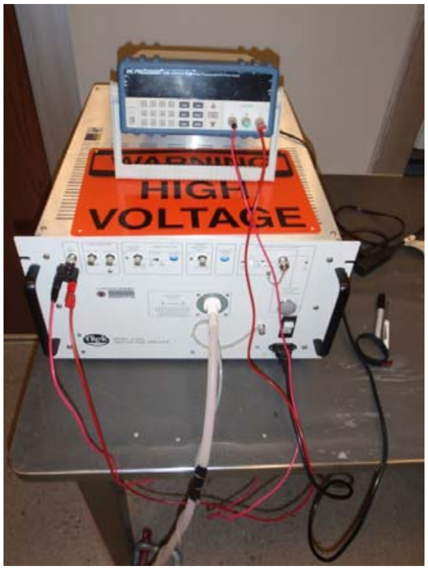



Figure 9- Power supply used for testing

Figure 9 shows the high voltage equipment used to actuate the elastomer. A standard one channel DC power supply (top) was used as an input for the high voltage power supply (bottom). The high voltage power supply is able to produce ten thousand volts at forty amps. This supply has a transformer that steps every volt inputted in to one thousand.

Figure 10- Lab view setup for experimentation

Figure 10 shows the lab view setup used to record data and control the system.

**Experimental Procedure**

See appendix pages 30 through 34 for complete wing assembly instructions.

Firstly make sure that the labview program is up and running, and that all data acquisition instruments are on for at least one hour before measurements are taken. Input initial values for the initial parameters if needed. Fasten the entire wing assembly to the sting balance and tighten both set screws until snug. Make sure that all wires are free from obstructing the linear motors at the base of the test platform, and leave the room. Check that the high voltage amplifier leads in and out to make sure there are no shorts in the electrical circuit. Make sure the input DC amplifier is set to zero volts and the wind tunnel is off and run the tareing program with lab view. After the system has been tared select the run icon on lab view and wait to be prompted to input wind speed. After desired speed is reach and the flow is at steady state, proceed with the running of the test cycle at a baseline with zero voltage applied. Next change the input voltage as desired keeping in mind that the gain on the input is one thousand. Now run the wind tunnel measurements program the same as was done for the baseline test. Once all the desired speeds have been reached for an applied voltage, change the input voltage and run the tunnel test at each desired wind speed. Continue this process until the entire test matrix (Appendix page 26).

## Results

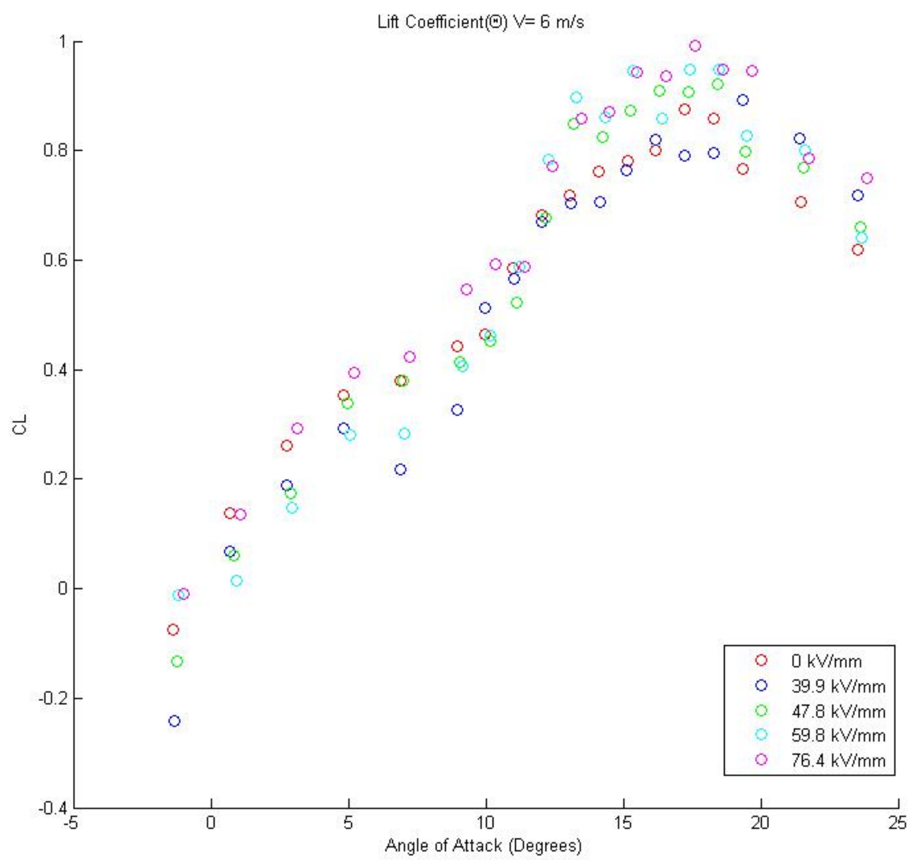



**Figure 11- Shows the $C_L$ versus AOA for six meters per second as voltage on the electrode is increased from 0 to 5.75 kV.**

The data above shows that in there is an increase in the lift coefficient and a stall delay at both test speeds for the wing with the entire membrane used as an electrode. The data for six meters per second is not as definitive as it is for ten meters per second. This discrepancy could be due to the sensitivity of the equipment. One major contribution to the variation of data in the six meters per second figure is due to vortical shedding from early flow separation.

This graph however shows that there is still an increasing trend in lift coefficient and delay of stall as the voltage applied increases. These runs also show an increasing trend in the coefficient of drag (See Appendix page 27). The inherent error due to instrumentation and standard deviation in this case is extremely small (on the magnitude of 1*10-8) making the error bars too small to view on the graph.

