MECHANICS OF FLUIDS
CLASS PROJECT 1

FLOW VISUALIZATION OF INK TRACES AROUND SCALED MODELS

Group 3
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ABSTRACT

This paper discusses the ink dot technique to create a visual representation of the flow of fluid around different bodies. The three objects used to examine the fluid flow were a car body, airfoil, and pelican wing. Using the ink dot method, the air flow over the paper created streaklines originating from evenly spaced ink dots, and streamlines were formed on paper moving tangentially around each object, leading to a discussion of the quality of each object's aerodynamic properties.

INTRODUCTION

Flow visualization makes it possible for the human eye to visually see how a fluid flows in different environments. Flow visualization essentially takes the normally invisible and makes it visible. Being able to see the fluid flow makes "further understanding of various flows at a fundamental level" possible [1]. This is extremely important for various fields in engineering, physics, sports, and even meteorology. Many flow visualizations make use of a wind tunnel, which allows air to flow around the specified test model. This provides "diagnostic information about the flow around the model" that many engineers and scientists, such as the aerodynamicists at NASA, use when creating aircraft components and engines [2].

Because of its use in many different fields, there have been a number of techniques developed to simulate the flow of different fluids. These methods can range from a simple ink dot technique to particle suspension with lasers. Some of the fluid visualization techniques are using smoke, tufts, laser sheets, surface oil flow, and schlieren photography. Each serves a specific purpose. For example, the tufts and surface oil flow provide information about the boundary layer which is important for analyzing the drag on an aerodynamic object, but the schlieren photography technique is specifically for flows that change drastically in density [2]. Figure 1 shows some images of the different flow visualization techniques.
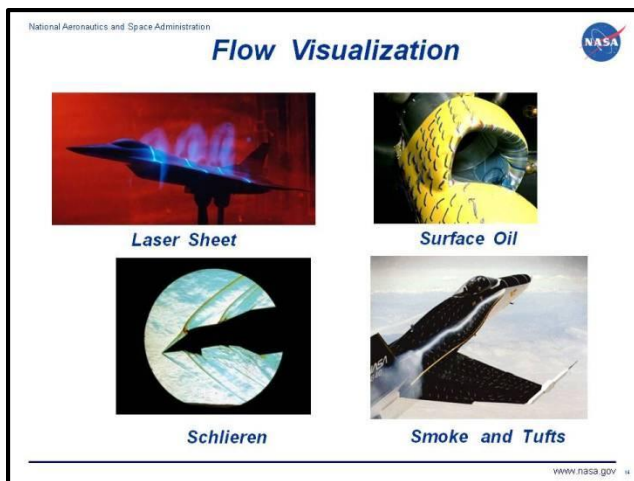

Figure 1: Flow Visualization images [a]

Other techniques have been developed that are more cost-efficient for students and low-budget operations. One example of this is the Ink Dot Technique. This technique makes use of the wind tunnel approach. By applying ink dots with a Sharpie (or some sort of marker) to glossy photo paper, securing the object of question to the paper, spraying the ink dots with an alcohol-water solution, and simulating a wind tunnel, streamlines can be obtained without the need of very technical equipment and cameras [3].

Understanding the difference between pathlines, streaklines, and streamlines is paramount to observing and discussing the results of the fluid visualization of the flow experiment. Streamlines describe the direction along the surface of a body tangent to the local velocity vector. Streamlines are useful indicators of the instantaneous direction of fluid motion, and flow always moves parallel to streamlines. The fluid flow visualization generated a final result

that depicts the streamlines traveling around the object. These are different from pathlines, which describes the actual path taken by an individual fluid particle over time. Pathlines are particle specific, and describe motion in a more detailed way, but can sometimes be harder to study than streamlines or streaklines due to the nature of following single fluid particles. Lastly, streaklines differ from both pathlines and streamlines, and they track the flow of particles from a stable source. Due to the nature of the ink dot method, as the air flow passed over the paper, streaklines were formed from each ink dot. In the final result, these lines appear identical to streamlines, as the experiment was conducted under steady state flow. Steady state flow indicates that the source of flow does not change position or intensity over time.

In this report, the flow visualization was obtained for three different objects: a model car, a bird wing, and an airfoil. The objects were created using 3D printers in the University of Arkansas MEEG building and the ink dot method was used to visualize the fluid flow. The purpose of the experiment is to demonstrate the flow visualization technique and characterize the lines that were formed from the ink dot method.

MATERIALS AND METHODS

Discussion of Model Design:

Study of fluid mechanics and the behavior of a fluid is often too complicated to undergo analytically, and therefore experiments utilizing scale models are used in order to better understand fluid flow. Rapid prototyping and design works best within the scope of 3D printing, as 3D printing is a fast and cost effective method of producing models for nearly all mechanical tests. It is important to understand how the models used in the experiment were printed in order to provide a complete analysis of how the fluid moves around the 3D printed objects.

There are many steps to 3D printing, but before a model can even be considered for manufacturing it must first be designed [5]. The process of designing a three dimensional model is generally classified as Computer Aided Design, due to the nature of the design process itself. The user builds the model from the ground up, using modeling tools or software in order to computationally create the design. SolidWorks is the software used to model the car body and airfoil tested in our flow visualization experiments. SolidWorks is a comprehensive modeling software that provides engineers with the proper tools to quickly design and manufacture prototypes, and is used in the professional theater because of the quality of its toolset [6].

