

# Initial Characterization of Self-Activated Movable Flaps, “Pop-Up Feathers”

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Self-activated movable flaps or pop-up feathers are used by a preponderance of feathered creatures as a means to modify foil characteristics during landing or incurred high angles of attack (gusts). When flow would normally separate, causing drastic decreases in lift, these pop-up feathers will activate, thus delaying the effects of stall. Although these flaps can almost entirely eliminate the stall region in a common UAV foil (NACA 2412), they have yet to be used commercially on any aircraft. The absence of these flaps is attributed mainly to the lack of understanding in their characteristics. This paper uses wind tunnel testing in an attempt to initially characterize the use of such flaps in low Reynolds number regions ( $1 \times 10^5$ - $5 \times 10^5$ ), including their placement, size and ideal material characteristics

## Nomenclature

$c$	=	chord
$C_d$	=	coefficient of drag
$C_l$	=	coefficient of lift
$C_m$	=	coefficient of moment
$x$	=	distance from leading edge, inches

## I. Introduction

As aircraft designs become smaller in the age of UAVs (Unmanned Aerial Vehicles) and MAVs (Micro Aerial Vehicles), engineers and scientists look to nature for new flight ideas and techniques. Birds, for example, are incredibly efficient fliers compared to their similar sized UAV counterparts. One aspect of birds' flight, which is believed to make them so efficient, is the effective means of dealing with flow separation on their wings. During landing or in gusty winds, feathers on the upper surface of the wing pop-up. These “pop up” feathers have been theorized to delay flow separation allowing higher lift at lower flight speeds and in adverse conditions<sup>1</sup>.

The advantageous effect on lift created by these pop-up feathers is one that UAVs, MAVs and possibly large commercial vehicles could benefit from. The behavior of such a flap is illustrated below in Figure 1. At low angles of attack the flap remains attached to the airfoil surface and, in theory, does not affect the wing's aerodynamics. However, as the angle of attack is increased and flow separation begins to occur along the trailing edge, the flap lifts and self-adjusts to a position dependent upon the aerodynamic forces and flap configuration/weight, to reattach the flow.

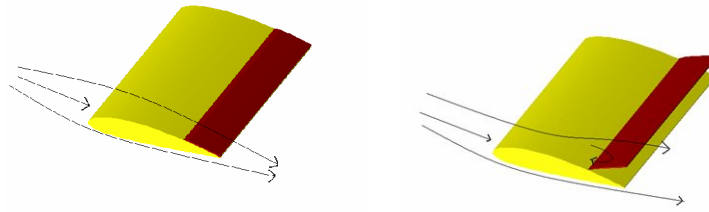
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**Figure 1. Effects produced by flaps. Left, wing at zero angle of attack (AOA); right, wing at high AOA (image reproduced from source 1)**

Self-movable flaps are a passive lift improvement device which, in theory, would require no external control, self-adjusting dependent on local flow conditions. The opening and closing of the flap is controlled only by the flow around the wing section. These flaps could prove to be useful on approaches to decrease approach speed or for high angle of attack (AOA) vehicles to keep flow attached during maneuvers (the latter may require active control of flaps). In passive control conditions, the flap deploys when the pressure force under the flap exceeds that above the flap, causing the flap to rise until an equilibrium condition is reached. Active control devices used to achieve similar effects require electronics, power systems and other equipment to control the mechanism, significantly increasing the weight and complexity of the vehicle, and in many cases increase the possibility of mechanism failure. It is the removal of extra devices and electronics which not only improve cost considerations, but also the reduction in weight while still improving lift in poor conditions, which make these flaps appealing. Unlike active flow control devices such as periodic suction and blowing or driven flap oscillation, the self-activated movable flaps provide a simple and cost-effective tool for increased lift, and may be very beneficial for smaller aircraft without the weight allowance or power necessary to use active flow control devices.

The beneficial effects of self-activated movable flaps have been proven but not explored in both the low Reynolds number regime of bird flight ( $10^4$ - $10^5$ ), by Müller and Patone<sup>2</sup> in 1990, and the Reynolds number range common to gliding aircraft ( $1$ - $2 \times 10^6$ ), by a joint coalition of Berlin technical institutes in 1995<sup>3</sup>. The purpose of the herein described wind tunnel experiments will be to initially characterize self-activated movable flaps in a low Reynolds number application, common to that of UAVs ( $1 \times 10^5$ - $5 \times 10^5$ ). Due to the breadth of testing required to fully characterize the effects of these flaps (all chord placements, a wide range of Reynolds number, airfoils types, and multiple flap configurations), this testing will instead attempt to begin characterizing these potentially revolutionary flight devices by adding insight as to some of the effects of flap placement and configuration.