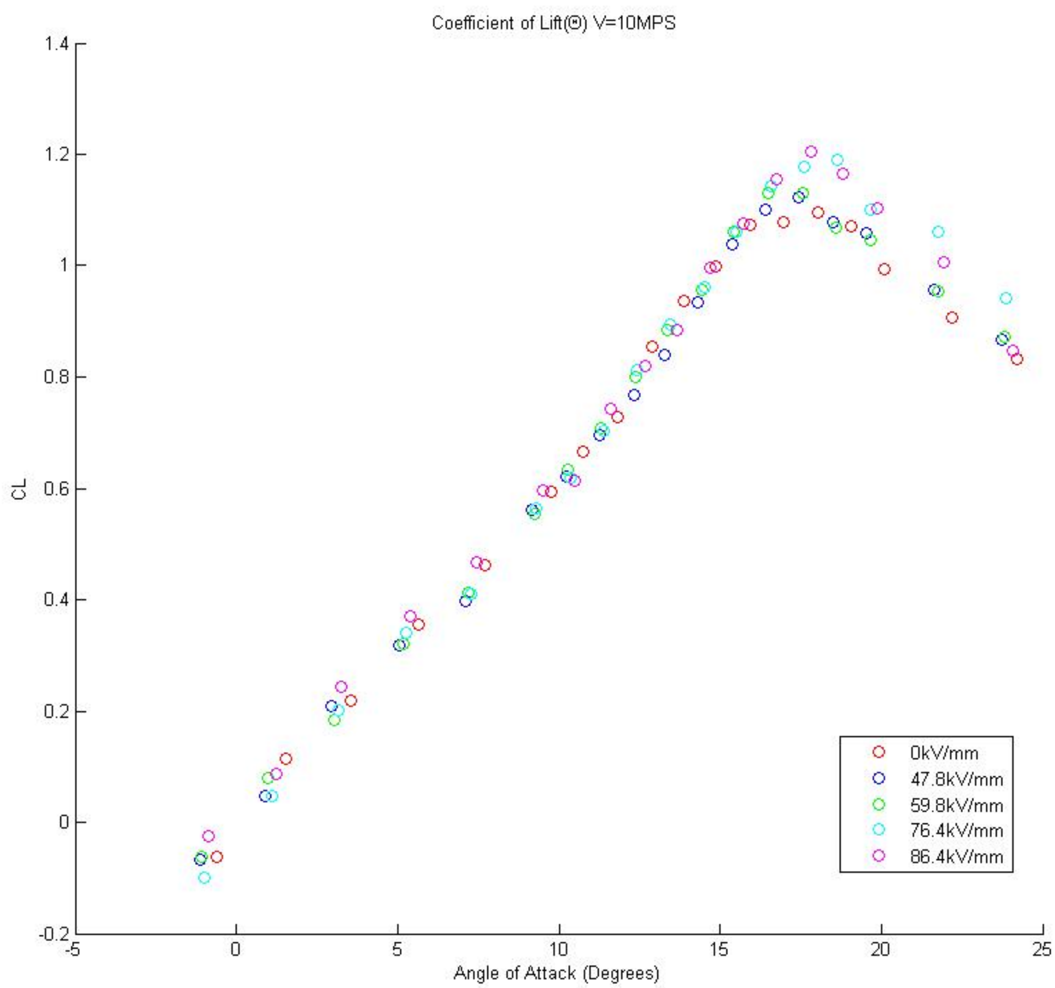



**Figure 12- Shows the $C_L$ versus AOA for 10 meters per second as voltage on the electrode is increased from 0 to 6.5 kV.**

The data from the ten meters per second runs for the full electrode configuration show a definite increase in lift coefficients and delay stall. As the voltage increases from zero to sixty-five hundred volts the lift coefficient grows by 20% and stall is delayed by three degrees. This is a substantial result considering that the wing itself does not have any sort of mechanical flap. These runs also show no major increase in drag until stall occurs (See Appendix page 27). As with figure 11 (page 14) calculated errors were low enough to not be seen on a graph of this size.

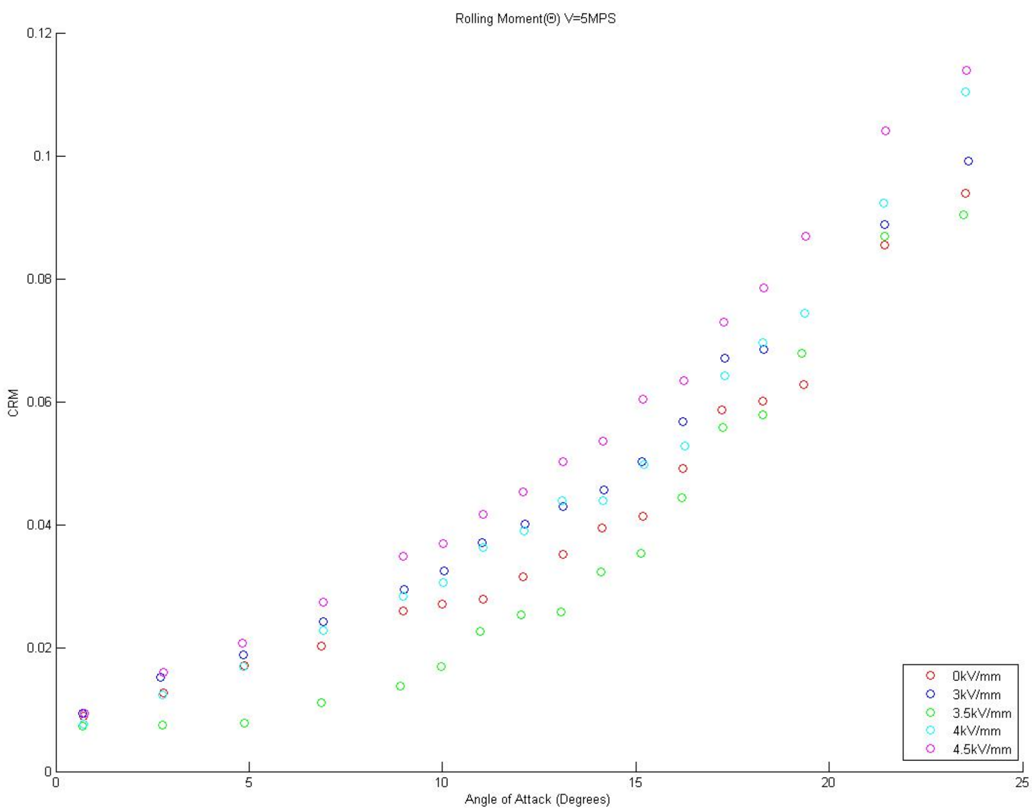



**Figure 13- Scatter plot of the coefficient of angle of attack vs. coefficient of rolling moment at a wind speed of 5 mps.**

