Analysis and Outreach Results of a Mobile Wind Tunnel STEM Learning Tool

Andrew Machemar

Follow this and additional works at: https://louis.uah.edu/honors-capstones

Recommended Citation
https://louis.uah.edu/honors-capstones/108

This Thesis is brought to you for free and open access by the Honors College at LOUIS. It has been accepted for inclusion in Honors Capstone Projects and Theses by an authorized administrator of LOUIS.
I. INTRODUCTION

The MAE Product Realization capstone design course offered at UAH takes the form of two semester courses designed to be taken consecutively. The first encapsulates the initial phases of the design, including preliminary research, patent searches, benchmarking, technical analyses, material analysis, hazard and risk assessment, human factors, and more. The culmination of the first semester is a design solution that satisfies all customer and course requirements and will be ready to be fabricated during the second semester. During the subsequent semester, the course focuses on the fabrication, updated technical analysis, engineering development testing, verification and validation testing, and final delivery to the customer. The purpose of the capstone design courses is to expose students to the process of initializing and completing a product while meeting customer specifications and the challenges that accompany any design process. For those teams designing a STEM education tool, student outreach is another critical component taking place during both semesters. This outreach takes the form of an initial market survey meant to factor student ideas and desires into the design to ensure that the end product is desirable to the students as well as the teachers. A second form of outreach is an educational presentation explaining the purpose and background of the product, demonstration of the final product, and a short survey designed to gauge the overall effectiveness of the tool and presentation in generating interest in the STEM fields.

Generating increased interest in the STEM fields among kindergarten through 12th grade (K-12) students is one national non-profit organization in the United States (US) known as Women in Defense (WID). WID’s program is titled the Science, Technology, Engineering, and Mathematics Initiative (STEMi). The primary focus of the initiative is to foster growth in the number of students pursuing an education, and later careers, in the STEM fields in order to foster growth in US STEM fields. WID and the MAE Product Realization capstone coordinator have worked together for the past 5 years to produce several STEM tools for North Alabama public schools. In 2013, WID funded 2 STEM-tool projects,
including an educational pulley system and the mobile wind tunnel.

Due to the nature of the operational usage that these tools will encounter, they must be durable and designed for repeated use over several years. As such, safety and durability of the tool were factors considered in every aspect of the design process. In order to ensure that the product would be able to meet the rigorous demands presented by a long life-cycle, there were multiple review processes that were evaluated by the instructor, the project sponsor, and the STEM tool recipient teacher. Only after all three reviewers approved the design could the project move forward to the next phase of design. The formal design reviews evaluated the design from the conceptual and preliminary design phases, culminating with a Critical Design Review (CDR) at the end of the first semester. Two formal reviews were conducted in the second semester, the Design Certification Review (DCR) and the Product Readiness Review (PRR). As in the first semester of the process, the product was required to meet the approval of all involved parties before being permitted to move to the next phase of design or, in the case of the PRR, final presentation and delivery.

Over the course of the Spring 2013 and Fall 2013 semesters, all UAH MAE Product Realization students worked to design, analyze, test, and fabricate various designs. The STEM tools that were designed in the course were also presented to the recipient schools by way of an educational presentation that delved into the history, science, purpose, and use of the tool. The presentations were accompanied by a survey that was administered before the presentation to gather quantitative data regarding the students’ knowledge of the principles behind the tool. After the presentation and product demonstration, the same survey was administered to determine if the STEM tool and presentation were an effective method of increasing interest and knowledge in the STEM fields.

II. UAH DESIGNED HARDWARE-MOBILE WIND TUNNEL

Over the course of the Spring and Fall Semesters of 2013, five MAE student design teams composed of 5-8 team members, worked to design, test, and fabricate various products according to customer requirements. One such team was tasked with designing a wind tunnel for Discovery Middle School (DMS) in Madison, Alabama (AL). The wind tunnel was designed to be a cart-mounted, mobile learning tool that can be used to aid students in learning the fundamental concepts of aerodynamics and flight. WID provided an initial budget of $500, later increased to $650. This budget did not include the cost of the cart that the wind tunnel was mounted upon. Ms. Jane Caudle, a science teacher and head of the science department, aided the team during the preliminary design phase. A Market Survey was completed to ensure that both teacher and student input was incorporated into the initial design. Technical analyses were performed on the preliminary design to ensure that all requirements for performance and safety would be met once fabrication began. These technical analyses included materials analyses and Finite Element Analysis (FEA). Hazard assessments were performed at both system and component levels using the military standard MIL STD 882-B to ensure that the product met safety requirements throughout the design process.

The completed wind tunnel consists of a test chamber 9.5 inches wide and 9.75 inches tall with a hexagonal honeycomb straightener at the inlet and an 8-inch inlet diameter axial fan at the outlet. A system of rods at the center of the test chamber allows students to mount test articles of various shapes and designs in order to test for lift generated. Included with the wind tunnel are four airfoils: flat plate, National Advisory Committee for Aeronautics (NACA) 0010, NACA 2410, and Clark Y. Each airfoil is mounted with a built-in angle of attack ranging from -5 degrees to 10 degrees in 5-degree increments. This allows students to examine the relationship between angle of attack and lift for various airfoil geometries.

III. WIND TUNNEL SYSTEM DESIGN

Safety and durability were top-level requirements when the wind tunnel was progressing through the design process. Other important factors included equations and problems for the DMS students to complete, keeping the product weight low enough for a 12-year old student to easily transport, include pre-fabricated test articles, and allow students to test their own test article designs.

The wind tunnel went through multiple design iterations before the final, operational design was completed. This final design was completed with the use of FEA, Computer Aided Design (CAD), and mathematics programs. These software suites proved invaluable in maturing the design quickly and efficiently, as well as performing engineering validation and requirement verification testing.

Changes to the design were made to improve performance and overall quality, as well as the result of dimension issues regarding the cart around which the wind tunnel was designed. The original design used a tiered design with the fan mounted below the test chamber and a ducting system that routed the airflow through the test section. However, the design
team was misinformed as to the clearance between shelves on the cart, forcing the use of a smaller axial fan that fit on the top level of the cart. This freed the lower portion of the cart to be used to store test articles and the accompanying educational graphics.

III. REQUIREMENTS AND CONSTRAINTS

As mentioned, the top-level requirements for the wind tunnel were safety and durability. They were paramount since the product was designed to be used by middle school students. Other requirements include the following: operations manual, graphics, mathematical equations for students to complete, DMS-student designed test articles, UAH team designed test articles, integration onto a moveable cart, and the ability to remove the wind tunnel for maintenance. These requirements were specified to the team from both WID and Ms. Caudle.