## II. Method

These experiments were completed using an induction wind tunnel with a 14 in. (0.356 m) by 10 in. (0.254 m) test section, and an adjustable speed of up to 150 mph (67 m/s). The wind tunnel uses suction to draw air at sea level pressure (14.7 psi) and room temperature (70° F) through a honeycomb mesh, two screens, and tunnel contraction upstream of the test section to reduce turbulence.

The attitude changes were conducted using a pyramidal-type mechanical force balance with rotational degrees of freedom in both yaw and pitch, capable of measuring lift, drag and moment forces. The forces were isolated to individual components and measured using piezoelectric load cell and an analog voltmeter. Calibration and zeroing of the components was conducted using free weights in both lift and drag directions to loads greater than expected. Output voltages were then trended to applied loads and regressed to develop output volt to load transfer functions. Tare forces incurred due to force balance interaction with the wind tunnel flow were removed from test data.

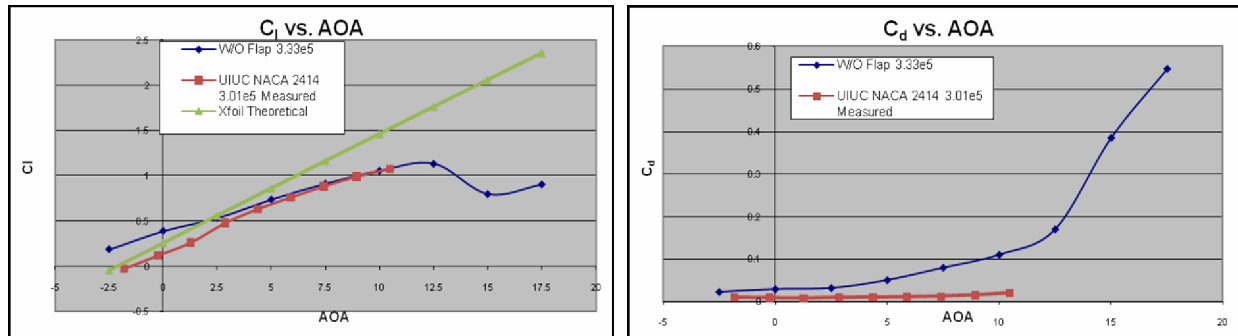
A NACA 2412 profile was chosen since it is a well-understood airfoil common to that of model aircraft and UAVs. In future tests, experiments should be conducted on other airfoils with varying shapes such as the RAF 19 (similar to soaring birds) or tapers to identify best configurations for these flaps. The wing section was created using existing foil data<sup>4</sup>, 3-D drafting software and a Rapid Prototyping Machine (RPM). The extruded ABS wing section was further sanded and filled to remove imperfections, and finally painted to increase contrast for later visualization.

The wing section was restricted to 11.75 in. in span, due to the height limitation of the RPM. Since the wing would not span the 14 in. cross section of the induction wind tunnel, two modifications were enacted to mount the wing. First, the wing was mounted offset by 0.5 in. to produce asymmetric forces on the wing section and prevent violent oscillations incurred in subtle asymmetric flow changes. Second, a single endplate of 1/16<sup>th</sup> in. thick and 2 in. high aluminum was used on an exposed wing tip to simulate an attached fuselage (or the body of a bird) and a single exposed wing tip.

Initial Reynolds testing ranges were determined from the wind-tunnel speed, mount limitations and the recorded Reynolds regime of UAV aircrafts. The initial feasible testing range was  $10^4$ -  $10^6$ , which was even further reduced due to potentially detrimental stresses at high angles of attack produced on the wing section at high velocities. The final acceptable testing range was determined to be  $3 \times 10^4$  -  $5 \times 10^5$ . Once testing began, one Reynolds number was chosen as an experimental constant in order to accurately compare the effects of flaps between different runs. The Reynolds number used throughout the experiment was  $3.3 \times 10^5$  with three exploratory tests completed outside this regime. Figure 2 shows the base case of the wing with no attached flaps at  $3.3 \times 10^5$  Reynolds number. Stall occurs in between 12.5 deg and 15 deg, as was to be expected from previous knowledge of the NACA 2412 airfoil.

