Analysis of Surface Augmentation of Airfoil Sections via Flow Visualization Techniques

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This report details an experiment done to verify the effectiveness of two passive flow control systems on two-dimensional airfoil sections. The flow control was tested on two types of airfoils: a symmetric NACA 0011, intended to represent an airplane in cruise, and a NACA16611, intended to represent an aircraft with flaps extended. Two types of passive systems were employed, a dimple surface augmentation, similar to a golf ball, and a grit system located at 20% chord. Airfoils without either augmentation were tested as a control case. Using a water tunnel and dye to perform flow visualization, the effects of each system were analyzed. Comparison of the image data demonstrated that the surface augmentation dimples aided in delaying the flow separation from the upper surface. The boundary layer separation was measured by using images and locating the point of separation and using the chord line to convert to percent chord separation. The data showed conclusively that the airfoil test section with surface augmentation from 8% chord to the trailing edge had reduced separation throughout the 6 different tests.

Nomenclature

\begin{align*}
\text{b} & = \text{span} \\
\text{c} & = \text{chord} \\
\text{Re} & = \text{Reynolds's number, } (\rho_{\infty} V_{\infty} c)/\mu \\
\alpha & = \text{angle of attack}
\end{align*}

I. Introduction

The experiment performed investigated the passive methods that can be employed to reduce flow separation from an airfoil section. The methods investigated were a surface augmentation dimple system at 50% chord, 23% chord, 8% chord and grit tape placed at 20% chord. Surface augmentation dimples can aid in reducing separation and reducing pressure drag and has been well studied and verified in golf ball aerodynamics. The testing in this experiment was to validate or disprove that the application of surface augmentation dimples will reduce separation and pressure drag of a standard symmetric airfoil section and the same airfoil section in a flaps configuration. One of the most dangerous conditions for aircraft is the takeoff and landing portions of flight where flaps are extended and speeds are slow. These combinations results in lots of separation that can result in stall. This method of surface augmentation could be applied to any surface that travels through a flow to reduce the separation and thus aid in drag reduction, such as planes, cars, boats, submarines and numerous other applications.

B. Previous Studies

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There have been numerous studies of dimpling surfaces to reduce separation and thus reduce the drag, though the main application is in Golfing. Fig. 1 shows the principle being tested on golf balls and how the dimples reduce the drag. The full detailed papers relating to this research were mainly done by major golf companies like Callaway and Titleist and are proprietary and thus not all the data is released to the general public.

![Image](image1.png)

**Figure 1. The principle of surface augmentation in its main application to date, golfing.**[1]

The idea of reducing drag on airfoil sections has been researched in depth because the longer the flow stays attached the less drag and more difficult it is to stall the aircraft. Examples of the systems in use today are shown in Fig. 2.

![Image](image2.png)

**Figure 2. Examples showing the most used and researched flow separation methods**[2]
The purposes of these modifications are to create vortices in a controlled and predictable manner to delay wing stall. Stall occurs when the wing reaches an angle of attack where the flow over the wing begins to separate from the wing surface. This flow separation results in a rapid loss of lift that may result in the aircraft becoming unstable and uncontrollable. These wing devices create vortices that add energy to the flow to delay the flow separation from the surface. As the vortex generators add energy to the flow they are creating an increase in momentum which encourages the flow to stay attached to the wings' surface longer. The result is that the wing is able to generate lift in areas where the wing would have previously stalled. These devices such as the vortex generators, seen in Fig. 3, are used in commercial aircraft to increase safety during critical stages such as takeoff and landing.

![Figure 3. Left, the theory of vortex generators and how they interact with the flow. Right, the liberal application of vortex generators to the surface of a fighter plane.][2]

These devices are effective because they create turbulence in order to delay the separation of the flow on the wing. Vortex generators keep the flow attacked by adding energy into the flow by disturbing the flow. By adding the flow and changing the momentum of the air, the flow stays attached longer reducing the separation. These vortex generation systems are used on both commercial and military planes due to the success and ease of integration. This experiment aims to determine if there is another practical passive separation reducing technique that could be employed or further tested.