Secondary requirements were collected via surveys given to Ms. Caudle’s class of eighth grade science students. The survey included questions asking the students for input on the size, shape, and overall air velocity of the wind tunnel. Input as to the types of test articles students wanted to test, variability of the air speed, adjustability of the angle of attack, and ability to simulate cyclonic airflow. Input for these design considerations was also collected from Ms. Jane Caudle. The survey also gauged student interest in aerodynamics and overall interest in having access to a wind tunnel in science classes.

The results from the survey led the team to design the wind tunnel with a test chamber length of 36 inches with variable wind speeds ranging between 10 and 20 miles per hour (mph). Despite great student interest, cyclonic wind activity was not included because it was deemed to be too difficult to manufacture in the timeline and budget. Ms. Jane Caudle also requested that the wind tunnel have storage space for test articles and any accompanying graphics.

After analyzing the survey results from the DMS students, the students expressed the most interest in cyclonic wind behavior. Despite the interest, it was determined that this feature would too difficult to produce within the timeframe and budget. High levels of student interest were also expressed in variable angles of attack and wind speeds. The DMS students also desired the ability to test their own designs for test articles, but did not express great interest in having access to test articles designed by the UAH design team. However, Ms. Jane Caudle expressed interest in having test articles included but expressed greater desire for the wind tunnel to be able to test DMS students’ test articles.

The survey question regarding the dimensions was open-ended, allowing a greater range of student responses. This led to a wide range of responses as to the overall length of the test chamber. The results for this question are given in Table I. The greatest number of responses indicated that students desired a wind tunnel greater than 5 feet in length, with the second peak at 4 feet. The third highest number of results is split between 2 and 3 feet. Because of practical size limitations and input from the teacher, the team ultimately chose 3 feet to be the length of the test chamber.

Students were also polled as to what type of test articles they would like to test in the wind tunnel. Again, this question was open-ended to encourage a wide variety of results. These results are given in Table II.

As students provided multiple answers to the question, the totals for each response are greater than the surveyed population. For example, if the student answering the survey indicated that he or she desired both the ability to test paper airplanes and model vehicles, each response was applied individually to both the “Paper Airplanes” and “Model Vehicles” category of responses. The overwhelming student response indicated desire to test paper airplanes, as well as interest in model airplanes and gliders. Responses outside of these two categories dropped precipitously.

The third open-ended survey question asked students to provide inputs as to the airspeed that the wind tunnel should generate. These responses are given in Table III.

Table I: Student Responses for Wind Tunnel Length

<table>
<thead>
<tr>
<th>Size Range (ft)</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1 ft</td>
<td>0</td>
</tr>
<tr>
<td>1 ft</td>
<td>1</td>
</tr>
<tr>
<td>2 ft</td>
<td>3</td>
</tr>
<tr>
<td>3 ft</td>
<td>3</td>
</tr>
<tr>
<td>4 ft</td>
<td>5</td>
</tr>
<tr>
<td>5 ft</td>
<td>2</td>
</tr>
<tr>
<td>5 ft+</td>
<td>6</td>
</tr>
<tr>
<td>No Response</td>
<td>4</td>
</tr>
</tbody>
</table>

Table II: Student Responses for Desired Test Articles

<table>
<thead>
<tr>
<th>Test Article</th>
<th>Total No. Of Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper Airplane</td>
<td>19</td>
</tr>
<tr>
<td>Model Airplane/Glider</td>
<td>10</td>
</tr>
<tr>
<td>Wing Shapes</td>
<td>1</td>
</tr>
<tr>
<td>Model Vehicle</td>
<td>1</td>
</tr>
<tr>
<td>Geometric Shapes</td>
<td>2</td>
</tr>
<tr>
<td>Origami Birds</td>
<td>1</td>
</tr>
</tbody>
</table>

Table III: Student Responses for Airspeed
Figure II: Updated Conceptual Design [1]

Table III: Student Responses for Wind Tunnel Speed [1]

<table>
<thead>
<tr>
<th>Velocity Range (MPH)</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10MPH</td>
<td>5</td>
</tr>
<tr>
<td>11-20MPH</td>
<td>6</td>
</tr>
<tr>
<td>21-30MPH</td>
<td>1</td>
</tr>
<tr>
<td>31-40MPH</td>
<td>1</td>
</tr>
<tr>
<td>41-50MPH</td>
<td>2</td>
</tr>
<tr>
<td>51-60MPH</td>
<td>0</td>
</tr>
<tr>
<td>61-70MPH</td>
<td>1</td>
</tr>
<tr>
<td>71+ MPH</td>
<td>3</td>
</tr>
<tr>
<td>No Response</td>
<td>5</td>
</tr>
</tbody>
</table>

Responses tended to fall into three distinct ranges with the greatest number of responses indicating that the airspeed should be between 11 and 20 MPH.

### III.II CONCEPTUAL DESIGN PHASE

During the early phases of the design process, the team designed a preliminary concept that was designed to allow the wind tunnel to be readily reproduced for extremely low cost with readily available materials and tools. This initial design was a simple rectangular test section with a square fan blowing air through a straightener, generating airflow over a simple hanging test article. This concept is shown in Figure I.

Figure I: Preliminary Design Sketch [1]

This initial design was drastically changed after the customer for the wind tunnel changed to DMS. The new design concept attempted to maximize test chamber length and viewing area. This was done by designing a two-tiered system where the fan was mounted on the bottom shelf of a mobile cart with a ducting system that routed the air from the test chamber mounted on the top shelf. This is shown in Figure II.

### III.III PRELIMINARY DESIGN PHASE

The primary considerations made during the preliminary phase of the design centered around three components: the test chamber, the cart, and the fan.

#### III.III.1 - COMPONENT AND MATERIAL IDENTIFICATION

The test chamber materials were identified using an Ashby Chart. The use of an Ashby Chart allows the team to compare materials in order to determine multiple possibilities for the design.