The airfoil measurements were then compared to theoretical values of  $C_l$  as produced by XFOIL<sup>5</sup> and measured values of similar airfoils for  $C_l$  and  $C_d$  by University of Illinois Urbana Champagne (UIUC)<sup>6</sup>. Although neither source can provide values near stall, or identical condition to these tests, the data can be used to validate magnitude and general trends.

As can be seen below, the data produced by UIUC follows the slope of this data in mid- angles of attack at which point the data is stopped, indicating similar angles of stall. The UIUC data, however, greatly diverges when compared to test data for  $C_d$  vs. AOA. The drag data does initial follow the same trend, but seems to diverge as angle of attack is increased. This deviation can most likely be attributed to the lift induced drag at the exposed wing tip, causing the drag to significantly increase as lift is produced.

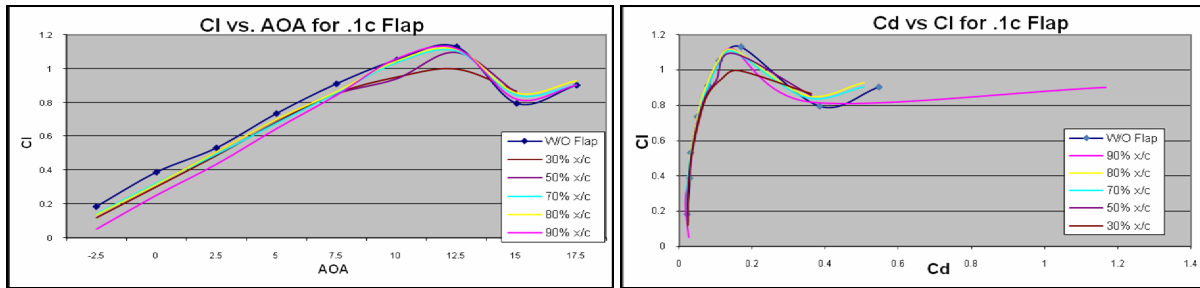


**Figure 2. Initial NACA 2412 airfoils tests without flaps**

For each experiment the airfoil would be mounted to the force balance inside the test section and zeroed. The wind tunnel would be initiated and allowed to settle in speed applicable for the test and measured using a digital manometer and pressure taps fore of the test section. The wing section would then be re-zeroed, and data collected. Data would be measured at 2.5 deg intervals along a pitch-up maneuver (continuous transitions from angle to angle: flow un-halted), between -2.5 deg and 17.5 deg angles of attack. In most cases the flaps were adhered to the wing section using half inch electrical tape. In cases where the tape would not adhere to the test specimen during the exploration of material types, duck tape was used. These tests were completed for varying flap lengths, placement on airfoil, composition, and other variations such as feathering (many small flaps) or multiple flaps. Finally, the data was compiled and calibration equations were used to calculate airfoil characteristic coefficients,  $C_l$ ,  $C_d$ , and  $C_m$ .

### III. Flap Placement and Chord-wise Flap Size

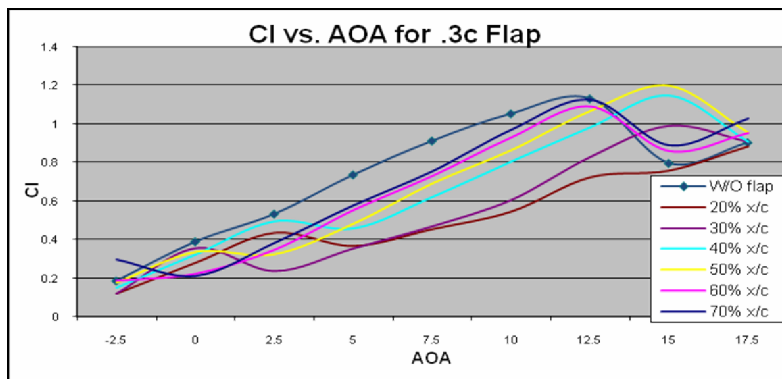
Previous research into self-activated flaps and “pop-up feathers” focused almost entirely on placement near the trailing edge of the wing. It was decided during this trial to experiment with flap placement and width along the entire chord. Therefore different flap configurations were tested from leading to trailing edge in 10% chord intervals including flap sizes from 10 to 40 percent chord. Initial exploration of flap size and placement was examined with rigid flap material consisting of 1/16<sup>th</sup> in. rectangular aluminum.