D. Objectives

This experiment was designed to investigate how various surface augmentations affect the airflow over an airfoil in symmetric cruise condition and a cambered flaps condition. Each airfoil section, both symmetric and cambered/flaps, was tested at 0, 5 and 10 degrees to analyze the effectiveness of the surface augmentation during various conditions of flight.

II. Model Design

To acquire data to investigate the flow that results from the surface augmentation dimples it was necessary to construct 4 models to test. A NACA 0011 was chosen for the cruise condition example because of its simple symmetric profile. For the flap condition this airfoil is given 16% camber at 60% chord, making it a NACA 16611.

A. Conceptual Design Process

The two airfoils selected are shown in Fig. 4 had to be sized to fit into the test setup in the water tunnel. Each test section has a length of 4 inches and a width of 6.25 inches.
B. Manufacturing

The models were built using a solid modeling program and ABS plastic as a medium. The reduced model required precision in construction, particularly the sensitive dimensions of the leading and trailing edges. The goal was to use CAD software to create the model in a computer and allow a CNC mill to construct the models to completion, but due to financial and time constraints another manufacturing method was used. Due to the precision that was desired the models should to be constructed on a CNC machine or by using a combination of tools that could be found at the Cal Poly Manufacturing hanger. To construct the airfoil sections the designer built the models in Solid Works and then took "steps" out of the known material stock to begin the shape of the airfoil section. Fig. 5 shows the Solid Works model with some of the steps taken to construct the NACA 0011.

Using the steps created in Solid Works the manufacturer took painstaking care to mill out each step one by one until the rough outline of the airfoil took shape. Each step was calibrated using the Mills interface and verified by using calipers after each cut to verify that the mills had no drift during construction that would skew the airfoil. Fig. 6 shows the NACA 0011 airfoil during construction on the Lagun Mill in the Cal Poly Manufacturing Shop.
Figure 6. The Lagun Mill that was used to take out the steps of the stock to shape the airfoil test sections. The upper right green numbers are used to calibrate each step to an accuracy of 0.0001 in.
This stage of the manufacturing was critical to the success of the testing because even small minuet deviations could result in significant airflow changes. Each step was checked and reviewed before the pass was made because some of the steps were very small and only removed a 1/100th of material; Fig. 7 shows some of the steps of the NACA 0011 airfoil in detail.

Figure 7. Showing the steps of the NACA 0011 after the top and bottom of the airfoil were completed on the Lagun Mill.

The NACA 0011 was constructed first on the mill and was significantly easier to construct than the NACA 16611 airfoil because the NACA 0011 was symmetric and did not require nearly as many steps and relief cuts as the NACA 16611 airfoil. Figure 8 shows some of the numerous steps that were used to shape the NACA 16611.

Figure 8. The steps shown are some of the over 100 steps milled out to get the shape of the NACA 16611.

During the manufacturing of the NACA16611 there was an error that resulted in a small gash near the trailing edge on the upper surface. This was caused by a small miscalculation that seemed correct at the time; fortunately after that pass was done it was immediately obvious that there was an error and solutions
to the gash were analyzed. Figure 9 shows the manufacturing error that resulted in the gash in the trailing edge of the NACA 16611.

![Figure 9](image)

**Figure 9. Left shows the mistake during the manufacturing process that resulted in the small gash in the trailing edge. Right shows the repaired gash through the use of JB Weld.**

The gash was filled with JB Weld, a high strength bonding/filler agent that bonds well to any surface. The next stage in the manufacturing process was the sanding and smoothing of the steps to produce the clean smoothed airfoil required for water tunnel testing. The sanding process began using 200 grit sand paper to reduce the possibility of taking out large chunks of the airfoil section. The process was repeated on both airfoils until final 1000grit wet sand was completed. When the sanding was completed, the JB Weld filled gash had almost identical surface textures and was deemed acceptable for testing.

Next each of the two large test sections were cut into two test sections apiece, each 6.25 inches long to be tested into the water tunnel. One of each of the test sections was chosen to be the control, smooth with no surface augmentation, and the other was sent to the next stage of manufacturing, the surface augmentation dimples. Due to the complex geometry of the upper surface and the number of dimples required each dimple had to be handmade. To make the surface augmentation dimples an Alltrade rotary tool was used with a rounded tip to individually make each dimple. Figure 10 shows the rotary tool and the dimples on the NACA 0011 airfoil.
Figure 10. The rotary tool with rounded surface and the dimples on the airfoil. The black dots represent different tests such that the first is at 50% chord the 2nd is at 23% chord and the very first row is at 8% of chord from the leading edge.