Three models were printed for the flow visualization experiment. The airfoil and car body models were provided for the lab as SolidWorks part files, and are depicted in Figure 2 below. The construction of their geometry is relatively simple, requiring the use of very few tools in order to make the models. The tools used in their construction include Sketch, Extrude, Fillet and Shell.
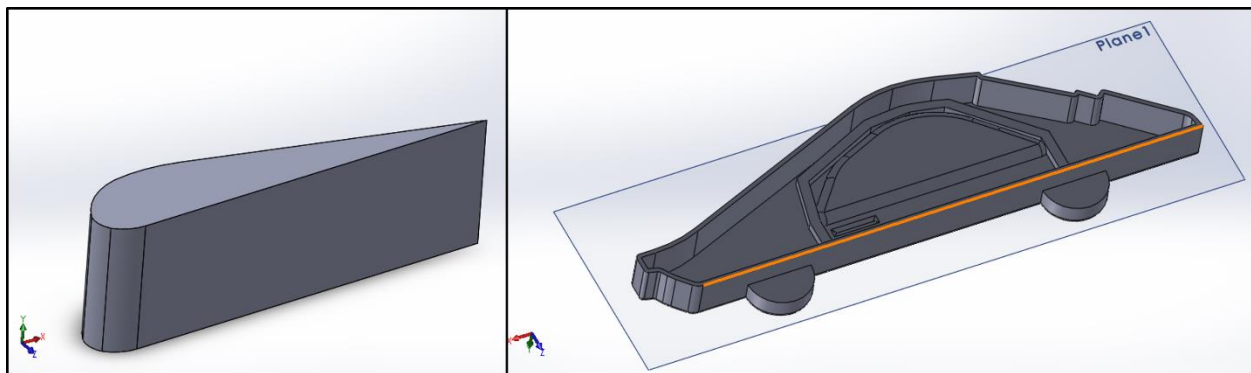

Figure 2: Car body model (right) and Airfoil model (left), as viewed in SolidWorks

Both of the provided models do not need additional modification and are ready for printing. However, the SolidWorks files themselves cannot be read by the printer's slicing program and must be exported as stereolithography files. This file type has the extension .stl, and is a mesh made up of small triangles which connect with one another to form the model's surface. This is a general process for designing models for 3D printers, as most

3D printers accept the .stl file type [7]. Figure 3 displays the outcome of this tessellation process, and it may be noted that more divisions per square area of the model are needed for curved surfaces than for flatter, larger faces.
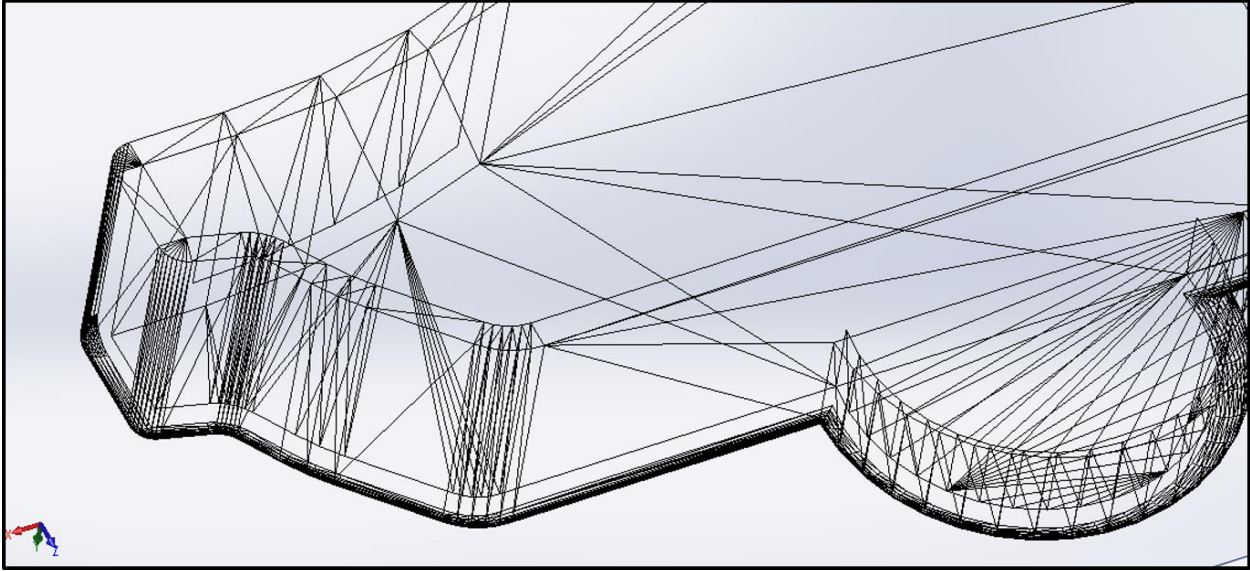

Figure 3: Example of the generation of a stereolithography file

After generating both .stl files, the third model was designed using a combination of SolidWorks and a mesh editing software called Blender. Blender is a free, open source software primarily used by 3D artists and modelers in order to edit files that have already been converted to .stl or of a similar file type. Software like SolidWorks, while powerful, can sometimes be limited in combining meshes, modifying parts, or deforming objects in ways similar to organic shapes. These bends, twists, and edits can be accomplished after the files are exported into .stl format, and make the design of much more complex objects possible.

The third design was chosen to be a bird's wing, modeled after the brown pelican. In order to properly design the wing, several images of the bird were used to get a general profile of the wing to proper proportions in SolidWorks. Figure 4 displays a picture of the brown pelican in flight, while Figure 5 compares the shape of the brown pelican's wing to what was designed in SolidWorks.

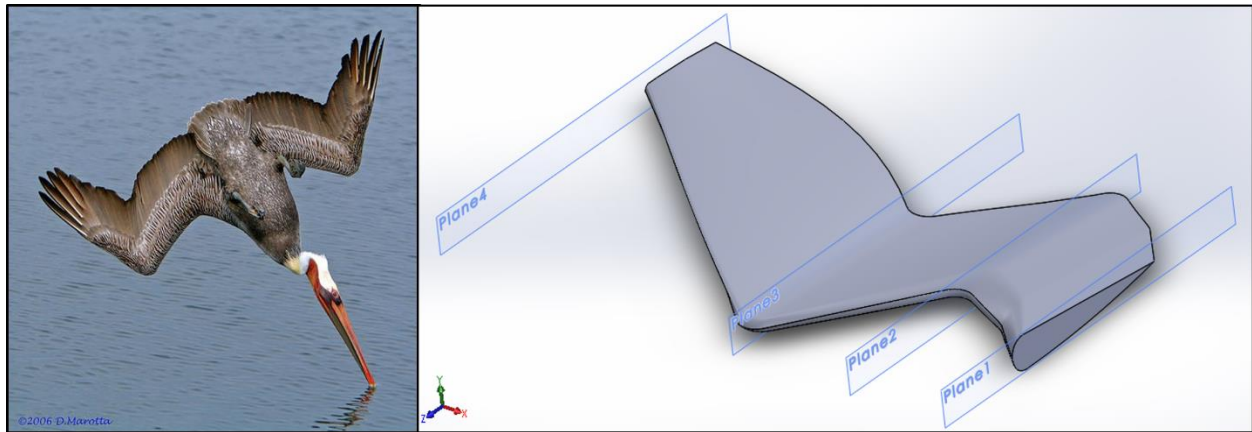Figure 4: Two examples of the brown pelican in flight [b]