Figure II: Ashby Material Chart [1]

It was decided in the preliminary design phases that polymers would provide the best potential materials, therefore this was the region in the chart that was examined. The line on the Ashby Chart evaluated represents the plate bending condition as this was determined to be the most probable load condition, i.e. a student or instructor leans on the test chamber or otherwise applies a force to the test chamber. The chart used in this analysis is shown in Figure III.
From the Ashby chart, it was determined that three materials that would perform equally well were PMMA (acrylic), polycarbonate, and Glass. Polycarbonate was eliminated as a member of the team had previous experience in manufacturing with polycarbonate and advised the team to pursue a more manageable polymer in lieu of polycarbonate. In order to narrow down the list of materials, a decision matrix was used to apply additional criteria beyond material properties. The major criterion that the team decided had the greatest effect on the decision was safety, namely fracture resistance and the safety of the shards if the material did fracture. The other major consideration was the overall visibility that the material would provide students seeking to see the effects of the airflow on the test article. The less critical criteria included ease of manufacturing, material availability, and material cost. In order to attempt to alleviate manufacturing issues with respect to materials, a concept using the PMMA with metal joints was proposed and added to the decision matrix to be compared against an all PMMA or all glass structure. The decision matrix used to determine the optimal material choice for the test chamber is shown in Table IV.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Scale</th>
<th>PMMA</th>
<th>PMMA/Metal Frame</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frailty</td>
<td>20.00%</td>
<td>1=Easy to fracture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3=Hard to fracture</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Complexity to</td>
<td>15.00%</td>
<td>1=Complex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacture</td>
<td></td>
<td>3=Simple</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Cost of Materials</td>
<td>10.00%</td>
<td>1=most expensive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3=least expensive</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Material Availability</td>
<td>10.00%</td>
<td>1=Material not readily Available</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3=Material readily Available</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Fracture Shard Hazard</td>
<td>25.00%</td>
<td>1=least safe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3=most safe</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Visibility</td>
<td>20.00%</td>
<td>1=least visibility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3=most visibility</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Weighted total in %</td>
<td>100.00%</td>
<td>81.67% 96.67% 53.33%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table IV: Test Chamber Material Decision Matrix [1]

The next major subsystem that required definition was the cart that the wind tunnel would be mounted upon. Ms. Deborah Fraley from WID expressed that the wind tunnel should have storage for the accompanying graphics, if not for the other parts, supplies, and materials included with the wind tunnel. This meant that the cart had to be able to accommodate the fan, adaptive cowling, and ducting as well as have a small amount of space to store the signage for the wind tunnel. Since the fan had to be mounted to the bottom of the cart, the ability for the fan to exhaust airflow was also important. An
Table V: Cart Decision Matrix [1]

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enclosed Storage</td>
<td>25.00%</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Air Flow</td>
<td>20.00%</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>10.00%</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Availability</td>
<td>10.00%</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Flanges</td>
<td>20.00%</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Safety</td>
<td>15.00%</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Weighted total in %</td>
<td>100.00%</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>93.33%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75.00%</td>
</tr>
</tbody>
</table>

Table V shows the decision matrix for the cart. The important design consideration regarding prefabricated carts was that many had flanges or sides on the top surface of the cart. Since the wind tunnel test chamber was to be the commensurate length of the cart top, these flanges would impede efforts to mount the wind tunnel test chamber. As the commercially available carts had already passed industry safety standards while being designed and produced, safety was lessened in significance for this particular decision matrix, though it was a large consideration in the overall safety of the wind tunnel as a completed product. Other criteria considered in the decision included cost and availability. The decision matrix for the cart is shown in Table V.

Pictures of the carts used in the decision matrix are shown in Figure V, Figure VI, and Figure VII.

![Figure V: Cart 1, Mobile Tool Cabinet [1]](image)

After considering the factors presented in Table V, it was decided that Cart 1 would be the best choice to use for the mobile wind tunnel.

The third system component considered was the fan. The fan needed to be powerful enough to pull air through the test chamber and ducting at sufficient velocities in order to perform basic aerodynamic experiments. In order to determine the minimum baseline performance that the fan would have to achieve, a basic fluid analysis of the proposed test chamber was carried out. The fundamental equation for the flow analysis is given as follows:

\[
\frac{d}{dt} \left( \int_C \frac{\partial \rho}{\partial t} dv \right) + \int_S \rho (V \cdot n) dA = 0
\]  \[1\]

The assumption for the airflow through the wind tunnel is incompressible, meaning that the \( \frac{\partial \rho}{\partial t} \) can be set to equal zero, reducing the equation to:

\[
\int_S (V \cdot n) dA = 0
\]  \[2\]

Assuming that the inlets and outlets are one-dimensional flows, the integral simplifies to:

\[
\Sigma_i (A_i V_i) = \Sigma_e (A_e V_e)
\]  \[3\]

For systems that have only one inlet and one outlet, the equation further simplifies to the following:

\[
A_i V_i = A_e V_e
\]  \[4\]

Or

\[
Q_{out} = Q_{in} = A_i V_i
\]  \[5\]

where \( Q \) is the volumetric flow rate of the fluid. By specifying a minimum desired velocity through a
known cross-sectional area allows the calculation of the required volumetric flow rate of the system, and thus the required fan flow rate. While these equations are derived to be used with circular cross-sections, they can be used as an approximation for square passages. For a 10” square cross section and a minimum desired velocity of 10MPH, the required volumetric flow rate is 600 cubic feet per minute (CFM). This became a critical parameter in choosing the fan for the wind tunnel. The other critical factor was that the assembled fan diameter fit within the dimensions of the desired cart. Variable speed settings and cost rounded out the other two parameters. The decision matrix for the fan is shown in Table [2].

III. III. III – PRELIMINARY VERIFICATION TESTING AND PROTOTYPING

It was determined that preliminary prototype testing would prove to be indispensable in maturing the product. Prototype diffuser cowlings were made from poster board and cut to the proper cone dimensions and attached to the Polar Aire® fan. When the fan was powered on, the air inside the cowling would over-pressurize and stall the fan. It was quickly determined that the Polar Aire® was not the correct type of fan to either push or pull air through the cowling. This led to a re-evaluation of the fan needed for the project. A suitable replacement was found using a 24 in. Ventamatic® drum fan. The enclosed shape of the fan means that the air is pulled through the fan housing and not simply circulated as with a standard floor model. The new fan had a lower volumetric flow rate with an advertised value of 4000CFM on high and 2800CFM on low. A photograph of the fan is shown in Figure VIII. When the Ventamatic® drum fan was tested with similar prototype cowling configurations it was able to generate airflow without causing backpressure that stalled the fan. The drum fan was tested using cowlings to adapt the 26 inch outer diameter to 4, 6, and 10 inch diameter ducts. These ducts were then attached to a cardboard mock-up of the proposed test section. A hand-held anemometer was used to record the velocity through the mock-up test section. These prototyping tests gave valuable insight into the behavior of the fan when the airflow is altered by ducting and the diffuser cowling, but was plagued with a major flaw in that the material used for the prototyped cowling would collapse under the negative pressures generated by the airflow from the fan. This is shown in Figure IX.