After the models had the required amount of surface augmentation dimples there were attached to their side plates and then used for testing in the water tunnel. After each surface augmentation dimple test was completely completed the test airfoil section was then re-dimpled up to the next test location. The first test had dimples starting from 50% chord length from the leading edge until the trailing edge, the second dimple test had dimples starting at 23% chord length and the final dimple testing was done with dimples starting at 8% chord from the leading edge to the trailing edge. During the manufacturing process there were over 1000 surface augmentation dimples that were applied to the two testing wings, all manufactured by hand.

III. Instrumentation and Procedure

The experiment used Cal Poly’s water tunnel, an Eidetics’ Flow Visualization Water Tunnel with model number 0710 S/N 0025 produced by Rolling Hills Research Company. Fig. 11 shows the three-view schematics of the water tunnel.
The water tunnel’s test-section measured 0.44 m by 0.25 m by 0.19 m with glass viewing windows on the sides. A flow straightener positioned upstream of the test section ensured water flow impinged directly onto the model and not at angles that may have caused irregular turbulence. An outlet pipe allowed for draining of the tunnel. Flow speed is controlled via a variable free stream velocity control mechanism capable of propelling the flow free stream velocity from 0 m/s to about 0.8 m/s.

A. Model Instrumentation

The water tunnel has no top cover, leaving the upper layers of water potentially susceptible to atmospheric disturbances. Avoiding any potential disturbances from ambient conditions or surface flow behavior necessitated filling the water tunnel to approximately 90% of full capacity to ensure the models had sufficient depth to prevent disturbances from the upper layers.

To release the dye into the water tunnel for the visualization tests the system that was already in place was modified slightly to provide steady undisturbed dye distribution. The original mechanism in the lab for dye release consisted of a rubber bladder filled with dye and hung several feet above the tunnel to provide a gradient that would move the dye through connecting plastic tubes. This system worked somewhat but was difficult to control the amount of dye being pushed into the water tunnel and would often spill and dirty the work bench. The bladder system was kept but using gravity to control the distribution of dye was replaced by applying pressure directly to the dye bag, using pressure on the dye bladder to control the flow worked spectacularly. The pressure was applied when needed by the operator and could be changed if excess or minimal dye was being put into the flow. An L-pipe was used to distribute the dye close to the leading edge of the model and could be moved depending on what angle of attack the test airfoil was currently at. The overall system is shown in Fig. 12 with the red bladder, tubing and L-pipe. It was important to first test the dye distribution system to determine the quantity of dye that is dispersed depending on the pressure on the dye bag. If excess dye was dispersed then the water tunnel water would shift color quickly and skew the data in the recorded images. If not enough dye was dispersed then the images would not be useful and the test would be a waste of time. Therefore careful pressure regulation of the dye bag was critical and was a top concern for the tester.
To fit the model into the water tunnel’s mounting system, two sheets of Plexiglass, with a thickness of 0.125in, were secured to each side of the airfoil test section as seen in Fig. 13. The test sections were screwed in instead of glued in was because the test sections needed to be removed from the Plexiglass side walls to be further modified with the addition of surface augmentation dimples. This method was chosen over the glue/ re-glue method because the screws ensured that after each alteration the model would be secured in the same place as before.
Figure 13. The top photo is the side view of the Plexiglass support structure, showing the screws, used to connect to the test apparatus. The bottom view is a top view of the Plexiglass support structure that was used to connect to the testing apparatus.

The mounting plates would induce two dimensional flow over the airfoil sections, and allow connection of the model to a mounting fixture on the water tunnel, shown in Fig. 14, constructed by previous researcher(s).

Figure 14. Left, a fixture of Plexiglass connectors used to connect the model to the water tunnel and control the angle of attack. Right, the entire system assembled in the water tunnel with no water.
In order to properly connect the tunnel mounting fixture with the Plexiglass mounting plates shown in Fig. 14, two sets of #4-40 x 3/8” nuts and screws and one set of #10-32 x 3/8” nut and screw are used. Fig. 15 shows the proper connections between the mounting mechanism and Plexiglass mounting plates.