The data above shows the five meters per second data acquisition for the roll prototype wing. Although the data plot resembles a generic coefficient of rolling moment graph, the increase in roll is not correlated to the increase of voltage across the electrode. This discrepancy in the data can be more understood by observing the $C_L$ vs. angle of attack as well as the net rolling moment plots shown on appendix page 28. Although the exact reason is unknown there are two reasonable hypothesis for the discrepancy. The first is due to the signal to noise ratio inherent in all measuring devices. The forces imparted on the wing are much smaller at five meters per second than they would be at nine meters per second. The second reason for scattered results may be due to vortical shedding resultant of early flow separation. As the wing begins to stall the vortices from the separation point will propagate from the wing and cause vibrations in the testing equipment. The error associated with these measurements is five orders of magnitude lower than the values receive so it is not shown. (See appendix page 28 for AOA vs. $C_L$ and AOA vs. CRM(net))

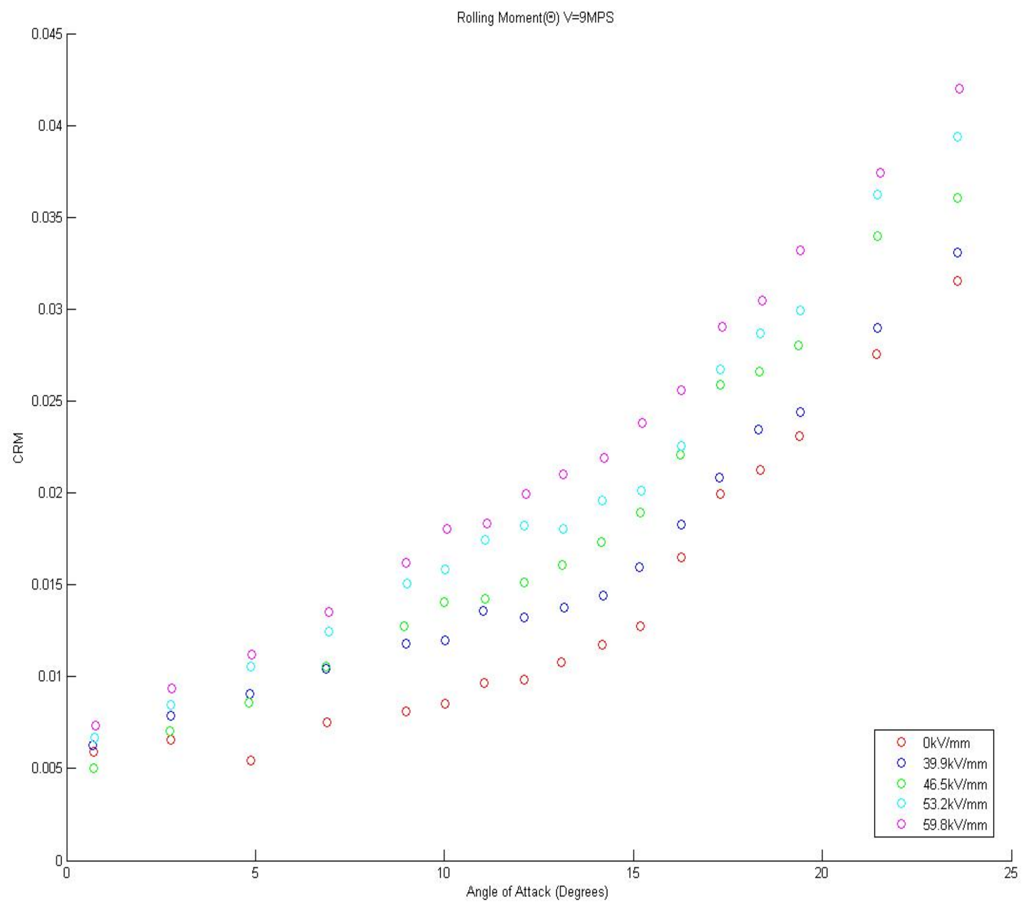



**Figure 14- Scatter plot of the coefficient of angle of attack vs. coefficient of rolling moment at a wind speed of 9 mps.**