Figure 5: A brown pelican in mid-dive (left) [c] compared to the designed SolidWorks model (right)

The wing base consists of four profiles lofted across one guide curve, and the model was based upon the brown pelican anatomy in order to copy the aerodynamic properties of the bird's wing and study how the wing can achieve lift. An arbitrary feather model was also created in order to add a realistic behavior to the wing, aiming to model the fluid properties of air as it moves across the pelican wing. The feather in itself is very simple, however it copies the shape of the profile of a brown pelican's feather, as Figure 6 shows below.
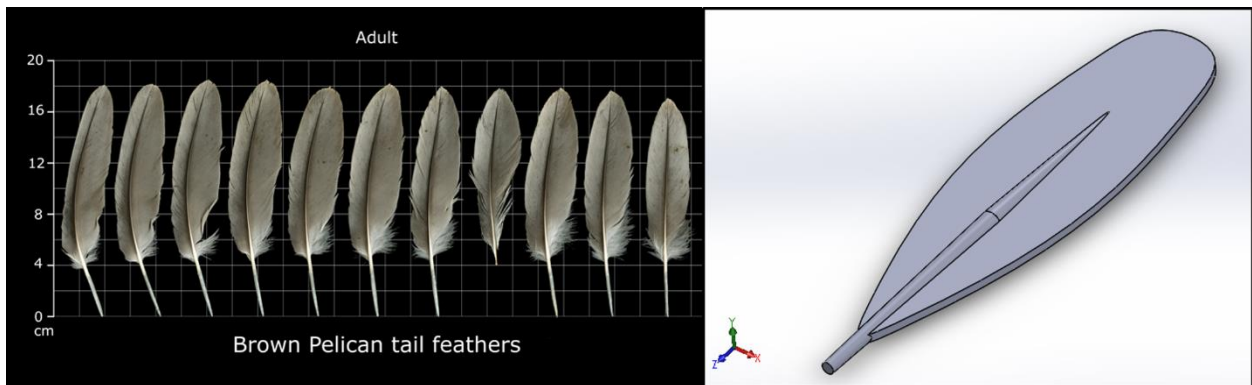

Figure 6: Example brown pelican feathers (left) [d] compared to the designed SolidWorks model (right)

The feather and wing base models can then be loaded into Blender as .stl files, and the feathers are added one on top of the other in a layering fashion. This was done in order to model how feathers grown on real bird wings, as there are multiple layers of feathers and the feathers overlap one another as they traverse the wing. Blender is a great software to accomplish this task, as it makes copying and pasting meshes easy and repeatable. The display can be set up as a 3 window view of the front, right, and top planes simultaneously, and this allows the full wing model to be rapidly assembled. Once the feathers are placed on the wing to the satisfaction of the modeler, each feather was rotated laterally 5 degrees. Lastly, the Simple Deform mesh modifier was added to the wing in order to bend the wing about the "z" axis. This mesh modifier is a tool built into Blender, and has the capability to take any .stl mesh and bend, taper, stretch, or twist it about a chosen axis. The "bend" option of this feature was selected in order to deform the wing into its bent and more natural looking wing shape. The last addition to the model was adding a base to the thickest part of the wing. This was to ensure the model rested flat on the paper for testing, had enough surface area to grip the paper once glued, and accurately demonstrate the effect of the body of the bird on the wing's overall shape. Figure 7 displays the finished model, as viewed inside the Blender software.
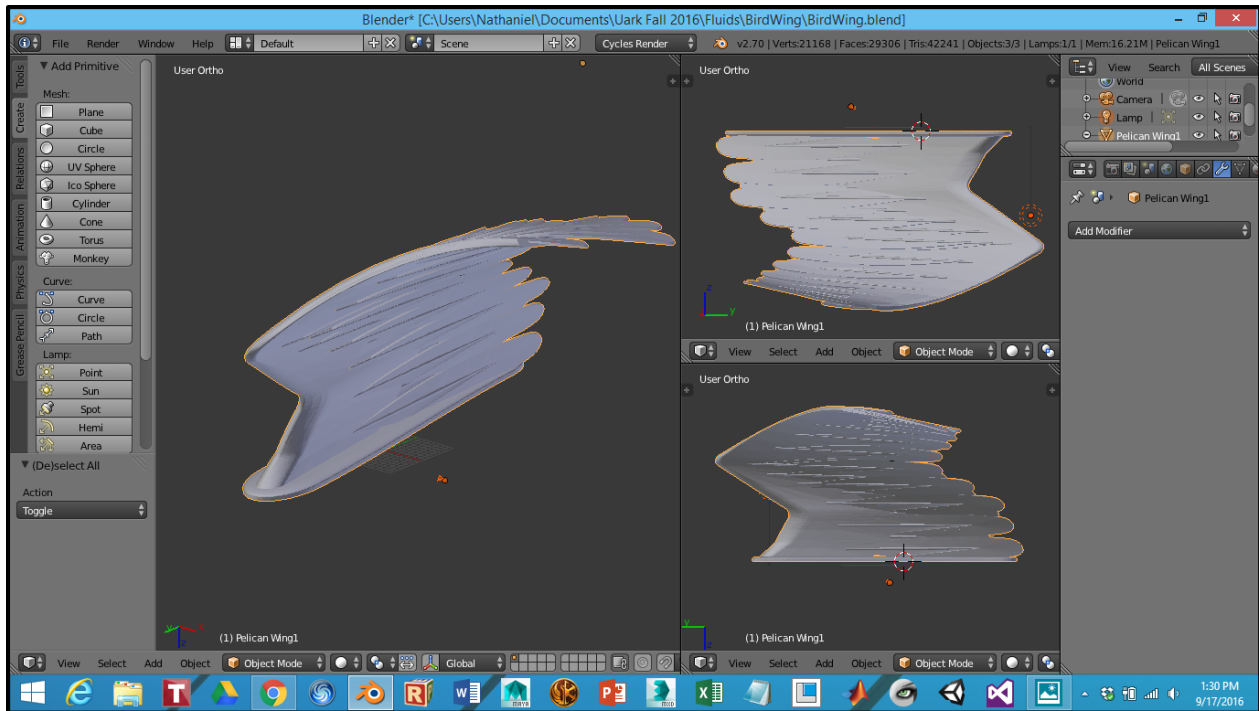
Figure 7: Finished model of the brown pelican wing