B. Experimental Procedure
The experimentation was split into five different tests: no surface augmentation, surface augmentation dimples starting at 50% chord to the trailing edge, surface augmentation dimples starting at 23% chord to the trailing edge, surface augmentation dimples starting at 8% chord up to the trailing edge, and grit tape placed at 20% in a 1 inch section. Each of these tests were performed at 0, 5, and 10 degrees and with both the symmetric and cambered/flaps airfoil test sections.

Figure 15. The tunnel mounting fixture held the model in place, and connected to the test section via tightened screws.

The control groups were tested first, both the non surf ace augmented symmetric and the cambered/flaps. The water tunnel was filled to 90% making sure that the drainage valve was in the off position. The water tunnel motor was then turned on and set to the proper speed and waited for the water to be at operation speeds before testing can begin.

The dye bag was filled with red fresh dye because during the testing of the dye distribution system it was clear that old dye became viscous and could jam and clog the system. The system was purged into an empty dye bottle to ensure that there were no air bottles or old dye inside the system that could skew the results. Fig. 16 shows some of the components of the dye system as well as the dye that was used in the experiments.
A rotational control rod adjusted the angle of the model to a zero degree orientation with respect to the free stream. It was set to 0 for the first test. Fig. 17 shows the location of the rotational control rod.
With all components in place, the water tunnel was turned on and its free stream speed set close to its maximum speed. Running the water tunnel at maximum speed over a long duration of time unnecessarily wears the system quickly. With the water tunnel active the dye system is activated and the video camera/still camera was turned on to record each test in its entirety. Each test over 15 pictures were taken and over 1 minute of video was taken to ensure that there was enough data to analyze. After the test/control group was tested the first dimpled group was tested and recorded under the same conditions as the control group except that the data recorded was doubled because this test could not be repeated. After the first dimple group was tested the airfoil test sections were taken off their Plexiglass side mounts and additional dimples were added to bring the start of the dimples up to 23% of the chord from the leading edge. The test airfoil sections were tested and 0, 5 and 10 degrees just like the others and the data was recorded for analysis. After the test the test airfoils were again dried off and re-dimpled until the start of the dimples was at 8% of chord. The 8% was the closest that could be dimpled without severely altering the leading edge structure and design. The non-augmented control test sections were then modified by putting a piece of black grit tape starting at 20% chord and ending at 45% chord. These sections were then tested like all the other models at the various angles of attack. After each set of tests, symmetric and cambered/flaps, the water tunnel was drained and cleaned because the water was starting to become red from the dye. All the models were then removed and dried, as well as cleaning the support structure and any systems that were used. The dye was then emptied into an unused dye container and the dye bag and lines were cleaned out to allow easy set up for the next researcher.

IV. Results and Discussion

The dye distributing L-pipe worked well but not as well as desired. There were times that the dye became coagulated and blocked the flow or resulted in two different streams coming out of the one opening. Overall the L-pipe worked well because of its variable adjustment height, changing the height between tests aided in the fine tuning of the flow stream. Having the L-pipe in the flow did result in some of the flow being disturbed and could have skewed the results but because all the tests used the same L-
pipe the data is consistent. The flow data that was gathered using the methods outlined in the report was consistent in each test and the red die system produced stunning images.

Each test was carefully recorded using the camera and notes recorded on the video and by hand. There is a high speed high quality camera that is usually in the water tunnel but was non operational so a Panasonic Lumix 14 Mega Pixel camera was used in conjunction with a tripod to ensure steady accurate images. The images were very clear and clearly demonstrated where the separation began and how the flow was acting both over the wing and downstream. When recording in video the camera outputted in 720p and on the computer it was easy to see the vortexes and eddies that formed as a result of the surface augmentation.