When the fan was powered on, the air inside the cowling would over-pressurize and stall the fan. It was quickly determined that the Polar Aire® was not the correct type of fan to either push or pull air through the cowling. This led to a re-evaluation of the fan needed for the project. A suitable replacement was found using a 24 in. Ventamatic® drum fan. The enclosed shape of the fan means that the air is pulled through the fan housing and not simply circulated as with a standard floor model. The new fan had a lower volumetric flow rate with an advertised value of 4000CFM on high and 2800CFM on low. A photograph of the fan is shown in Figure VIII. Error! Reference source not found. These lower volumetric flow rates indicate that the velocities through the test chamber will be lower. Returning to Equation 5, the values for the volumetric flow rates of the Ventamatic® give peak velocities of 65.5MPH while running on its high setting and 45.8MPH when on its low setting. When the Ventamatic® drum fan was tested with similar prototype cowling configurations it was able to generate airflow without causing backpressure that stalled the fan. The drum fan was tested using cowlings to adapt the 26 inch outer diameter to 4, 6, and 10 inch diameter ducts. These ducts were then attached to a cardboard mock-up of the proposed test section. A hand-held anemometer was used to record the velocity through the mock-up test section. These prototyping tests gave valuable insight into the behavior of the fan when the airflow is altered by ducting and the diffuser cowling, but was plagued with a major flaw in that the material used for the prototyped cowling would collapse under the negative pressures generated by the airflow from the fan. This is shown in Figure IX.
The collapsing prototype cowling had an extremely detrimental effect on the test results, rendering them nearly invalid. The results can be used to determine only the gross effects of changing the geometry of the system. The results from these tests are shown in Table VII. Since the cross-sectional areas of each of these ducts was less than the 100 in\(^2\) of the test chamber for which the initial fluid analyses were performed, the velocities should measure higher than the previously calculated values. Instead, they are significantly lower. This would indicate that the volume of air moving through the system is less than the purported performance level of the fan. This warranted further investigation with materials-accurate prototypes or full system testing to determine the true flow rates for the fan being used. Using the anemometer used to gather the previous velocity data, a velocity profile for the fan was measured by creating a polar grid on the fan outlet face. There were 49 radial spokes on the grid, each separated by an angle of approximately 7.35 degrees. This corresponds to the width of the anemometer. Each spoke was then measured in 1.5-in increments from the center to create a measurement point.

In total, each velocity profile is comprised of 441 data points. These data points were then input into the MATLAB\textsuperscript{®} software suite and a 3-dimensional surface fitting function was used to fit a fifth-order polynomial to the data as a best fit surface. The fit functions for the high and low speed settings for the Ventamatic\textsuperscript{®} fan are shown in Figure X and Figure XI. As would be expected, the values for the velocity approach zero as the measurement point reaches the
center, as this is where the motor for the fan is located. The general trend is that the velocity increases as the measurement point moves from the center to the outer radii with the maxima occurring at the edges near the tips of the fan blades. Equation 3 shows that the volumetric flow rate is the sum of the areas multiplied by the velocity. By evaluating the double integral of the velocity fit function across the surface area of the fan outlet face, the empirically determined volumetric flow rate can be obtained. The values calculated from this procedure predict a volumetric flow rate on the high speed setting of 2881 CFM and 2338.2 CFM on the low setting. These values differ drastically from the values reported by the manufacturer of the fan. Examination of the data shows that there is a high level of variance along the radii of the fan face, even though it can be assumed that the velocities for each radial value would be identical. Simply put, an ideal fan would have symmetric rings of velocity radiating outward from the center. If that assumption is made, then it can be said that all values along a radius of the fan are measurements of the same value. This allows outlying data points to be eliminated by applying Chauvenet’s Rejection Criterion. Removing outlying data should serve to increase accuracy of the results after integration by increasing the accuracy of the fit equations. Application of Chauvenet’s Criterion changed the calculated flow rate for the high velocity setting to 2919 CFM and the low speed setting flow rate was changed to 2818 CFM. The regenerated surface plots for these new surfaces are shown in Figure XII and Figure XIII. While the high speed setting flow rate increased to nearly 3000 CFM, this is still less than 75% of the advertised flow rate. The low speed setting flow rate, however, has become an overestimated value. Neither value is exact because the functions that the calculations are based on are approximations in and of themselves, meaning that any error in the measurements will propagate forward. However, it can be assumed that these are reasonable approximations. Increasing the sample size or improving the quality and accuracy of the anemometer would both serve to help mitigate some of the errors that are affecting the data.

A materials-accurate cowling was built by the
team for the purpose of preliminary testing to determine the effects the addition of the cowling had on the flow and performance of the fan, testing deemed necessary after the failures of the first tests. The same method was used as with the unobstructed fan to determine the velocity profiles and volume flow rates. The results for the high and low speed settings after the application of Chauvenet’s Criterion are shown in Figure XIV and Figure XV. The addition of the cowling to the fan caused significant decreases in fan performance. The volumetric flow rate for the Ventamatic® fan on the high speed setting was calculated to be 1239.8CFM and the low speed flow rate was calculated to be 484.8315CFM. Using Equation 5, this gives predicted velocity values of 20.29 mph on the high speed setting and 7.93 mph on low. These values do not include any velocity lost due to friction and head loss in the ducting. As such, these values are considered extremely optimistic. The low speed velocity value is below the desired 10 mph benchmark established by the team though the high speed setting met this baseline. The cause of this lowered performance is attributed to the formation of a low pressure region within the cowling which causes the ambient pressure at the face of the fan to resist the flow out of the face, causing the fan to have to resist a counter-directional pressure flow as well as pull the air through the narrower entrance to the cowling. Dimensional constraints have limited the size of the cowling, but it is hypothesized that decreasing the angle of the cone would alleviate this negative pressure formation and streamline the flow out of the fan. The formation of the low pressure region was confirmed using a digital manometer. On the high speed setting, this pressure varied between -1.0 and -1.6 mBar gage pressure. This pressure value was between -0.2 and -0.5 mBar gage pressure.