Discussion of Model Fabrication:

After exporting the models and ensuring they were ready for printing, the files were imported into the printer and the mesh was processed for printing. The two smaller objects, the car body and the airfoil, were printed first while the model of the wing was being made. The software used in the MEEG print lab and on the MEEG printers is Catalyst EX 4.5. This software comes with its own internal slicing software. A slicing software is needed because the 3D printer does not know what contours to follow unless it is strictly given the coordinates. Slicer software exports what is called G Code, and this becomes the list of instructions the printer needs in order to 3D print the prototype object [8].

A uPrint SE plus 3D printer was used to print the models (MEEG printer number P55451), and the printer uses ABS material along with dissolvable support material. The printer is a dual extruder, meaning it can print both types of material using the same movable apparatus. Some bends, such as the curve of the pelican wing, cannot be printed without having a base of support; otherwise, gravity would force the plastic to droop downwards before it can harden, and the print would come out deformed despite the accuracy of the 3D printer. The support material used is dissolvable in the heated chemical bath located on level 1 of the MEEG building.

The wing model was rotated 45 degrees about the "y" axis in order to minimize both print time and support material used in the print. The part was then soaked in the chemical bath for a total of 4 hours, dissolving most of the support material printed with the model. The support that was left, such as the white material between some of the feathers and the wing base, was determined to have minimal effect on the experiment, and was decided to be kept intact so as not to risk any deformation of the part through extended time in the heated bath. At the end of the printing process, three prints were produced ready for testing with very minimal post processing requirements. While the printers themselves maintain a small amount of inaccuracy in producing the part, generating a surface that is not perfectly smooth, the part resolution is within the required accuracy of the experiment, as the external defects have minimal effect on the flow visualization around the models.

Discussion of Grid Design:

Two different grid sizes were used for the flow visualization. It was decided early on that it would be nice to have a grid beneath the ink dots for reference. The grids were produced thanks to the help of an online graph paper generator [4]. The first grid, used for the car body and airfoil, was constructed with 1.5 cm squares, and the

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second grid, used for the bird wing, was constructed with 2 cm width squares. These numbers were chosen based on the suggestion from someone who had previously done a flow visualization. However, after a brief test to see how the spacing would work we decided to cut each of the squares in the smaller grid into fourths, thus making each square 0.75 cm in width. It was also decided that the proper spacing for the larger grid would be to cut them in half horizontally, so that there would be two "hot dog" rectangles where each square had been. These decisions were made based on the amount the marker bled into the paper. Too many dots of ink would have resulted in an unreadable flow visualization (an example of which is recorded in Figure 11 of the Results and Discussion section) as all the lines blur together, and too few ink dots would have resulted in a flow visualization that didn't show the flow in all positions around the object.

Materials:

After printing the models, the experiment was performed and the results recorded. Several materials were necessary in order to generate results of the experiment. Items included in conducting the experiment are listed below:

- High speed hairdryer (with variable temperature and air velocity settings)
- 70% Isopropyl Alcohol blend
- A fine mist spray bottle
- Shiny photo paper
- Super glue
- Multicolored fine tip Sharpie markers
- Scotch tape

Once these materials were obtained, the isopropyl alcohol was put into the fine mist spray bottle (a repurposed cologne bottle), and a work surface was cleared off in order to make room for conducting the experiment.

Experimental Procedure:

The experiment was performed in under three hours start to finish, and involved several test runs of the acquired materials until a good result was achieved. The general procedure can be described as follows:

1. Mark a pattern of dots with the chosen spacing dimension onto the glossy photo paper using a Sharpie marker.
2. Apply a small layer of super glue onto the bottom of the model base and position the model onto the paper.
3. Press and hold the model to the paper for 30 seconds to ensure it will not move during the experiment.
4. Tape both sides of the photo paper to the experiment surface parallel to the planned direction of air flow.
5. Position the blow dryer in front of the photo paper so that the air passes closely over the surface of the paper.
6. Spray a consistent layer of IPA onto the surface of the photo paper, concentrating on the areas immediately surrounding the model.
7. As soon as the spray is finished, blow a high velocity cool air current across the paper for 30 seconds or until the evidence of fluid flow begins to slow down.
8. Turn the hair dryer onto a hot air setting, continuing to blow a consistent stream of air across the paper's surface until all IPA has evaporated from the surface.
9. Remove model from the table by lifting its tape, and observe the results of the experiment.