The control group with no surface augmentation could be analyzed using the 2D software program JavaFoil to get a rough estimation of how the flow should act, where as the other test airfoils could not be analyzed using software because of their unique upper surface geometry. It should be noted that for most tests the 2D JavaFoil data corroborates the water tunnel data. The data will be discussed in the following manner: the control tests of the symmetric airfoil, the grit test, the 50% surface augmentation dimples, 23% dimples then finally the results of the 8% from leading edge dimpled upper surface. Each will be discussed in sequence: all five tests at 0 degrees angle of attack, each of the five tests at 5 degrees angle of attack, and finally the results of the 10 degree angle of attack tests. At the beginning of each section there will be a table showing the test type and the separation distance from the leading edge that was observed. Note that the numbers are not a single number because depending on the flow the separation would move forward or aft giving a range of separation values instead of a single exact number.

### Symmetric airfoil at 0 degrees angle of attack

The data collected showed that there was some variance of all the data and depending on the flow properties at any given time the separation length varied. The maximum values observed are tabulated for the tests of the symmetric body airfoil section at 0 degrees in Table 1.

<table>
<thead>
<tr>
<th>0 degrees</th>
<th>Chord separation</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 rows dimpled 8%c</td>
<td>90-95%</td>
<td></td>
</tr>
<tr>
<td>13 rows dimpled 23%c</td>
<td>82-91%</td>
<td></td>
</tr>
<tr>
<td>8 rows dimpled 50%c</td>
<td>66-80%</td>
<td></td>
</tr>
<tr>
<td>Black grit 20%c</td>
<td>60-90%</td>
<td></td>
</tr>
<tr>
<td>No surface augmentation</td>
<td>77-92%</td>
<td></td>
</tr>
<tr>
<td>JavaFoil</td>
<td>90-98%</td>
<td></td>
</tr>
</tbody>
</table>

The data from JavaFoil suggests attached flow for the entire section of the airfoil and may be making assumptions that are incorrect for the water tunnel test. The velocity flow field of the JavaFoil test results is shown in Fig. 18.
The results for the water tunnel test at 0 degrees with the control airfoil test section yielded data that showed the flow separating earliest at 77% and latest at 92% chord from the leading edge. To calculate the percent chord where the separation began a ruler was used on the printed image and the distances were measured and then converted into percent chord. Fig. 19 shows the non augmented symmetric airfoil separation.

![Figure 19. The flow over the non augmented airfoil section separating between 77% and 92% chord length.](image)

The grit method demonstrated some interesting properties including flow seperation earlier than any other airfoil test section. This was probably due to the grit height as it protruded into the flow and caused disturbances that created separation. The disturbances caused by the grit sometimes caused the flow to separate early yet other times the flow was attached until 90% of the chord length. Figure 20 shows the flow properties of the grit tape experiment.

![Figure 20. The separation using Grip located at 20% chord, separation of flow happened between 60% and 90%](image)

The data for the 50% chord length and 23% chord length will be discussed but the figures will be shown when they are necessary. The 50% dimpled surface showed that the dimples did affect the flow and caused the flow to separate earlier in some cases compared to the control. Figure 21 shows the separation on the 50% dimpled case. The test airfoil section with the dimpled surface starting at 23% showed a reduction in separation spread. The separation was delayed until after the control tests separation and stayed attached almost as long as the control test airfoil. The reason that these cases were not as successful as the control group could be the result of the transition from laminar surface to surface augmentation being so far back from the leading edge.
The last test at 0 degrees with the symmetric airfoil was the test section with surface augmentation dimples starting at 8% and running until the trailing edge. This test showed conclusively that with dimples starting at 8% of chord the flow stayed attached the longest with the smallest spread. In every test and recorded image the flow was attached along almost the entire surface. The dimples tripped the flow and made the flow turbulent and thus kept the flow attached along almost the entire chord length. Fig. 22 shows the airfoil test section with dimples starting at 8% chord.

An alternate way to think about the dimples is in terms of pickup truck aerodynamics. The truck bed creates a vortex of recirculation air that sucks the air over the cab of the vehicle down and thus reduces the separation of flow over the truck which in turn reduces drag. The dimples create little pockets filled with rotating recalculating air that suck the flow over the airfoil down reducing the separation. This test suggests that the flow transition from laminar to turbulent needs to be as immediate as possible to get the most out of the passive system.
Symmetric Airfoil at 5 degrees angle of attack

Table 2. The data recorded for the airfoil test sections at 5 degrees.