**Figure 3. .5 inch flap tested with 1/16<sup>th</sup> in. thick aluminum at 3.3x10<sup>5</sup> RN**

Initial tests identified many negative effects produced by flaps at all chord positions, including decreases in lift at all AOA with significant decreases near stall. The reduction in lift at small angles of attack can be attributed to the small lip produced at the leading edge of the flap caused by material thickness. As the flap tests are moved toward the leading edge, significant reductions in lift are incurred because of the rigid flap's inability to follow the curvature of the airfoil. This inability to follow contour at fore chord positions produces a gap at the flaps trailing edge and causes the flow to prematurely separate decreasing the lift produced and thus, the lift coefficient.

The flaps which have been placed at mid- to trailing edge positions show that the loss in lift is negligible at high angles of attack. The flap rises slowly for each incremental angle of attack until the region of stall has passed the flap, at which point the flap begins to flutter widely in the vortices produced by separation.



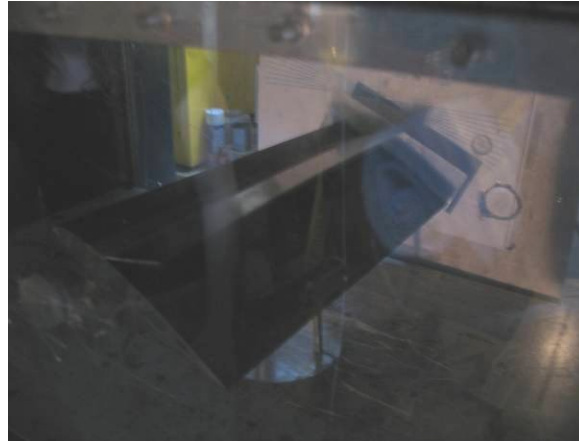
**Figure 4. 1.5 inch flap tested with 1/16<sup>th</sup> in. aluminum at 3. 3x10<sup>5</sup> RN**

The testing of large flaps was consistent with was expected from literature; that is an improvement in lift and delayed stall during high angles of attack for flaps placed near the trailing edge. The drop in lift at low AOA seen in Figure 4 is attributed to the initial deployment of the flap. Because the flap is significantly longer than the early tested flaps, the pressure drop over the flap is significant at even small angles to deploy the flap prematurely, causing a small gap at the trailing edge of the flap and the wing's top surface. This gap causes the flow to be redirected to a path parallel to the plate causing a reduction in lift. The significant reduction in lift for flaps placed near the leading edge is again due to the inability for the rigid flap to follow the curvature of the foil. Because the flap is significantly larger than the 0.1c flap, the negative effects can be expected to greatly increase.

As the angle of attack is increased, the flap gradually rises. When separation occurs on or fore of the flap the reduction in pressure above the flap causes the flap to rise to an equilibrium point. The flap pulls on the flow while the reduction in pressure pulls on the flap, causing the flow to be drawn down and keeping the flow attached for an extended period of time, increasing the lift. In theory, the beneficial effect of the flaps should be experienced as long as some portion of the flap can meet with the free stream flow. Thus, in the use of thick flaps for a passive device, trade-offs must be made as to the loss of lift during low angles of attack to that of the increase in lift and delayed stall at high angles of attack. (If release mechanisms are used and the flaps are submersed into the airfoil contour, trades may not be necessary.) After the separation region has completely covered the flap, the flap will begin to flutter, producing no beneficial or negative effects on lift. Thus, the positive effects seen with rigid flaps can be achieved with flaps of 0.3c and 0.4c placed near the trailing edge.

Below, in Figure 5, an example of a 0.3c test condition for an aluminum flap at stall can be seen. The flap has a subtle bow which is caused by the variation in separation at mid-wing and at the wing tip. As a result of the induced

vortices produced at the exposed wing tip, the flow will naturally stay attached long than the unexposed midsection of the wing. Since the flap must reach some span-wise equilibrium height, the flap is causing some flow near the wing tip to separate prematurely and full beneficial effects mid-wing are not achieved. Thus, this bow produced by localized separation and decreases in lift at low angles of attack produced by material thickness led the authors to investigate alternative material types and flap configurations.