Before performing the full experiment, the materials were first tested under variable circumstances. The types of variables changed in pursuit of the best result were the grid sizes (the larger 2 cm grid and smaller 1.5 cm grid), the size of dot made with the Sharpie marker, the temperature of the air flow, and the concentration of the dots inside the grids. An example of this testing process, along with a demonstration of dotting the gridlines, is shown in Figure 8.
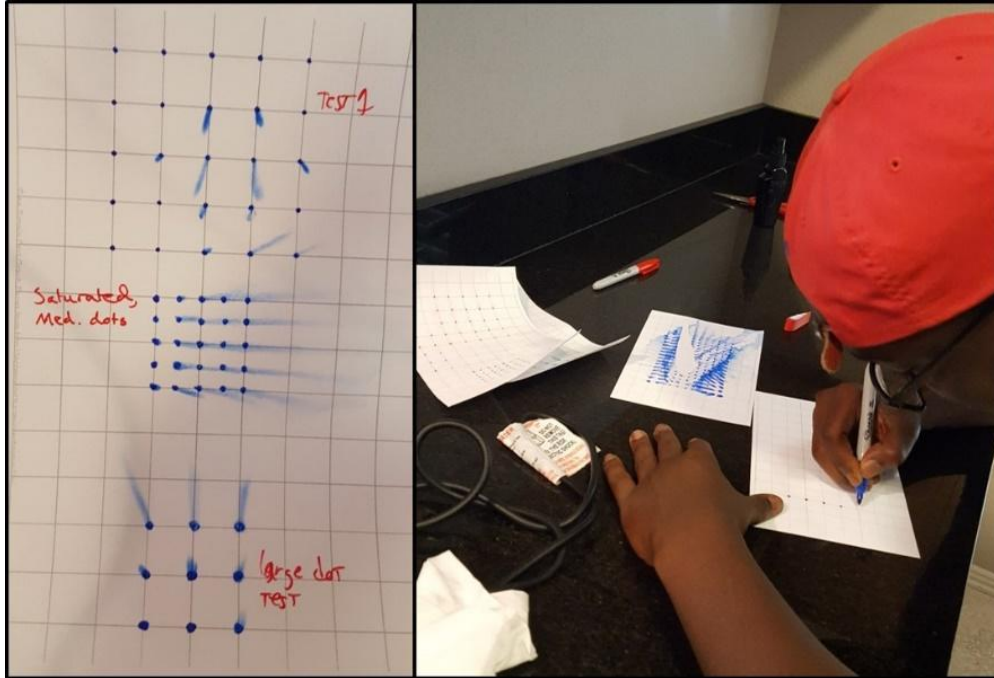
Figure 8: The test results of several dry tests (left), and an example of the dotting process (right)

RESULTS AND DISCUSSION

In this section of the report we will display the results of the experiment and discuss the observed fundamentals of aerodynamics by applying the definitions of streamlines, pathlines, and streaklines. The airfoil, the car, and the bird wing all exhibited laminar flows on the underside of the object, while the tops of the models exhibited more of a turbulent flow. This can be seen through the spacing and organization of the lines after the ink dots have been forced to move around the object due to airflow from a hairdryer.
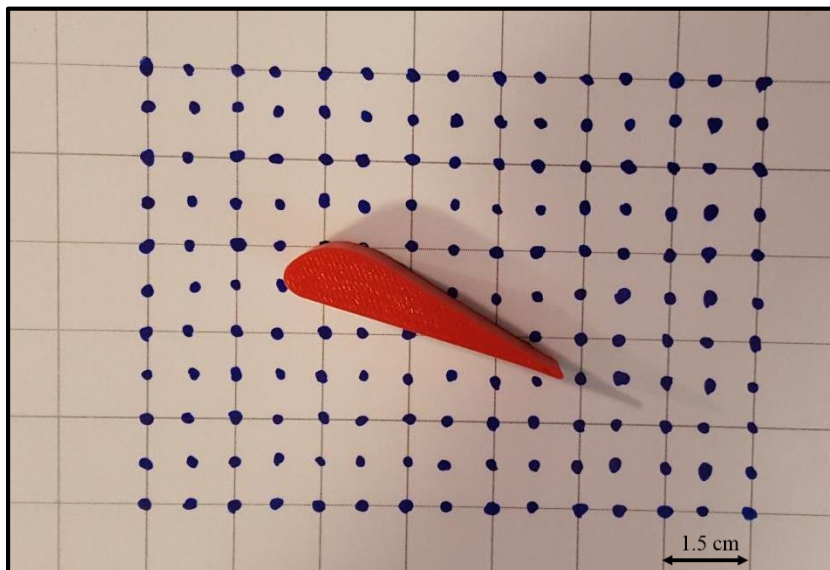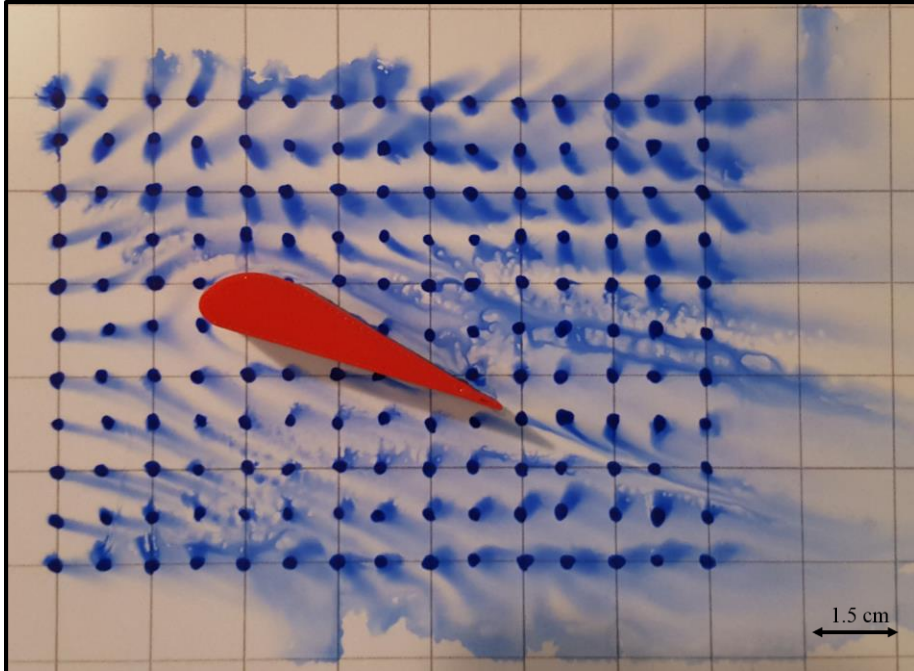