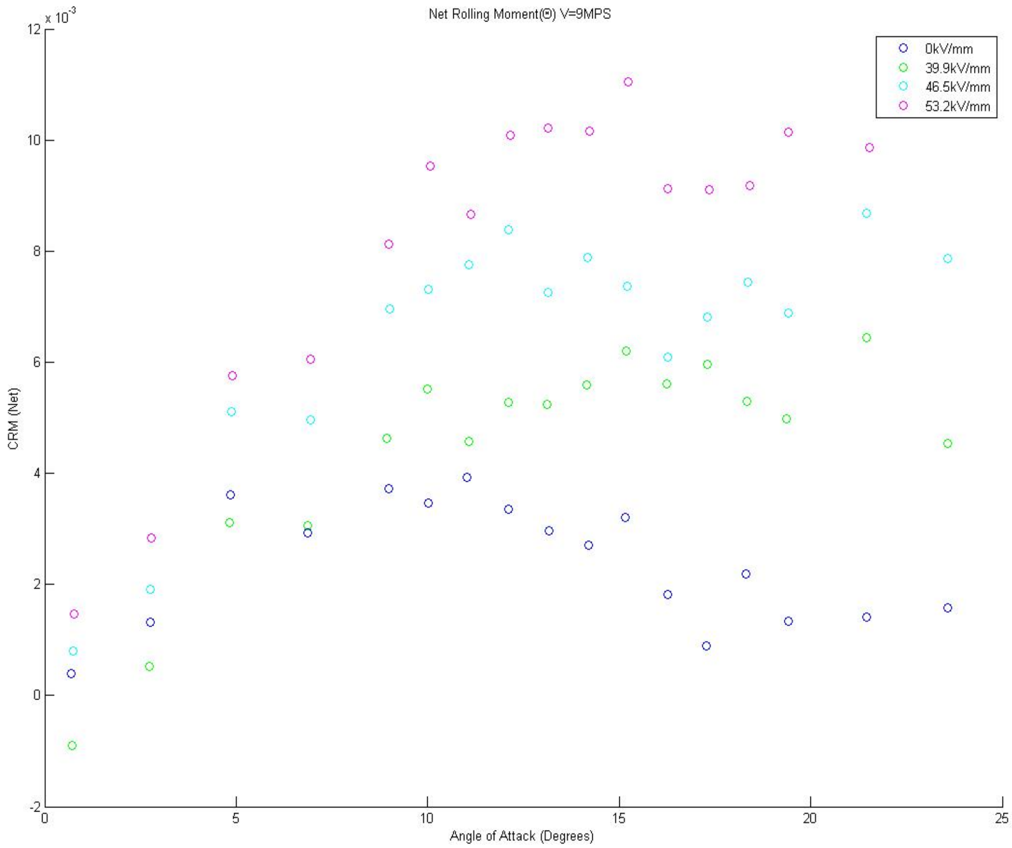



**Figure 15-Scatter plot of the coefficient of angle of attack vs. net change in rolling moment at a wind speed of 9 mps.**

The data acquired from the nine meters per second for the rolling wing prototype is shown above (figures 14&15). Figure 14 shows the magnitude of the angle of attack vs. coefficient of rolling moment. This graph shows a positive correlation between an increase in voltage and an increase in rolling moment. As the voltage increases from 0 to 4.5 Kilovolts there is an eighty-five percent increase in rolling moment at the point of stall. This is a substantial increase that is backed by figure 15 which shows the net change in the coefficient of rolling moment. As before error in the data is too small to show on the plot. (See appendix page 29 for AOA vs. $C_L$)

**Conclusion**

The ultimate goal of this project was achieved. The client, Dr. Dickinson, gave specific instructions that the viability of rolling an aircraft with an adaptive structure be tested. The client also asked the group to verify the data found in the summer of 2010 by PhD. candidate Michael Hays. The test results showed an increase in the coefficient of rolling moment of eighty-five percent at airspeed of nine meters per second, as the voltage applied to the membrane ranges from 0-4.5 kilovolts. These results prove that a dielectric elastomer could be used as a control surface and ultimately replace hydraulic motors and there heavy components. The data from lower tunnel speeds is inconclusive due to what the group belives to be the signal to noise ratio of the testing equipment and the early separation of flow. This early separation of flow may have generated vortices in the air which may have had an adverse effect on the testing equipment such as vibration.

The lift results show an increase in lift of twenty percent and a delay of stall of 3 degrees at a wind speed of ten meters per second.  These results verify the previous work done in this field and provide proof that adaptive structures are able to increase lift and possibly replace current control surfaces such as deployable flaps. As with the rolling prototypes the results are not as definitive for lower wind speeds. The lift prototype shows and generally increasing trend as the voltage is increase from 0 to 5.75 kilovolts, but nothing substantial.

**Future work**

In the future the possibilities for the implementation of dielectric elastomers are endless. One of the first things that must be done is flow visualization in order to get a visual grasp on the flow behavior that causes a discrepancy in the data. The properties of this wing make it ideal for beginning research in control surfaces. Due to the capacitive nature of VHB 4910, the entire membrane could be considered a strain gauge. With proper calibration it is possible that a control system could vary the voltage though changes in air speed and angles of attack to maintain the same coefficient of lift or rolling moment. These are the next inevitable steps in the field of smart materials and there affect on MAV's.

**Environmental Impact**

VHB 4910 is an acrylic tape. Like all other plastics VHB is very hard to recycle, is not readily biodegradable, and has a petroleum base. Its production involves the use of volatile chemicals such as acrylic acid. That being said hopefully advancement with this material will replace common mechanical or hydraulic control surfaces in aviation applications. The amount of fuel and raw materials that will be saved in weight reduction and replacement of hydraulics make this an environmentally friendly implementation (enotes.com).

**Works Cited**

1) Dickinson, Benjamin. Oates, William. "Aerodynamic Control of Micro Air Vehicle Wings Using Electro active Membranes". © August 2010.
2) "Dielectric Elastomers" http://en.wikipedia.org/wiki/Dielectric_elastomers. Accessed November 20, 2010.
3) "Acrylic Plastic" http://www.enotes.com/how-products-encyclopedia/acrylic-plastic. Accessed March 7. 2011

# Appendix I

## Calculations

Voltage Applied/ Area

$L_1 := 2in$ $W_1 := 4in$ $T_1 := .04in$ $V_1 := L_1 \cdot W_1 \cdot T_1$

$V_1 = 5.244\times 10^{-6} \cdot m^3$ $L_2 := 3 \cdot L_1$ $W_2 := 3 \cdot L_2$ $T_2 := \frac{V_1}{L_2 \cdot W_2}$

$T_2 = 2.963\times 10^{-3} \cdot in$ $v_1 := 3KV$ $F_1 := \frac{v_1}{T_2}$

$$F_1 = 39.862 \frac{KV}{mm}$$

**Test Matrix**

| Run | Protoype | Wind Speed (m/s) | Volatge (kV) |
|---|---|---|---|
| 1 | Roll | 5 | 0 |
| 2 | Roll | 9 | 0 |
| 3 | Roll | 5 | 3 |
| 4 | Roll | 9 | 3 |
| 5 | Roll | 5 | 3.5 |
| 6 | Roll | 9 | 3.5 |
| 7 | Roll | 5 | 4 |
| 8 | Roll | 9 | 4 |
| 9 | Roll | 5 | 4.5 |
| 10 | Roll | 9 | 4.5 |
| 11 | Lift | 5 | 0 |
| 12 | Lift | 9 | 0 |
| 13 | Lift | 5 | 3.5 |
| 14 | Lift | 9 | 3.5 |
| 15 | Lift | 5 | 4.5 |
| 16 | Lift | 9 | 4.5 |
| 17 | Lift | 6 | 0 |
| 18 | Lift | 10 | 0 |
| 19 | Lift | 6 | 3 |
| 20 | Lift | 10 | 3 |
| 21 | Lift | 6 | 3.6 |
| 22 | Lift | 10 | 3.6 |
| 23 | Lift | 6 | 4.5 |
| 24 | Lift | 10 | 4.5 |
| 25 | Lift | 6 | 5.75 |
| 26 | Lift | 10 | 5.75 |
| 27 | Lift | 10 | 6.5 |