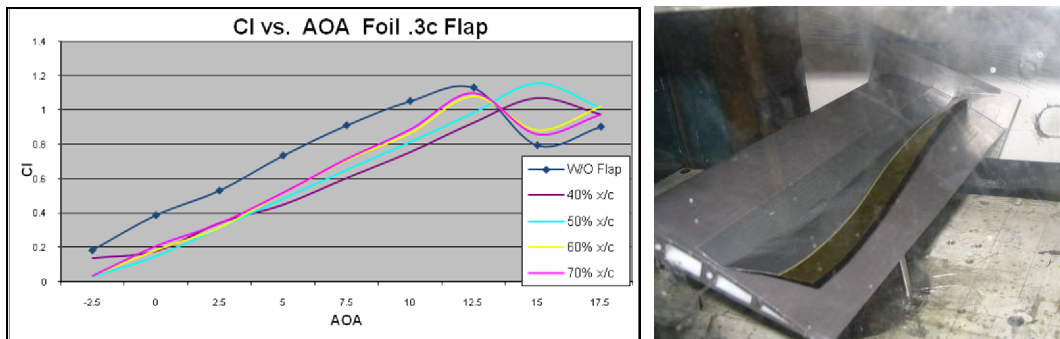


**Figure 5. 1.5 inch aluminum flap identifying flap bow**

#### IV. Flap Material Composition

The material compositions of self-activated movable flaps were explored due to the negative attributes experienced when using rigid flaps. Several different types of materials were examined. An initial sample of thin ( $1/60^{\text{th}}$  in.) industrial aluminum foil was selected as a specimen. As seen in Figure 6, the curvature of the flap has greatly increased when compared to Figure 5. This variation shows the earlier onset of stall in the center of the wing and a delayed stall near the exposed wing tip.

The flexible aluminum flap has provided very similar results. The flap produces a decrease in lift at low angles of attack and a delayed and increased coefficient of lift at high angles for flaps placed near the trailing edge. Although this thin aluminum specimen shows a greater flexibility, the rigidity of the flap still produce a gap at the flaps trailing edge. Also, because of the type of adhesive required to attach the flap, a shear force on the exposed surface of the flap caused the flap to rise further off the surface of the airfoil than the rigid aluminum, causing larger decrease in lift at low AOA. This decrease in rising flexibility at the hinge point may also be the cause of the reduction in lift at high AOA when compared to the results of rigid aluminum plates. Tests with the aluminum foil indicate the material must be easily adhered to the surface, but also more flexible to follow the contour of the wing.



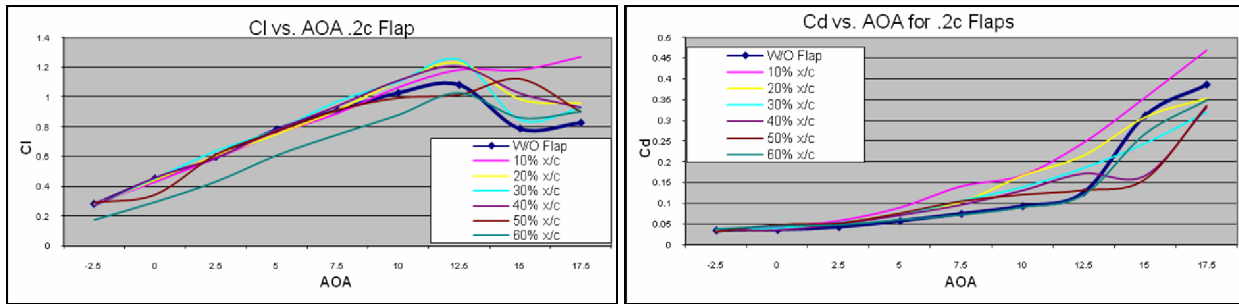
**Figure 6. Test results from  $1/60^{\text{th}}$  in. thick aluminum flap at 3.3e5 RN**

As an exploratory study, standard printing paper was tested as a flap material, however, the aforementioned material was quickly found ineffective. The material, although capable of following the contour of the wing, would shred when stall was approached due to the adverse span-wise pressure gradients caused by localized separation producing strong opposing forces.

Following tests with aluminum foil and paper, certain criteria were ascertained. First, the material must be

flexible in order to shape itself along the curvature of the wing. Rigid flaps were found to rise to a point of average separation causing some areas to separate prematurely, resulting in a loss of lift at low angles of attack. The thickness of the flap material also contributes greatly to the effectiveness of the flap design. Thicker flaps protrude from the wing surface as a finite ridge, disrupting the flow and causing premature flow tripping, again resulting in a loss of lift. The last major criterion requires the flap material to have adequate strength to prevent tearing and, ultimately, destruction at high angles of attack. It was due to these criteria that a thin vinyl plastic was used in flap creation during this trial.