<table>
<thead>
<tr>
<th>5 degrees</th>
<th>Chord separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 rows dimpled 8%c</td>
<td>56-65%</td>
</tr>
<tr>
<td>13 rows dimpled 23%c</td>
<td>51-58%</td>
</tr>
<tr>
<td>8 rows dimpled 50%c</td>
<td>42-49%</td>
</tr>
<tr>
<td>Black grit 20%c</td>
<td>43-53%</td>
</tr>
<tr>
<td>No surface augmentation</td>
<td>46-51%</td>
</tr>
<tr>
<td>JavaFoil</td>
<td>50%</td>
</tr>
</tbody>
</table>

The control airfoil was tested at 5 degrees angle of attack to determine a baseline to compare the other airfoil test sections to. The 2D JavaFoil data showed that the separation should begin at approximately 50% of chord and the test data shows separation at closely the same location. The test data again lines up the 2D data which suggests that the testing method is accurate and the data is reliable. Figure 23 shows the separation on the control airfoil at 5 degrees angle of attack, note the vortices and stagnate flow located near the trailing edge.

Figure 23. The control section shows separation at approximately 46% to 51% of chord.

The test section with the black grit at 20% chord showed separation beginning earlier than the control airfoil section but during some tests later that the control airfoil test section. The black grit separation data seems to fluctuate more than the control test data in almost every testing case. Notice the recirculation and large separation near the trailing edge of figure 24.

Figure 24. The grit test section showing the separation at 43% to 53% of chord
The data for the 50% dimpled surface showed separation before the surface augmentation dimples had any effect on the flow. The separation happened at approximately 42% to 49% of the flow suggesting that the dimples either created more separation by affecting the upstream flow or that the control group should have separated earlier. The test airfoil with dimples at 23% chord showed a decrease in separation with the flow separating at 51% to 58% of chord. The data show that the dimples aided in delaying separation as seen in the final test at 5 degrees angle of attack, as seen in figure 25.

![Figure 25](image)

**Figure 25. The test section with dimples staring at 8% showing the reduced separation which occurs at 56 to 65% chord length.**

The final test at 5 degrees angle of attack with dimples at 8% chord showed a significant delay in separation by as much as 14% chord length compared to the control test section. The data that this test provided was surprising due to the high delay in separation caused by the passive dimple system. As seen in Figure 25, the dimples are creating small vortex's after separation occurs which aid in pulling the separated flow back towards the surface, reducing the pressure drag the wing produces.

**Symmetric airfoil at 10 degrees angle of attack**

The separation of the airfoil test sections at 10 degrees angle of attack were all occurring around the 5% to 16% chord length. The high angle of attack results in separation happening almost immediately with the exception of the test section with dimples at 8% chord. The data for the 10 degree test is shown in Table 3; the most noteworthy and interesting test is shown below in figure 26.

**Table 3. Test data at 10 degrees angle of attack.**

<table>
<thead>
<tr>
<th>10 degrees</th>
<th>Chord separation</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 rows dimpled 8%c</td>
<td>8-16%</td>
<td></td>
</tr>
<tr>
<td>13 rows dimpled 23%c</td>
<td>6-12%</td>
<td></td>
</tr>
<tr>
<td>8 rows dimpled 50%c</td>
<td>5-10%</td>
<td></td>
</tr>
<tr>
<td>Black grit 20%c</td>
<td>5-10%</td>
<td></td>
</tr>
<tr>
<td>No surface augmentation</td>
<td>5-10%</td>
<td></td>
</tr>
<tr>
<td>JavaFoil</td>
<td>10%</td>
<td></td>
</tr>
</tbody>
</table>
Figure 26. The dimpled airfoil test section at 8% with separation happening almost immediately.

At higher angles of attack it was seen that the flow stays attached for almost no time at all is almost entirely separated by approximately 10% chord. Only test airfoils that showed any significant reduction of separation was the airfoil with surface augmentation dimples at 8% chord.

**Cambered/flap test section at 0 degrees angle of attack**

The cambered/flaps testing was tested to see how an airfoil in a dirty, flaps deployed; configuration with the passive separation system behaves at various angles of attack. The 2D analysis in JavaFoil was employed to get a baseline of what type of separation can be expected at 0, 5 and 10 degrees angle of attack. The data for the cambered/flaps test at 0 degrees angle of attack are summarized in table 4.