## Additional Graphs

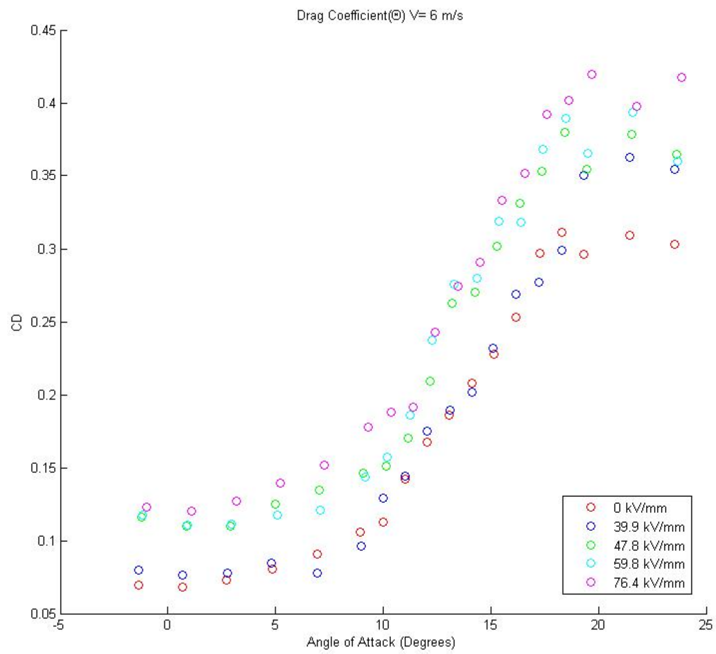



**Figure 16- Shows drag coefficient vs. AOA for 6 meters per second**

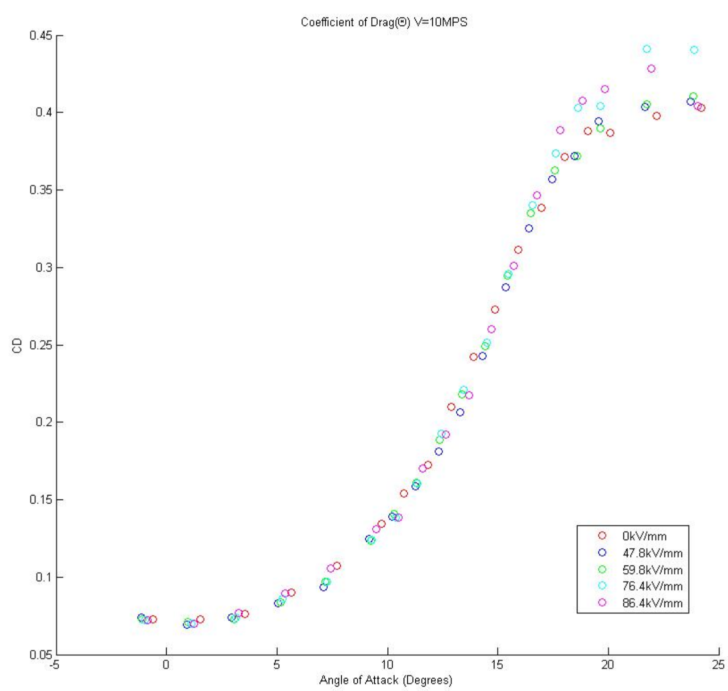



**Figure 17-Shows drag coefficient vs. AOA for 10 meters per second**

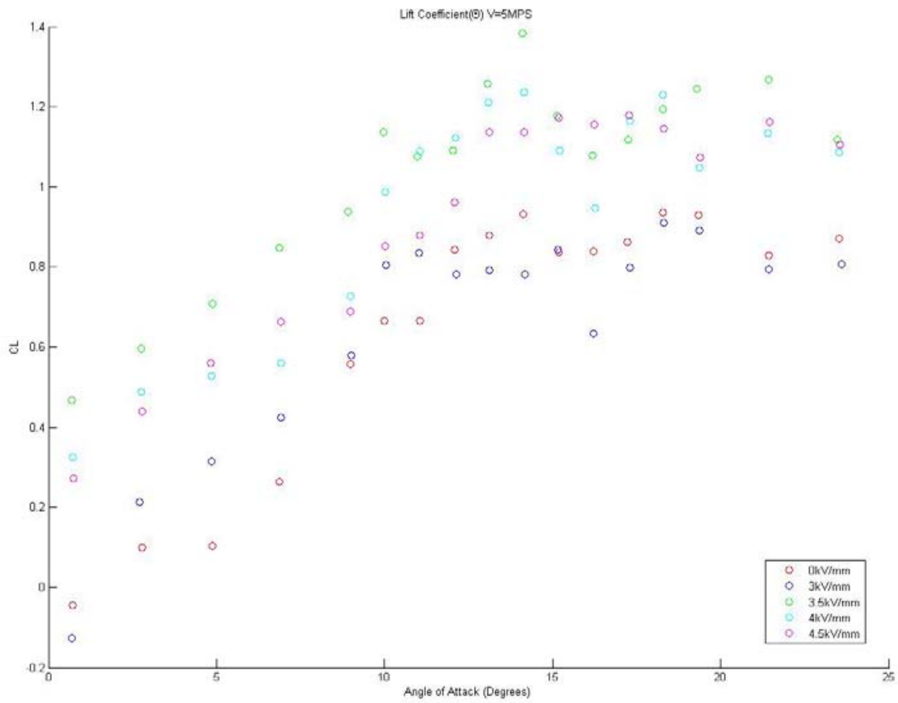



**Figure 18-Shows lift coefficient vs. AOA for 5 meters per second**

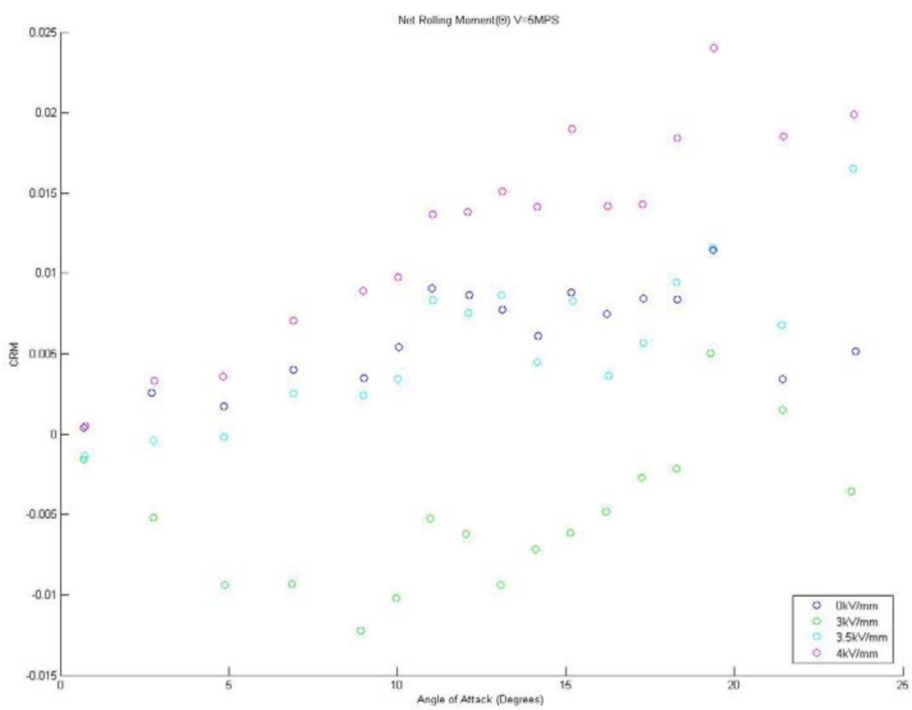



**Figure 19-Shows net coefficient of rolling moment vs. AOA for 5 meters per second**

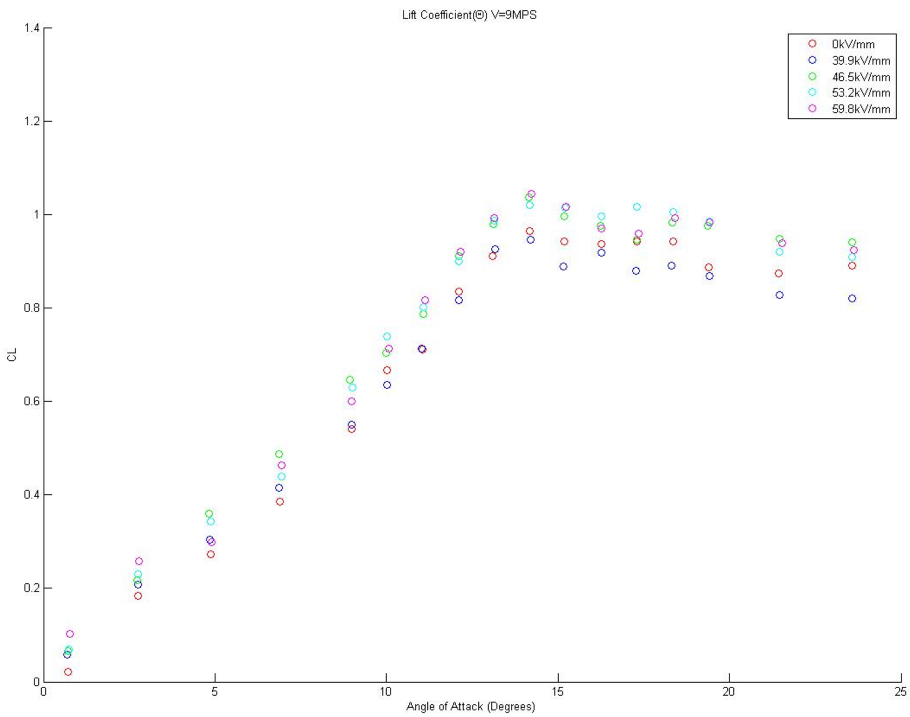