Several types of plastic were attempted with the best results obtained from the clear protective overlay on standard three ring binders. Many plastics were found to be too flimsy or too rigid, in either case causing the material to tear. Very different results than from literature were obtained using this strong but flexible plastic.



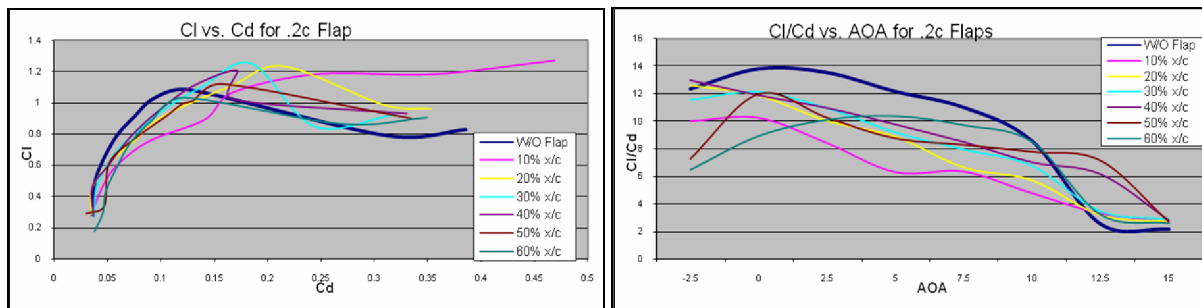
**Figure 7. 1 inch flap plastic flap at 3.3e5 RN**

The best placement of the flap was not near the trailing edge of the wing as previously believed, but instead near the leading edge. Both the lip at the leading edge of the flap and the gap at the trailing edge were nearly removed, causing the flap to follow the contour of the wing, removing the drop in lift at low AOA. The beneficial effects of lift were most significant with a 1 in. flap at 10 percent chord where the effects of stall on lift were nearly eliminated.

The lift curve continues to increase past airfoil  $C_{lmax}$ . The flapped airfoil, after reaching a larger maximum lifting coefficient, achieves a stall angle of attack which produces almost no reduction in lift before the wing section continues to rise in lift.

The drag increase for this flap configuration has also significantly increased, but this increase can most likely be attributed to the testing method with the flaps adhered to the surface of the wing, tripping the flow and causing early transition to turbulent flow. This incurrence of turbulent flow caused by the connection method may prove to increase the similarity of these results to that of our feathered friends. When feathers pop-up on birds, the long barbs on each feather are likely to separate, increasing the turbulence, and thus producing a coupled benefit from a decrease in separation due to these pop-up feathers and turbulent flow.

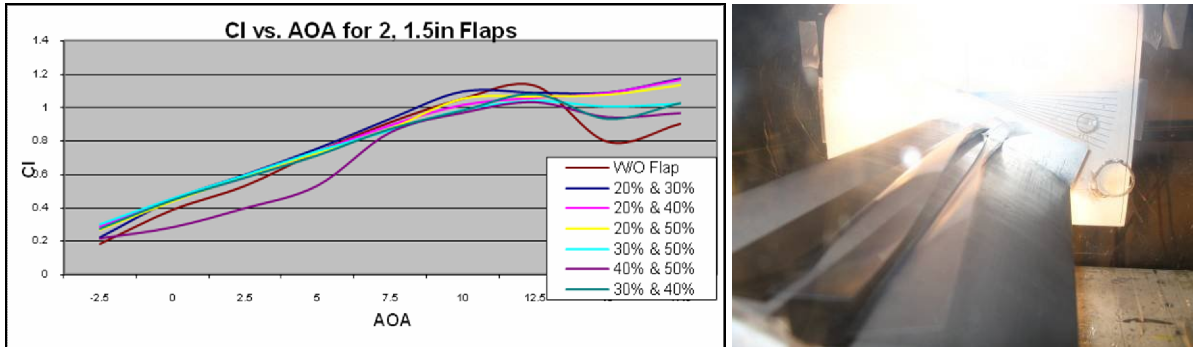
As seen in Figure 8, a lower value of lift-to-drag is developed for nearly the entire test range of the flaps because of the increased turbulence. If these self-activated movable flaps can be introduced into the wings surface, producing only turbulent flow when deployed, these similar lift-to-drag ratios to a standard airfoil are likely to be achieved throughout the testing.