At the request of the customer, the UAH team planned to include multiple airfoil shapes to provide a working baseline of airfoil and test article performance. Initially, five airfoil shapes were considered for inclusion with the final product: flat plate, symmetrical diamond wedge, NACA 0010, NACA 2410, and NACA 5410. The initial selection was not based on performance parameters, but rather in providing a wider variety of airfoil shapes to better indicate how airfoil geometry affects performance. To ensure that the selected airfoils would generate enough lift to provide a dynamic display, lift calculations were performed using data calculated from an online resource titled JavaFoil® as well as an aerospace engineering textbook by John D. Anderson, Jr. titled Introduction to Flight. Both sources were used in order to cross reference results from multiple calculation sources in order attempt to verify results. In the event that the calculations did not agree, the lower value was assumed to be the more accurate in order to generate a margin of error that tended to be pessimistic rather than proceed with an overestimate of performance.

The performance calculation equations were used on the data points generated from both sources. The initial airfoils had chord lengths, c, of 4 inches and a span, b, of 8 inches. Using this information, the planform area $S$ can be calculated using Equation 6:

$$S = bc$$  \[6\]

This results in each of the proposed airfoils having a planform area of 32 in². Using the solution from Equation 6, the aspect ratio of the airfoil, $AR$, can be found using the following equation:

$$AR = \frac{b^2}{S}$$  \[7\]

For each proposed airfoil, this value was determined to be 2.

The results of Equation 7 are then used in the calculation of the lift slope for the finite airfoil, $a$, given by the equation

$$a = \frac{AR}{AR+2} \cdot a_0$$  \[8\]

This is calculated as

$$C_{L,\text{max}} = a \cdot (\alpha_{\text{stall}} - \alpha_{L=0})$$  \[9\]

where $\alpha_{\text{stall}}$ is the stall angle for the airfoil and $\alpha_{L=0}$ is the angle of zero lift. These values are estimated using the JavaFoil® applet for both calculation techniques. The next calculation was to determine the minimum velocity at which the airfoil will generate enough lift to carry its own weight and generate useful and measureable data. This is the stall velocity, $v_{\text{stall}}$, and is calculated by

$$v_{\text{stall}} = \sqrt{\frac{2W}{\rho_c s C_{L,\text{max}}}}$$  \[10\]

where $a_0$ is the lift slope for the respective airfoil. This is generally assumed to have a value of 0.1 per degree for most airfoil shapes and is assumed to be an accurate approximation.

This value is then used to find the maximum coefficient of lift, $C_{L,\text{Max}}$.

In Equation 10, $\rho_c$ is the value for the density of air (assumed to be at standard sea level), and $W$ is the total weight of the airfoil. For aircraft design, the velocity required for liftoff is offset from the stall velocity by a factor of safety of 1.2. This new value is called the liftoff velocity, or $v_{\text{liftoff}}$. In the terms of the analysis of the airfoils, this value is used for the minimum airspeed through the test chamber to ensure that the test articles will perform as required. The liftoff velocity is given as
All calculations for the performance parameters were completed using the MATLAB® computation package using data collected from the JavaFoil® applet. The applet operates by utilizing geometrical inputs based on existing parameters and general shapes (cambered plate, cambered wedge, NACA 4-digit series). The applet produces coordinate points representing the shape of the airfoil with a native chord length of 1 inch. Using the built in scaling function, this was increased by 400% to represent the desired airfoil dimension. The polar tool was used to generate data that was then used in the calculations of the performance of the airfoil. The values for angle of attack, $\alpha$, were set between -15 and 15 degrees with a step size of 1 degree. The Reynolds numbers were generated using a calculator from the Engineering Toolbox®. The values returned from this tool for the low and high speed setting values were found to be approximately 780,000 and 1,180,000, respectively. These values show that both flows are considered to be within the turbulent regime [3].

The results of these calculations were utilized to determine which airfoils should be included with the final product. This was decided on the basis of the greatest lift capability and most dynamic performance ranges. Because of the nature of the STEM tool, the experiments must be dynamic and visible, providing a variety of results that encourage discussion and analysis. These calculations also provided a baseline to determine if any airfoils would fail to function and if another airfoil would need to be considered in its stead. The results from these calculations are located Table VIII, Table IX, and Table X. Comparisons of the calculated datasets yield very different results. The textbook-based calculations yield a maximum added weight of less than 1.5lbm for the best performing airfoil whereas the JavaFoil®-based calculations yield a maximum added weight of over 2.5lbm for even the lowest-performing airfoil.

These dissimilarities continue in the value for the stall speeds and liftoff speeds of the airfoils, the values that determine if the airfoil will exhibit any lift in the wind tunnel. The largest dissimilarity occurs in the calculation of the behavior for the diamond wedge airfoil. The textbook calculations indicate that the wedge requires airflow moving a minimum of 17.72 mph to lift, 21.275 mph accounting for liftoff speed corrections. The JavaFoil® based calculations have these values being below 4 mph on both the high and low settings.

Analysis of the results of both datasets forces the team to consider the textbook-based calculations to be accurate in order to ensure that minimum baseline performance is considered. This pessimistic approach ensured that, in the event that the finished product did not perform as predicted, the airfoil performance requirements were still met. As such, the decision was made not to include the diamond wedge airfoil.
unless the performance parameters and requirements could be more accurately reconciled or the lowest estimate was under attainable parameters. This decision was based on not only the required liftoff speed (wind tunnel velocity predictions exceeded this value) but also on the range of performance. The angle of maximum lift was determined to be 1 degree where the angle of zero lift was 0 degrees. This gives DMS students performing calculations on the preliminary design one step increment of increasing performance whereas the other airfoils provide at least 7 degrees. The third factor considered was the low performance in carrying weight. The textbook estimates rate the diamond wedge as being able to support less than 0.1 lbm added mass. The team decided that this was an unacceptable performance baseline.

The origin of the source of the discrepancies in the data is hypothesized to be in the methods used by JavaFoil®. JavaFoil® uses differential equation solvers to approximate the coefficients whereas the textbook method relies on coefficient approximations. The difference between these methods most likely accounts for the bulk of the error. The other factor in the error is the scaling of the airfoil. While it is labeled as a geometric scaling factor, it appears to scale the values of the coefficients by a similar amount. Because of these uncertainties, it was decided that JavaFoil® would only be used to find critical flight angles to be used in the textbook-based calculations.