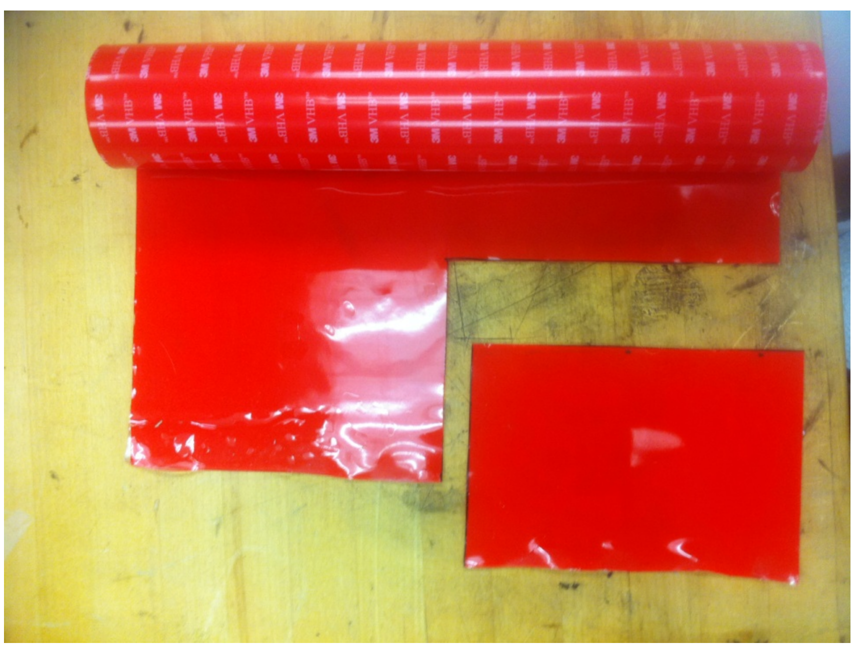

**Figure 20-Shows lift coefficient vs. AOA for 10 meters per second**

# Appendix II:Operations Manual

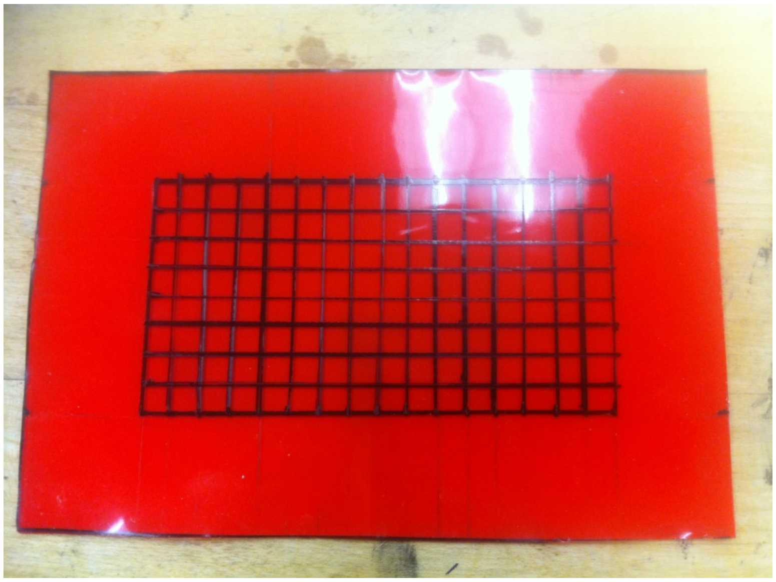
**Materials needed**

1) One sheet VHB 4910 (4"x  6")
2) One tube of Carbon conductive grease
3) One 12" x 6" wooden Frame
4) One elliptical wing frame (20cm x 10cm x 1.6mm)
5) One New or very sharp razor blade
6) One pair of scissors