**Figure 8. One inch flap at 3.3e5 RN**

## V. Effect of Flap Dimensioning and Shape

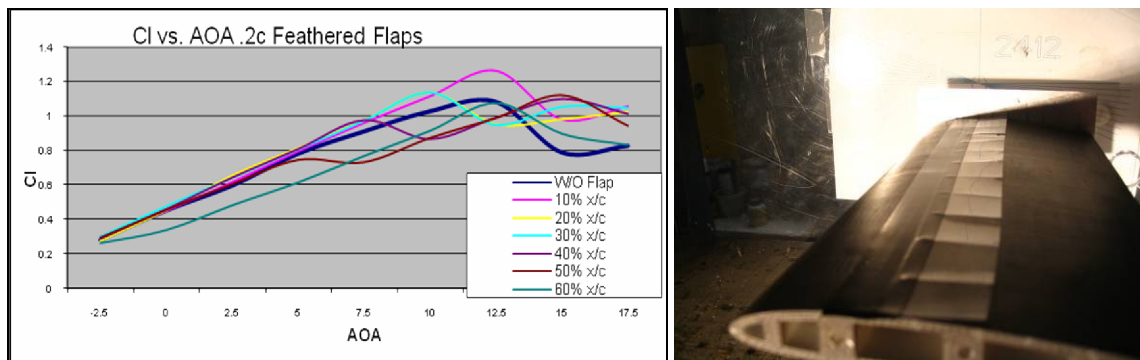
The flap which showed the clearest improvement in previous tests was one inch or 20% chord. This flap not only increased the lifting coefficient at the point of stall but also nearly eliminated the effects of stall on the lift. Figure 7, above, showed these improvements in lift with the greatest values when the flap is placed near the leading edge at 10%-30% chord. Thus, plastic flap material was used in further tests of varied configurations. Up to this point all test were conducted on single continuous rectangular flaps but the authors wondered as to the possible effects produced by modifying the flaps to more closely replicate those of birds' feathers.



**Figure 9. Layered flaps at 3.3e5 RN**

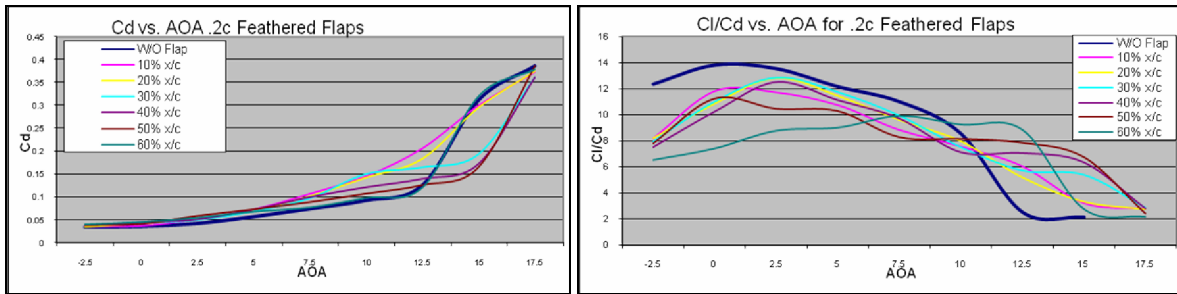
The first configuration changes were to layer the flaps with varying sizes and placements along the chord, where the flap lengths and relative position were varied. An example of layered flaps is shown in Figure 9 above. The 2 in. flap was placed fore of the 1.5 inch flap with the leading edge of each flap placed at the position specified in the legend. Increases in lift at normal  $C_{lmax}$  conditions are no longer present, but the flaps still produce significant increases in lift after stall. After several configurations were tested with similar effect, testing of layered flaps were halted due to the reduction in  $C_{lmax}$  and the instabilities incurred during testing. The wing would oscillate violently at some mid- to high-AOA, leading the authors to believe this may not be useful for a passively controlled device.

A second flap shape tested was based upon the biological makeup of “pop-up” feathers. Instead of having one solid rectangular flap, the flap was cut into 1in. sections, or feathers. It was theorized that these feathers would allow sections of the wing to behave separately and would, therefore, better act to eliminate forced localized separation that was seen with continuous flaps. Figure 10 shows  $C_l$  versus AOA for a 1 in. feathered flap. In general the feathered flaps tended to follow the lift curve of the wing section in the low AOA region and then show either an increase in lift, a delay in stall, or both characteristics at high AOA.