III.IV - DETAIL DESIGN

Following the completion of the first semester and the CDR, the product was matured to the detail design phase of the design process. During this phase, the team began parts and material acquisition and fabrication, as well as preparation for the DCR. After completing the requirements of the DCR to the satisfaction of the instructor, customer, and sponsor, the team began final fabrication and assembly. The final review, the PRR, was then completed to the satisfaction of all reviewers. The assembled wind tunnel was then delivered to DMS, during which the design team gave an information presentation and administered preliminary and post-presentation surveys to gauge interest and knowledge bases among the DMS students.

III.IV.1 – DESIGN CHANGES

It was during this design phase that the team encountered an assembly issue regarding tolerances between the cart and the fan. A miscommunication between the supplier of the cart and the design team led to the purchase of a cart that did not have sufficient clearance between the bottom and top shelves to mount the fan without potentially destructive modification to both. In an effort to stay within budget and timeline, the team was able to perform an even trade of the Ventamatic® fan for an 8-inch axial blower fan. Since the axial fan was significantly smaller, this eliminated the need for a two-tier design, and thus the need for the ducting system. The final design is shown in Figure XVI. The removal of the bulky fan and ducting system also allowed the addition of storage for test articles and supplies as initially requested by the customer and sponsor.

The airfoils included in the final product were originally hand-crafted by a member of the design team, but when tested proved to be inconsistently shaped and performed poorly. It was determined that pre-fabricated replacements would need to be ordered in order to ensure that the airfoils were properly manufactured. This change forced the geometry of the airfoils to be changed as a compensatory action. The manufacturer of the airfoils sells airfoils at a minimum length of 12 inches in sets of two. In order to maximize the number of airfoils purchased while staying under budget, the airfoil
span was decreased from 8 to 6 inches and the chord from 4 inches to 3 inches in order to maintain aspect ratio (See Equation 7).

Another design change that the team was required to make was the design of the test article stand. The original concept, shown in Figure XVII, was a sliding system with a rotating attach point that allowed the user to set the angle of attack. This system was fabricated but during testing it was discovered that the moment generated by the airfoil would cause the inner sleeve to catch against the outer, providing excess friction that the airfoils with the greatest lift could not overcome. The airfoils that provided lesser amounts of lift were unable to lift the mass of the sliding system to any useable degree. The system that replaced the original design consists of two vertical rods placed through the top of the test chamber and into a base on the bottom of the test chamber. The new airfoils had sleeves added that slide over the rods. This system allowed the airfoil to traverse the entire height of the test chamber and was not limited to a fixed height as with the previous design. The final test stand design is shown in Figure XVIII. The design is more restrictive in what DMS students can design to test in the wind tunnel, but still allows for custom test articles to be designed and included, albeit a more challenging assignment.

A hexagonal honeycomb straightener was added using material donated by the UAH Machine Shop in lieu of the team-fabricated straightener. Benchmarking research completed by the team determined that a hexagonal cell shape approximately 4 to 6 times longer than the cell width performed well as straighteners for airflow. Locking casters were also added to the cart as a safety measure to prevent the cart from rolling away from the operator during use.

### III.IV.II – VALIDATION AND VERIFICATION TESTING

<table>
<thead>
<tr>
<th>Position</th>
<th>Volume Flow Rate (CFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>593.78</td>
</tr>
<tr>
<td>Outlet</td>
<td>465.4</td>
</tr>
<tr>
<td>6 in.</td>
<td>483.94</td>
</tr>
<tr>
<td>12 in.</td>
<td>467.86</td>
</tr>
<tr>
<td>18 in.</td>
<td>445.1</td>
</tr>
<tr>
<td>24 in.</td>
<td>449.95</td>
</tr>
<tr>
<td>30 in.</td>
<td>649.97</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>74.49330267</td>
</tr>
<tr>
<td>Mean</td>
<td>508</td>
</tr>
<tr>
<td>97.5% Interval</td>
<td>125.89</td>
</tr>
</tbody>
</table>

Table XI: Calculated Flow Rates for Axial Fan

The change that most affected the performance of the product was the reduction in fan size. Cursory testing showed that it was capable of producing a minimum of 10mph through the center of the test chamber, but a more rigorous approach was desired. With the completion of the test chamber, it became possible to mathematically derive an estimation of the volume flow rate of the fan in multiple iterations as comparison points to try to statistically determine the most accurate value. The values for the volumetric flow rate were calculated using the same procedure as the measurements in Section III.III.II adjusted for the rectangular cross sections, i.e. measurements were taken on a Cartesian grid rather than a polar grid. These measurements were taken at the fan outlet, inlet to the test chamber, and five cross-sectional planes in the test chamber. The test chamber inlet and each cross section was comprised of 100 data points and the fan outlet, being a smaller rectangular section, was comprised of 49 data points.

The results for each volumetric flow rate calculation are shown in Error! Reference source not found. Table XI, as well as the accompanying statistical information. Unlike the calculations done with the circular fan, no assumptions can be made as to any symmetry of the velocities. As such, few improvements, if any, can be made to the curve fits. Averaging the results gives a more accurate value for the volumetric flow rate that can be confirmed by recalculating the results of Equation 5 using the average velocity at the inlet and comparing that calculated flow rate to that calculated by the integral approximations. The value and 97.5% confidence interval for the value of the volumetric flow rate was found to be 508±125.89 CFM. This represents a wide spread of data with a very wide confidence margin. Application of Chauvenet’s Rejection Criterion using the 97.5% confidence interval removes the value of the flow rate that occurs at the 30 inch mark in the test chamber (for reference, this plane occurs at the inlet of the duct connected to the fan). Removal of the outlier changes the value of the flow rate to 484.34±85.42 CFM. This is still a large range
representing over 20% of the full measured value. In order to gain a more accurate measurement, a more precise anemometer should be used and the sample size increased.

Another output from this data is the composite plot of the velocity surfaces of all test section planes. This shows the change in velocities as changes in topography of the surface plots taken from the cross sectional velocity data. This gives the team another reference that visually simpler as to how the velocity changes with respect to the position in the test chamber. These are approximate surface fits, not plots of collected data. This plot is given in Figure XIX. The inlet to the test chamber is the lowest surface and each surface moving in the positive y-axis represents moving 6 inches into the test chamber.