<table>
<thead>
<tr>
<th>0 degrees</th>
<th>Chord separation</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 rows dimpled 8%c</td>
<td></td>
<td>34-39%</td>
</tr>
<tr>
<td>15 rows dimpled 23%c</td>
<td></td>
<td>31-35%</td>
</tr>
<tr>
<td>9 rows dimpled 50%c</td>
<td></td>
<td>26-30%</td>
</tr>
<tr>
<td>Black grit 20%c</td>
<td></td>
<td>31-37%</td>
</tr>
<tr>
<td>No surface augmentation</td>
<td></td>
<td>25-31%</td>
</tr>
<tr>
<td>JavaFoil</td>
<td></td>
<td>20-30%</td>
</tr>
</tbody>
</table>

The 2D JavaFoil analysis suggested that with such a high cambered or dirty setup the flow would be separated at approximately 20 to 30% of chord. The control test airfoil showed separation within the 2D analysis window yet again showing that the data is reliable. Figure 27 shows the separation on the control airfoil; note that there is recirculated flow that can be seen under the separated flow at approximately 40% chord. The separation for the control test airfoil varied from 25% to 31% of chord length.
The grit test provided some interesting results showing that the grit significantly improved the attached flow over the chord length. The data showed attached flow from 31% to 37% chord length, all due to the roughness of the grit tape. Figure 28 shows the grit test at 0 degrees angle of attack and it is clear in the photo that the grit tape keeps the flow attached longer than the control test. In figure 28 there are vortices being shed from the wake of the grit tape that can be seen clearly. It should be noted that in this test the grit tape data had a limited spread compared to other tests where the separation data varied by about 10% to 15% chord length where as this data only varied by 6% chord length.

The test section with dimples starting at 50% chord length showed no real improvement over the control airfoil section. This is because the dimples have no affect when the separation occurs so far before the dimples; the flow effectively sees a non augmented airfoil test section. The test section with dimples starting at 23% chord length shows an improvement over the control test section and is almost identical in
separation numbers as the black grit. The separation for the 23% chord length test section is 31% to 35% chord length. These results are overall better than the control group shown in Fig. 27.

Figure 29. The test airfoil with surface dimples starting at 8% chord has separation occurring between 34% and 39% chord.

The final test for this configuration showed a significant improvement over the control test airfoil, delaying the separation between 34 and 39% of the chord length. The data and images show that the dimpled surface keeps the flow attached well past where the control airfoil test section was separated. Figure 29 the flow remains attached until about the 39% chord, the longest attached flow for any of the cambered airfoil tests.

**Cambered/ flaps tests at 5 degrees angle of attack**

During the course of testing it became clear that the results of this test were very similar with few major changes despite the 5 different test sections. Table 5 shows the resulting data from these experiments were very close together with the exception of the fully dimpled surface test airfoil.

<table>
<thead>
<tr>
<th>5 degrees</th>
<th>Chord separation</th>
<th>length</th>
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<tbody>
<tr>
<td>18 rows dimpled 8%c</td>
<td>24-31%</td>
<td></td>
</tr>
<tr>
<td>15 rows dimpled 23%c</td>
<td>19-25%</td>
<td></td>
</tr>
<tr>
<td>9 rows dimpled 50%c</td>
<td>19-23%</td>
<td></td>
</tr>
<tr>
<td>Black grit 20%c</td>
<td>19-27%</td>
<td></td>
</tr>
<tr>
<td>No surface augmentation</td>
<td>19-22%</td>
<td></td>
</tr>
<tr>
<td>JavaFoil</td>
<td>20-25%</td>
<td></td>
</tr>
</tbody>
</table>

The control test and most of the other methods all had separation starting at approximately 19% chord length. Most test sections, under ideal circumstances, had flow separating by the 23% to 25% chord length. This shows that at 5 degrees angle of attack the flow is not attached for long and there is a great deal of separation regardless of the test method employed. The control airfoil had separation between 19% and 22% chord length as seen in Figure 30. The grit did slightly decrease separation resulting in a maximum attached flow at 27% chord for the grit airfoil test section.
Figure 30: The separation of the control case. Note this is the case with the longest attached flow for the control test, resulting in separation occurring at 22% chord.