7) One sharpie
8) One ruler
9) Two 3' strands of insulated copper wire (no less than 20 guage)
10) One cotton ear swab
11) One bottle of super glue
12) One EMCO C80 High voltage linear amplifier
13) One two channel DC Voltage supply

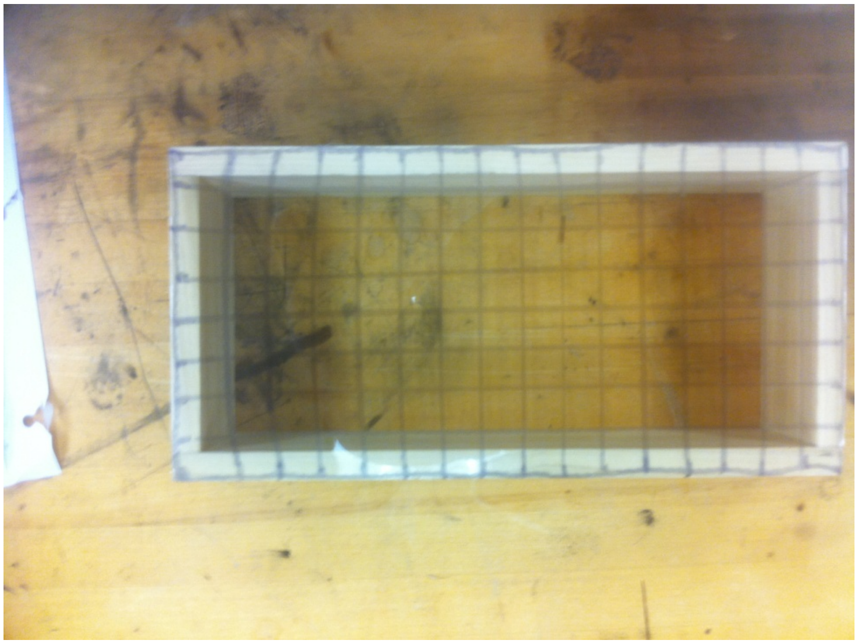
Step 1: Cut out a 4" by 6" piece of VHB2910 as shown below.



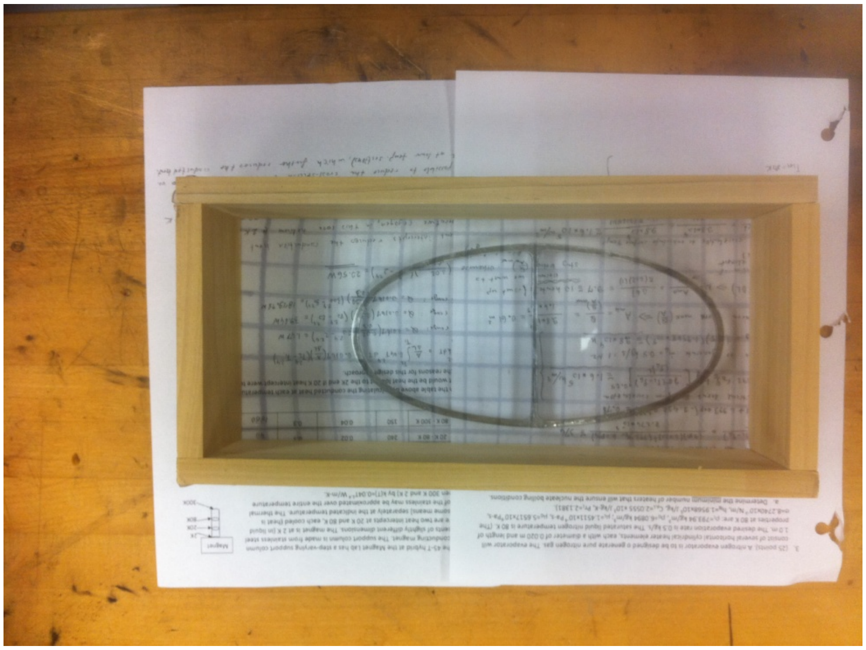
Step 2: Draw a 2” by 3” square with .25” gridlines on the adhesive side of the tape.