The shape of the surfaces shows that the closer the measurements were taken to the inlet to the fan itself, the more irregular the surface generated. Each surface shows a trend of stagnation toward the outer edges, reminiscent of the no-slip condition of fluid mechanics. As the data points proceeded toward the fan, the velocities increased in the center, showing that the velocity of the airflow is concentrated around the inscribed circle created by the ductwork attached to the fan. Adding a reducer to gradually reduce the rectangular cross section to the circular cross section of the inlet may create a more uniform flow field by eliminating the sudden transition region.

This same data was then used to determine the vector field present in the wind tunnel test chamber. This information allows the team to judge the most effective location for the test stand by identifying the most uniform velocity regions. It also gives the potential to identify stagnant regions that may cause turbulence or flow disturbances. If such flow patterns had been detected, the team would have had to perform flow tracking experiments to determine the location of the disturbances. Due to budget constraints, these experiments were reserved only in the even that large disturbances were detected that would require mitigation for the product to function effectively. No such disturbances were readily identified from the data. The vector field produced by these calculations is shown in Figure XX. 

Reference source not found. It should be noted that the flow through the test chamber is assumed to be one-dimensional after passing through the straightener. The vector arrows are color-coded to magnitude with blue shades representing larger magnitudes, i.e. green-shaded arrows are lower.
velocities than yellow and blue arrows, despite appearing larger.

Looking at the vector plot, the results from examining the profile plots are supported. The velocity increases moving from the inlet toward the fan with the greatest rates of change in the circular region inscribed by the fan inlet. The plot also shows that the velocity drops near the corners of the test chamber on the data plane taken at the fan inlet. This is not unexpected, as the ducting connected to the fan inlet extends into the test chamber approximately 5 inches. The only expected airflow behind this plane would be expected to be circulation or entirely stagnant. So long as any vortices formed to not break the plane at the fan inlet, these will not affect the test article itself.

The position of the test article stand would be optimally placed 18 inches into the test chamber, or in the center line. This supported the team’s hypothesis and made for a more visible design for the test stand. Ultimately, the velocity filed proved to be very valuable in confirming multiple hypotheses regarding the fluid behavior in the test chamber. The results of the analysis also provided the team insight as to what improvements could be made to better direct and normalize the velocities through the wind tunnel. Just as with the velocity surface analysis, the conclusion is that a reducer would help reduce the rapidity of the velocity change as the measurement plane approaches the face of the fan inlet. Due to the change in the fan used for the air supply the velocity, and therefore the Reynolds Number, in the test chamber has been altered. Using the Engineering Toolbox® to calculate the Reynolds Number using the values for velocity in Section III.IV.II gives a value of 25000. This is still considered within the turbulent region.

The same equations and calculation methods from Section III.III.II (Equations 6-11) were used to reevaluate the performance of the airfoils. However, the NACA 5410 was replaced with a Clark Y airfoil due to manufacturing limitations and the chord and span of each airfoil were reduced to 3 and 6 inches, respectively. The results of the finalized analyses are found in Table XII and Table XIII.

The results are more similar than in the first set of analyses, but still vary significantly from one form of analysis to another. Only basic validations of airfoil performance were completed due to time constraints, i.e. each airfoil was tested for behavior and performance but not empirically tested to determine lifting ability. From these results, the textbook-based calculations seem to be the more accurate representation. Proper validation experiments need to be performed before any data can be declared a valid model. The scaling factor for this set of JavaFoil® values was removed, meaning that the current difference is the result of the approximation methods used by JavaFoil®. Another source of this error may lie in the approximations used in the textbook-based calculations, specifically the value of $a_0$. Each airfoil has a distinct value of $a_0$ that is generally close to the 0.1 per degree value used in the calculations. However this difference may be significant enough to

<table>
<thead>
<tr>
<th>Airfoil</th>
<th>Projected Weight</th>
<th>Stall Angle</th>
<th>Angle of Zero Lift</th>
<th>Cl Max</th>
<th>Stall Speed</th>
<th>Liftoff Speed</th>
<th>Max Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate</td>
<td>.045 lb</td>
<td>7 degrees</td>
<td>0 degrees</td>
<td>0.35</td>
<td>3.48 MPH</td>
<td>4.17 MPH</td>
<td>.34 lb</td>
</tr>
<tr>
<td>Wedge</td>
<td>.297 lb</td>
<td>4 degrees</td>
<td>0 degrees</td>
<td>0.2</td>
<td>11.83 MPH</td>
<td>14.18 MPH</td>
<td>0.2</td>
</tr>
<tr>
<td>NACA 2410</td>
<td>.332 lb</td>
<td>11 degrees</td>
<td>-0.5 degrees</td>
<td>0.63</td>
<td>7.08 MPH</td>
<td>8.49 MPH</td>
<td>.61 lb</td>
</tr>
<tr>
<td>NACA 0010</td>
<td>.333 lb</td>
<td>13 degrees</td>
<td>0 degrees</td>
<td>0.65</td>
<td>6.93 MPH</td>
<td>8.32 MPH</td>
<td>.64 lb</td>
</tr>
<tr>
<td>NACA 5410</td>
<td>.334 lb</td>
<td>14 degrees</td>
<td>-4 degrees</td>
<td>0.9</td>
<td>5.91 MPH</td>
<td>7.09 MPH</td>
<td>.88 lb</td>
</tr>
</tbody>
</table>

Table XII: Final Textbook-Based Airfoil Analysis [1]
cause the difference found between the values.

The data from the JavaFoil® analysis was used to generate a plot to compare the lifting capability of each airfoil compared to its angle of attack. While this behavior cannot be declared a valid model, especially in consideration of the disparity between models, it can be used as a reference for expected behavior, assuming the error is a scaling error. This is shown in Figure I.

The results of the plot indicate that the Clark Y airfoil would support the most weight and continue to perform at higher angles of attack. The wedge airfoil continues to be the lowest performing airfoil, generating less lift and through a narrower angle of attack range than the flat plate. The overall trend of the results show that the higher the camber present in the airfoil, the more weight the airfoil can lift and the higher the angle of stall. This supports the general theories of airfoil design. This also verifies that the airfoil shapes chosen will provide distinctive enough results during DMS student labs to give the students a clear insight into the effects that airfoil shape have on performance. This provides insight to the team as to whether or not the product can be projected to be an effective tool in teaching the principles of flight and aerodynamics.