Figure 31: The fully dimpled test airfoil section with attached flow up until 31% chord length.

The test section with the dimples starting at 8% chord showed an improvement over the control test section, having attached flow up until 31% chord length. The data and images show that having dimples on the entire upper surface help create turbulent flow that delays separation. As seen by comparing figures 30 and Fig. 31 the separation with no surface augmentation is much earlier than with the upper surface augmented by dimples.
Cambered/flaps at 10 degrees angle of attack

As with the symmetric airfoil the tests at higher angles of attack show flow separation almost immediately regardless of the surface augmentation on the test section. These tests were done to see if there was significant attached flow in comparison to the control test airfoil section. The data for the 10 degree angle of attack study is summarized in Table 6.

Table 6

<table>
<thead>
<tr>
<th>10 degrees</th>
<th>Chord separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 rows dimpled 8%c</td>
<td>10-16%</td>
</tr>
<tr>
<td>15 rows dimpled 23%c</td>
<td>9-13%</td>
</tr>
<tr>
<td>9 rows dimpled 50%c</td>
<td>9-13%</td>
</tr>
<tr>
<td>Black grit 20%c</td>
<td>9-12%</td>
</tr>
<tr>
<td>No surface augmentation</td>
<td>9-12%</td>
</tr>
<tr>
<td>JavaFoil</td>
<td>5-10%</td>
</tr>
</tbody>
</table>

The control airfoil section validated the 2 D aerodynamic JavaFoil data which suggested that the flow would separate within the first 10% of chord. The control airfoil section shown in Figure 32 shows the separation resulting from the high angle of attack coupled with the high camber of the airfoil. Most of the airfoils preformed similarly with flow separation happening between 9% and 13% chord length.

![Figure 32. The control airfoil test section with no surface augmentation and flow separation happening between 9% and 12% chord length.](image)

The cambered airfoil with surface augmentation dimples starting at 8% chord did perform slightly better than the control and other airfoil test sections. Similarly to how a golf ball reduces drag by using the dimples to trip the flow around the ball, the dimpled airfoil section tripped the flow and that turbulent flow stuck to the airfoil. The separation was between 10% and 16% chord for the 8% dimpled airfoil.
showing that it did help aid in separation reduction. Figure 33 shows the fully dimpled airfoil test section with the flow attached much longer than the control Figure 32.

Figure 33. The separation was delayed on the 8% chord airfoil test section because the dimples tripped the flow changing the flow to turbulent instead of laminar.

The data in these tests show that the data for the control tests were generally within the 2D JavaFoil boundary layer separation numbers. At higher angles of attack, such as 10 degrees and greater, the flow is almost completely detached and the passive system can only do so much. The dimple system, when employed on the entire upper surface, delays separation better than a smooth surface or the grit method. Unless the dimples or surface augmentation starts as early as possible there are limited benefits or actual detriments can occur.

V. Conclusion

The addition of surface augmentation dimples along the entire upper surface, stopping at 8% chord length, provided benefits in both types of tests, symmetric and cambered. The symmetric or cruise tests showed that the dimpled surface aided in delaying separation over the airfoil which will result in less pressure drag on the airfoil. During the cambered/flaps tests it was clear that having dimples on the upper surface to trip the flow to create turbulent flow greatly aided in delaying separation. On average during the 0 degree tests the fully dimpled airfoil test section delayed flow separation by 10% chord length. The testing was aimed to determine what the effects of having dimples on the camber/flaps test section related to the effects the dimples caused on the symmetric/cruise test section. Through testing the data showed that regardless of the shape of the test section, either symmetric NACA 0011 or cambered NACA16611 airfoil, having a fully dimpled surface aids in delaying separation. The delay in separation reduces the pressure drag and gives the airfoil less drag and more lift at the cost of manufacturing difficulties. Though this data shows that the dimples did aid in delay of separation there are still numerous tests that could be done to optimize and refine the design of the dimple system. The dimples were chosen by what could be manufactured in the time provided and if more time was permitted, wind tunnel tests using larger test sections, with different dimple sizes would have been preferred. The surface augmentation dimples showed a clear and distinct advantage over the traditional control group smooth airfoil surface, delaying the separation and thus decreasing the pressure drag.
Acknowledgements

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References