**Figure 10. Feathered flaps at 3.3e5 RN**

The results indicate drastic improvements in lift with placement of feathered flaps within the first 10-30% of the chord. The  $C_{lmax}$  has increased by 15% and the effects of stall on lift have been greatly reduced. This configuration of flaps has also reintroduced the drop in lift after stall has been encountered, and at this point, this deviation for the previously ascertained results is not fully understood.



**Figure 11. 1 inch feathered flap 3.3e5 RN**

An unexpected effect of feathered flaps was the decrease in drag in the mid- to high regions of AOA when compared to the un-feathered flap. Although, as can be seen in Figure 11, there is a 50% increase in  $C_d$  at 12.5 deg AOA, this is less than the increase in drag with the un-feathered flaps. Another interesting effect of these flaps is produced when flaps are placed near the trailing edge, specifically a decrease in drag. The decrease in drag, although unexpected, can be explained. Because the flap is no longer continuous, the flaps do not cause flow to separate prematurely, likely increasing the drag. With individual flaps, the flaps no longer rise at the wing tip, and instead create a bulge in the center of the wing very similar to that seen on birds.

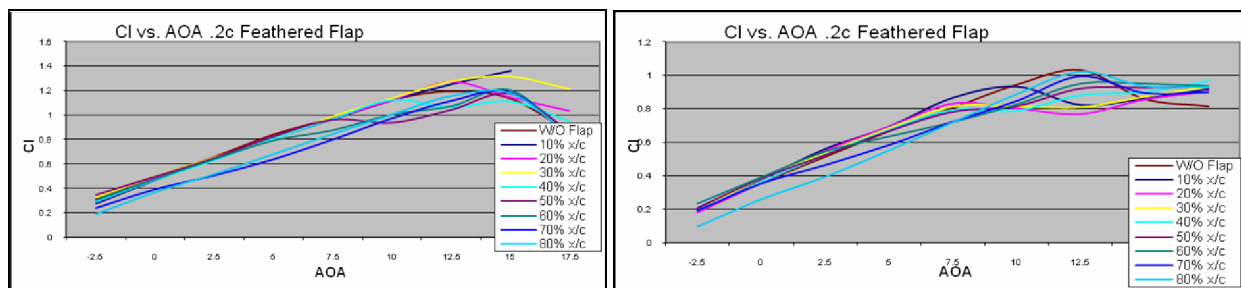
This decrease in drag has significantly increased the lift-to-drag ratio when compared to the un-feathered flaps, and it is the authors' belief that this reduction in drag can further be achieved by introducing the flaps into the stream line of the airfoil.

## VI. Reynolds Number Selection

A brief exploratory test was conducted at both a lower and a higher Reynolds number within the testing range. These tests illustrate that self-activated movable flaps behave differently at different Reynolds numbers. A feasible explanation is that these flaps are more strongly affected by either inertia forces or viscous forces than the ratio between the two. Thus, the flap size, placement, material and possibly configuration will need to change with varying Reynolds numbers, and new dimensionless values may need to be determined.

The higher Reynolds numbers flaps could not sustain the added forces from the increased velocity, and tears would propagate through the flap, in some cases requiring testing to halt. Similar effects of flaps when compared to earlier tested Reynolds numbers can be seen, but the increase in lift is significantly less.

Positive increase in lift at stall is non-existent at lower Reynolds numbers; however, some positive effects can still be seen in the region after stall. The flaps still produce a less drastic transition from stall, and when stall does occur, the drop in lift is significantly reduced as indicated by Figure 12, right.



**Figure 12. Reynolds number variation for 1 inch feathered flap: left,  $4.53 \times 10^5$ , right  $1.66 \times 10^5$**

## VII. Conclusions

This study focused mainly on the development of flaps as a passive lift enhancement device, and explored many different aspects, including size, chord placement, configuration, material selection, and variations in Reynolds number. This study's intentions were not to define the best configurations, but to identify many beneficial effects of these flaps, and characterize new aspects which can later be explored.

Through trial and error it was determined that the flap width could range between 10%-40% of the chord length to produce positive effects. The flaps smaller than 10 percent chord were ineffective due to the suddenness of stall passage, and flaps larger than 40 percent chord were also ineffective due to the drop in pressure over the flap at low



AOA causing premature deployment. The material considered should be strong enough to prevent fracture, but flexible enough to allow the material to respond to localized separation.

### **Acknowledgments**

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