Figure 9: Initial Airfoil Orientation

Figure 10: Fluid flow visualization of Airfoil Model

Analyzing the results from our Airfoil trial, we gathered a lot of information about this model's aerodynamics. The result of the fluid flow across the Airfoil can be seen above in Figure 10, and should be compared to the initial state of the Airfoil as depicted in Figure 9. Each of the ink dots pictured above represent the path that the air interacting with the model will take when moving through fluid at the demonstrated velocity. The incident air is approaching the airfoil from the left and breaking into two portions, one above the Airfoil and one below. It appears that the airflow is streamlined underneath the Airfoil because of the lack of disturbance of the ink dots as well as the consistency of the ink dot direction of travel. Above the Airfoil there is a higher pressure of air than below the airfoil. This result is supported by the amount of disturbed ink dots as well as the intensity of the air flow. We observed the ink dots being more aggressively agitated as well as the appearance of a less streamlined flow as the air gets to about the last third of the model. At the location on the model the air appears to undergo a type of back pressure, and is supported by the reversed direction of the ink flow. The flow pattern is no longer a smooth path that follows the geometry of the model, and the paths of individual points on the paper become indistinguishable from the neighboring particle pathlines.

This result can be compared to the result of an unsuccessful fluid flow test, as seen below in Figure 11. This test was conducted as the first recordable experiment, but failed in a number of respects. The marker bleeds unevenly across the paper, and makes an interesting pattern around the model as observed in the referenced image below. While these qualities may seem to be attributed to a successful fluid flow test at high speeds, during the experiment it was noted that the alcohol solution across the surface of the paper was concentrated the point of conglomerating in very thin layers of liquid. These liquid puddles then appeared to move across the surface of the paper and wash away the marker dots instead of staining the glossy photo paper. This is most likely due to an oversaturating of the alcohol mixture. The successful test corrects these problems by using less sprays of the alcohol solution and a prolonged stream of constant airflow moving across the paper. These changes, in unison with improved technique by those completing the lab experiment, produced better results, and learning from the mistake of one failed test allowed the experiment to ultimately be completed in a timely manner.
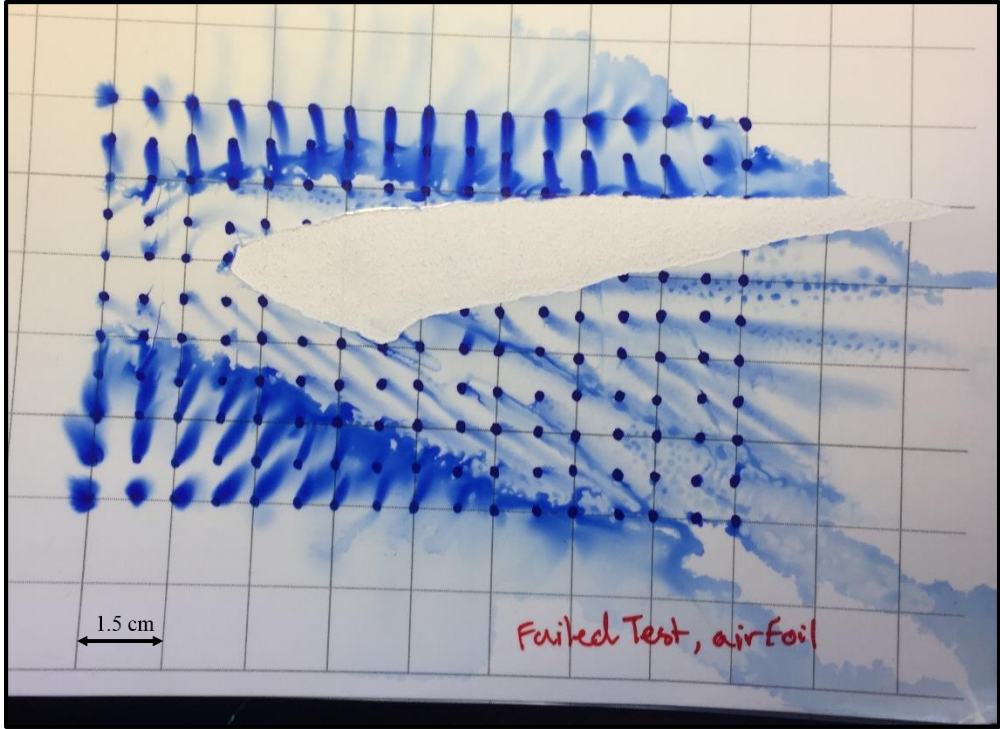
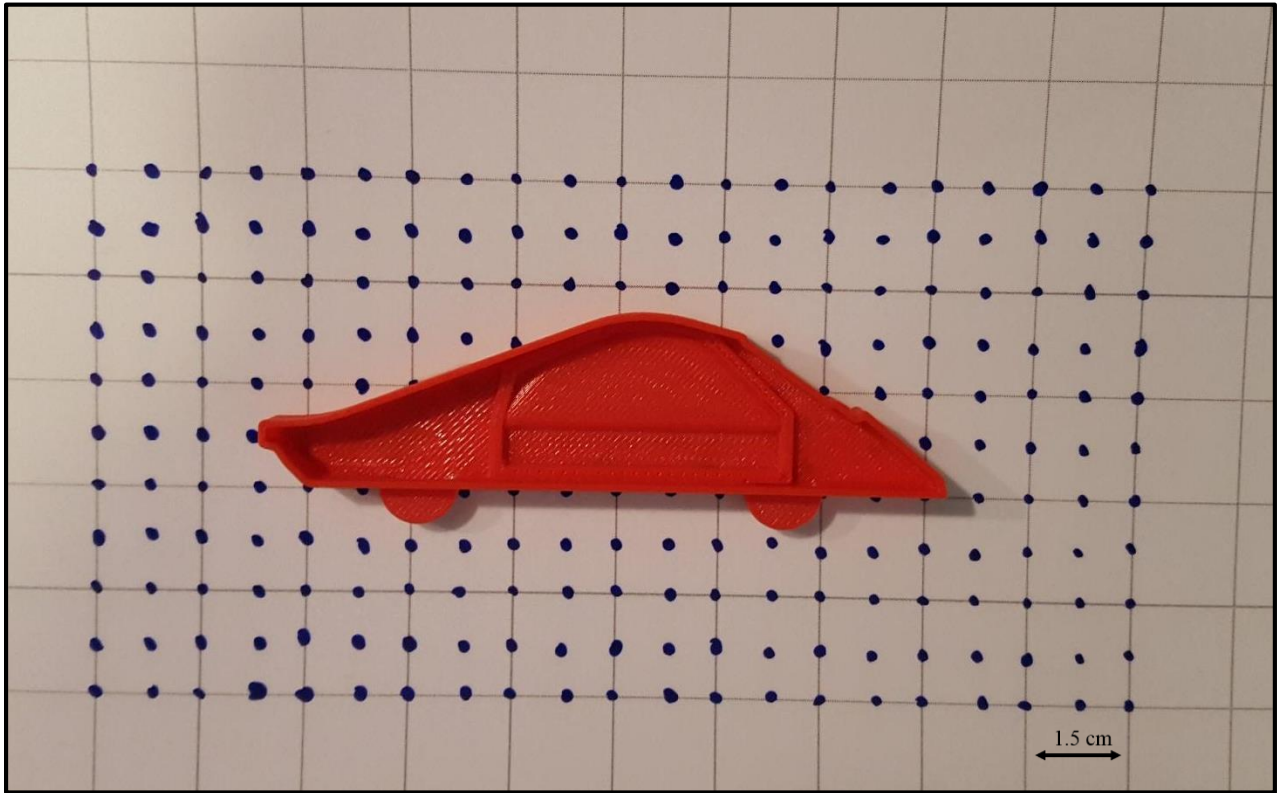Figure 11: Failed fluid visualization test on Airfoil