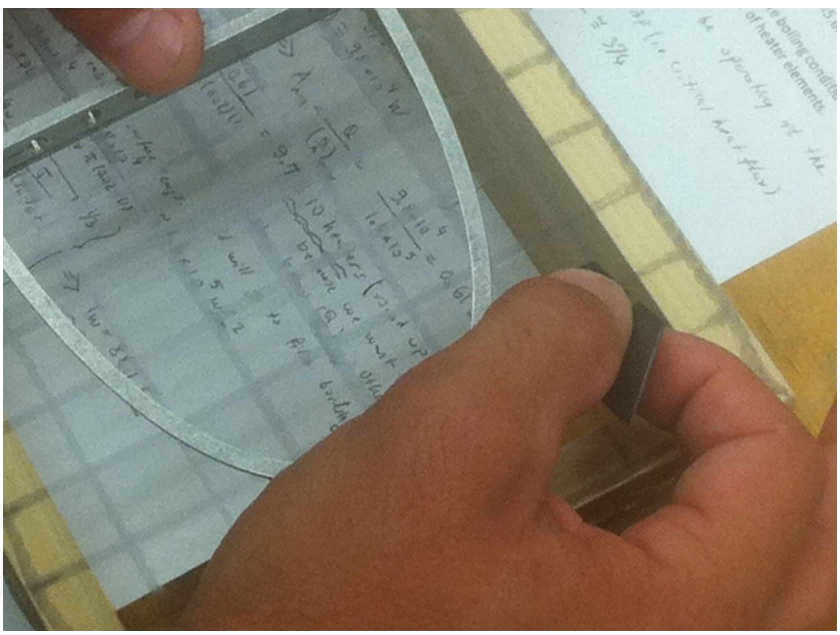
Step 3: Remove the tape from the protective skin and stretch it over the wooden frame. Make sure that the outside lines of the grid match up with the outside edges of the wooden frame Make sure that the stretching is done as carefully as possible to ensure a uniform biaxial strain of 300%.



Step 4: Take the elliptical wing frame and set on the tape with the mounting bracket face up. In order to ensure strong adhesion flip the frame over on a non-stick background and leave to set for at least 12 hours.

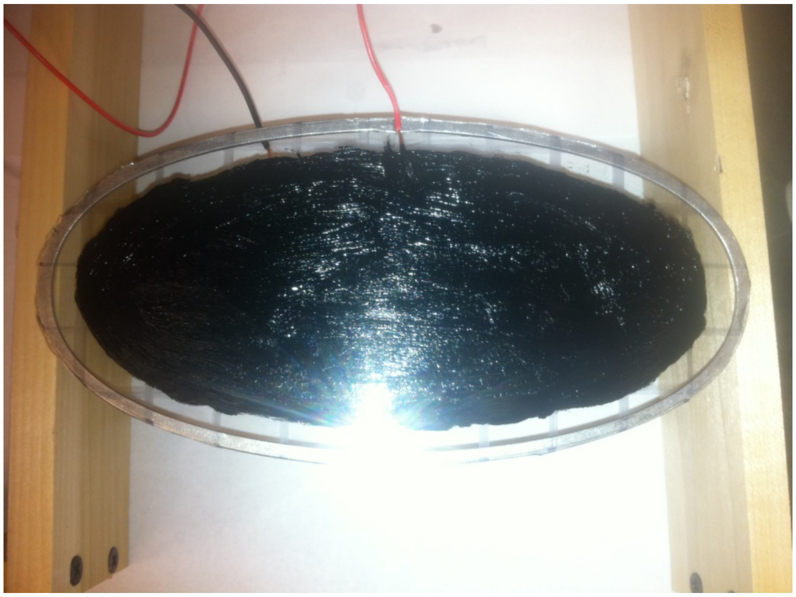


Step 5: After letting the frame set for 12 hours, flip the wooden frame over. Take a new utility razor and carefully cut around the edges of the elliptical frame making sure that spare VHB does not double up and stick to itself.

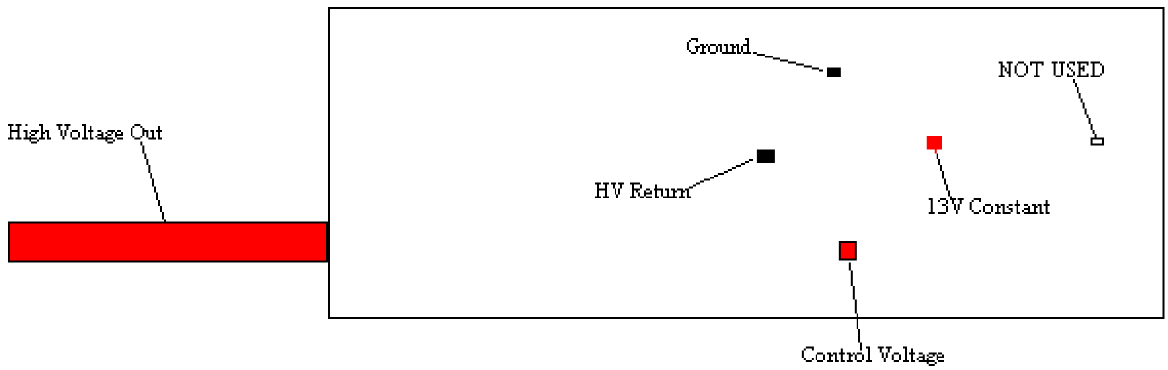


Step 6: Using the cotton ear swab carefully apply a thin layer of carbon conductive grease to both surfaces of the wing. Do not spread grease to close to frame to avoid arcing and failure (grease was spread about .25" away from the frame).

Step 7: Strip .5" off both of sides of both 20 gauge wires. Place the wire on the edge of the frame insuring the part in contact with the frame is insulated and the part in contact with the membrane is striped. Apply a small amount of super glue to the edge of the wing and hold until it has set. Repeat this process for the opposite side and cover the exposed copper in carbon grease.



Step 8: Connect the EMCO C80 high voltage linear amplifier as shown below in the diagram.




Activation: Ensure that the power supply connected to the 13V constant terminal is set to 13V and 0A. Next program the second channel of the supply to desired voltage keeping in mind an amplification of 1 volt to 850 volts. Once both channel are on and set the wing will activate and there will be a visual change in the area of the electrode.

NOTE: Voltage applied can range from 0- 6kv. Wings will experience failure if voltage is exceeded. Beware of electric shock.