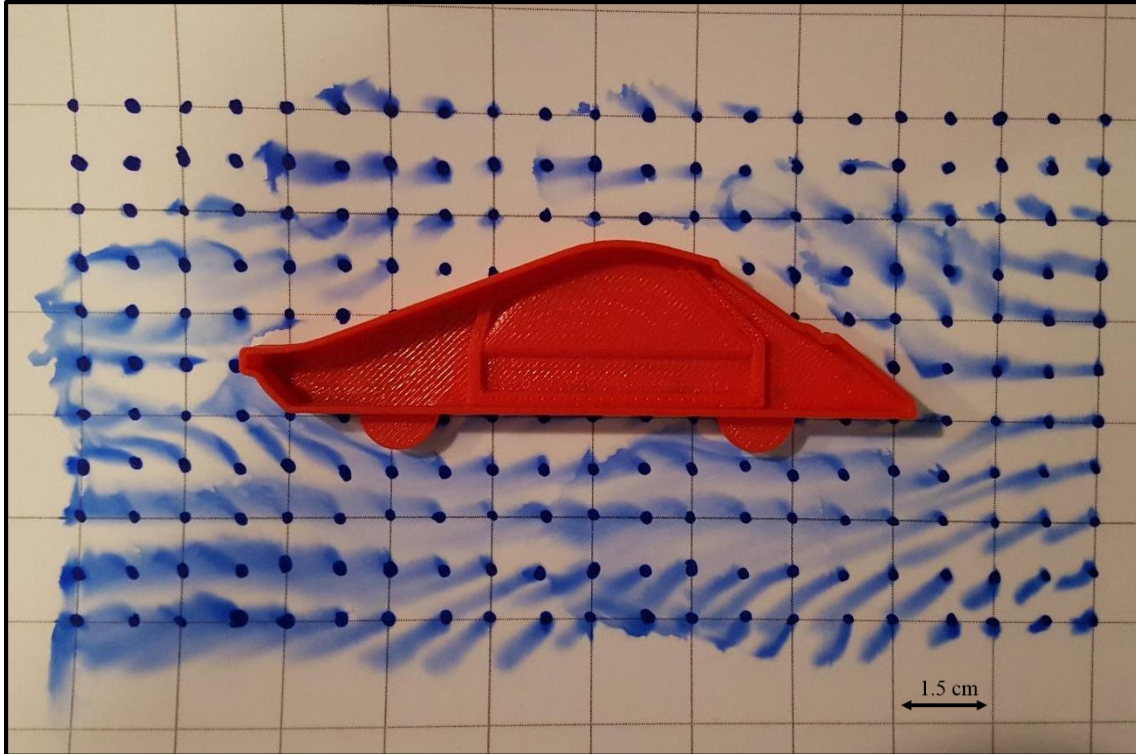

Figure 12: Initial Car Body Orientation

Figure 13: Fluid flow visualization of Car Body Model

The flow visualization model of the Car Body, as pictured in Figure 12 and 13, did not result in very clear data. The incident airflow approached our Car Body model from the right side and traveled horizontally, suggesting very little evidence of this model possessing aerodynamic qualities. From these results it was found that the majority of the air was observed to be flowing underneath the car, and very little flowed over the top side. This indicates that this ink dot flow visualization are in a streamline, because if we released a steady air flow from a single point, it is likely that the entirety of the stream would travel underneath the model and stay on this same path for the entire time span the airflow is present. This conclusion is supported by viewing the above image and observing that every ink dot below the car is disturbed in some way shape or form because of the increased amount of airflow compared to the top side, and the ink dots above the model; except in the front and rear; are largely intact.
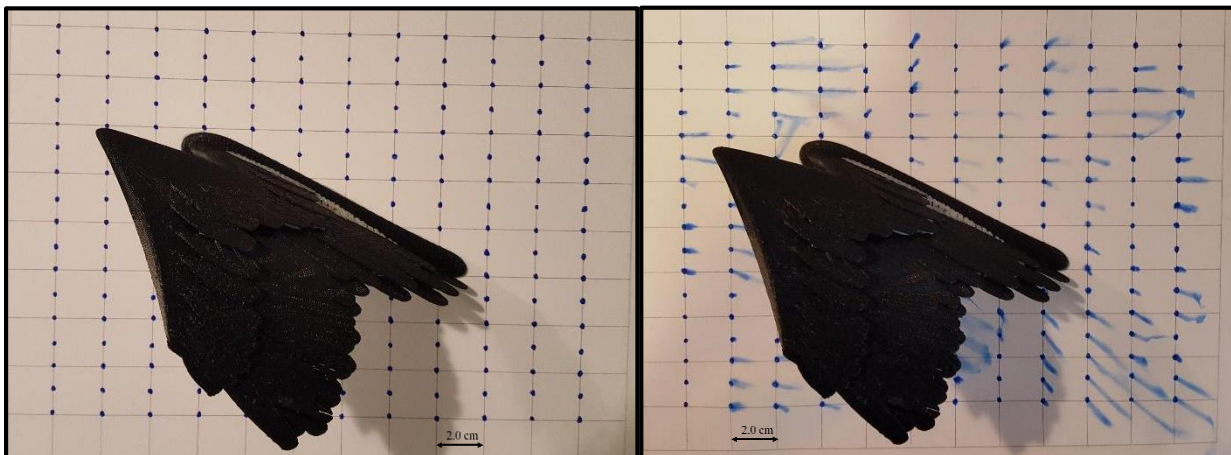

Figure 14: Initial Bird Wing Orientation (left) and flow visualization of Bird Wing Model, Top View (right)
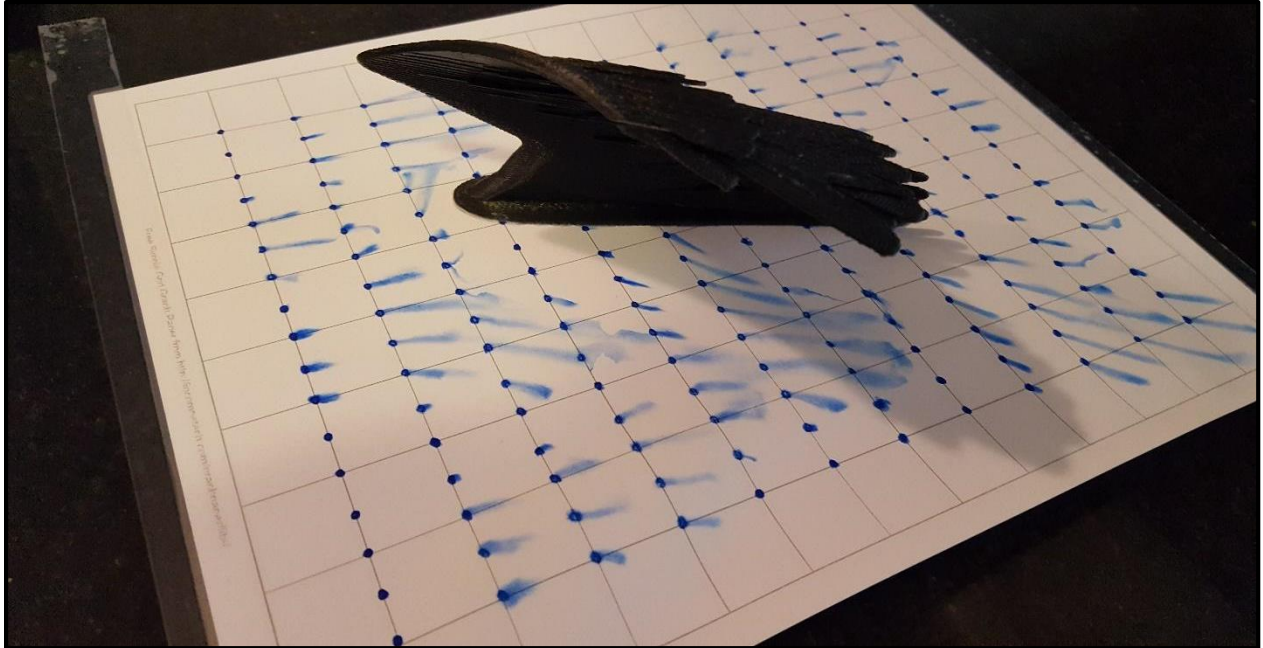
Figure 15: Fluid flow visualization of Bird Wing Model, Trimetric View

For our selected model we observed faint but interesting data. The Figures above showcase the collected results; Figure 14 portrays the bird wing before and after flow visualization has occurred from a birds eye view, and Figure 15 reveals the results along the wing's interior side that are blocked by the curve of the wing. As we introduced the airflow from the top left corner traveling to the bottom right corner, we witnessed very little air resistance with this model due to the lack of disturbance of the ink dots. This means that this model produces very little drag, the force which acts opposite to the direction of fluid motion. However when we analyzed the locations the majority of air flow traveled we found that almost all of the air flowed under the wing. This provided a streamline effect with all the ink flow traveling tangent to the incident air's velocity. Because of the majority of the air flowing underneath the wing this created a much higher pressure than the top side. This is especially interesting because in nature, when analyzing an actual bird wing, this is the exact result the wing is designed to output. The difference in flow rate, and the difference in pressure, between the underside and the top side of the wing is the reason why birds are able to fly. If a body can be created such that more air is directed below the wing than over the top, the net force of that body will be in the vertical direction and the body will move upwards, a phenomena that is called lift.

CONCLUSION

The ink dot fluid flow visualization experiment was successful in producing observable data and delivering promising results. The resulting fluid flows recorded on the glossy paper were expected, and the experiment proved the theory of fluid bending around objects under current flow to form streaklines. The study of the experimental results greatly improved the understanding of pathlines, streamlines, and streaklines, and aided to classify the difference between the three types of visualizations. The streamlines produced around all three models suggests the experiment successfully models the physical characteristics of fluid flow across static surfaces.

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