IV. STEM OUTREACH EFFORTS

The ultimate goal of the wind tunnel project is to stimulate interest in the STEM fields by allowing students to have access to a hands-on, practical tool to demonstrate the applications of science and engineering principles. Some concepts may seem abstract and difficult to understand, but if presented visually, it becomes easier for some students to comprehend the lesson. This was why a wind tunnel was chosen for the project. The concepts behind lift and flight can seem abstract on paper, but a physical demonstration of how airfoil geometry and other factors affect airfoil performance may allow students to better understand these topics. The hands-on aspect encourages students to participate, especially if students are encouraged to design their own test articles. Allowing students to explore beyond set boundaries encourages them to try new solutions and experiment with designs to try to create the best performing article. Fostering a healthy level of competition encourages students to challenge themselves to perform at their highest potential. This attitude will allow the United States to remain competitive in the STEM fields as the DMS students who choose an education and later careers in STEM enter the work force.

IV.I SECONDARY SCHOOL STUDENT AND TEACHER IMPACT

The overall effectiveness that the presentation and demonstration had in respect to these goals was measured by the administration of a survey before and after the presentation. The questions in both surveys were identical. The survey was designed to gauge the DMS students’ knowledge of the topics discussed in the presentation in order to establish a metric for improvement. Comparing the pre- and post-presentation results will give a measurement of the effectiveness of the presentation.

The presentation focused on four main aspects: wind tunnel history, the four primary forces of flight, the Bernoulli and Newton explanations of lift and misconceptions associated with the former, and airfoil geometry and its effects on lift. These are the same topics covered by the lesson plan that was included by the team with the wind tunnel.

The first questions of the survey were intended to gauge overall interest and estimate the established knowledge base of the class in terms of wind tunnels and aerodynamics. These questions were the primary metric of student learning and increased interest in the STEM fields. The pre-presentation results to these questions are shown in Figure XXII.

The most prominent result from the preliminary survey shows that students are not familiar with the concept of airfoils. Since the included test articles are all airfoils, this shows that there is a great deal of information that the wind tunnel and associated
lessons can teach students, specifically the sections on geometry as it pertains to airfoil performance.

Students show moderately more familiarity with the concept of a wind tunnel, though most of the results indicated that they knew little or an average amount about them. The presentation covers the topics of the origin of wind tunnels and the history of the device, so improvement in this category was expected in the post-presentation survey.

Students also indicated that they only had a small or average knowledge base on the subject of aerodynamics, though the responses were more confident than the responses about the concepts of wind tunnels. Once again these topics are covered in the lesson plan, so improvement is expected.

The focus question of the survey, interest in STEM fields, shows an overall average interest in education in STEM fields. There is a second peak showing a very high level of interest in STEM fields, but this is a lower level response than those indicating only an average interest in STEM. By demonstrating a hands-on demonstration and showing students the kind of projects they can become involved with, the team hoped to increase these number and encourage students who had not yet decided or are trying to decide if they want to pursue an education in STEM to do so.

An identical survey was then administered following the presentation and product demonstration to determine if the presentation and product were effective in the goals set by the design team and WID. The questions were worded identically and in the same order. The results from this secondary survey also serve as an indication in how well the presentation, and the accompanying literature, was written for the grade level. Over-complex explanations or vague examples can leave students more confused than informed, counterproductive to the goals that the team tried to meet. The results to the second survey are shown in Figure.

The primary factor to note is an overall decrease in STEM responses. The number of students that answered “Yes. Extremely so.” decreased from 8 to 7, those that answered “Very much” increased from 3 to 4, the “Some/Average” responses decreased from 12 to 10, the “Very Little” responses increased from 6 to 8, and the “No/Not at All” responses remained at 2.

These results are counter to the expectations of the team. It is hypothesized that the concepts in the presentation were presented in too complex a manner, leaving students confused and thus disinterested in the subject. It is also possible that some students had an ideal of what STEM education entailed and the team’s description of the project and coursework dissuaded them from pursuing the fields. The overall decreases are small, so the wind tunnel project is not entirely ineffective, and poor content design of the presentation cannot be ruled out as a source of the decrease in interest. Having a trained educator present the information may yield improved results.

The other foci of the first four questions, conversely, showed marked improvement in comprehension and understanding of the subjects. The number of students indicating very little to no familiarity with the concepts of a wind tunnel decreased to zero while those indicating an average familiarity increased from 10 to 18, those indicating a better than average familiarity increased from 5 to 9, and the number of students indicating a greater under familiarity with the concepts of wind tunnels
increased from 1 to 4. This gives a clear indication that the presentation and demonstration were able to convey the concepts of wind tunnel operation and basic theory.

Similarly, the number of students indicating at least a basic understanding of airfoils increased. The number of students indicating no understanding decreased to 0 whereas only 3 students indicated they still had “Very little” familiarity with airfoils. The number of students indicating an average level of familiarity increased from 2 to 17, an extremely dramatic increase. The number of students indicating a better than average and greater familiarity with airfoils increased from 2 to 9 and from 0 to 2, respectively. Once again this shows that the presentation and demonstration were able to better familiarize students with an unknown or unfamiliar concept. This is significant when it is taken into consideration that all included test articles are airfoils. A lack of student understanding would make for a disinteresting lab experience, thus discouraging the critical thinking and analysis the student lab manual tries to encourage. It also indicates that students may be able to better design their own test articles to get dynamic performances out of their own test article designs, promoting critical thinking and hands-on experimentation.

Familiarity with aerodynamics is the only category that retained any students indicating no level of familiarity following the presentation with one response of that type, decreased from three. There were four students that maintained that they still had very little familiarity with aerodynamics. This number decreased from nine students. The number of students indicating an average level of familiarity increased from 13 to 14. Six additional students indicated that they had a better than average familiarity with aerodynamics after the presentation and the number indicating that they had a greater familiarity remained constant at three. These results seem to indicate that the presentation did not convey the principles of aerodynamics as effectively as it did the concepts regarding airfoils, but still served as an effective method of instructing students in the basic theories of aerodynamic principles.

The next portion of the survey focused on the students’ retention of information learned during the survey. The questions covered the entire range of topics discussed during the presentation, ranging from the history of wind tunnels to having students use the information taught to make a superficial analysis to choose the airfoil that is expected to generate the most lift from a lineup.

The fifth question of the survey asked students to name the individual(s) credited with inventing the first functional wind tunnel. During the presentation, students were informed that Frank H. Wenhem is credited with inventing the wind tunnel in 1831. The results of the survey are shown in Figure XXIV. The results show that students were clearly able to retain the information and that the presentation was able to convey the information in a comprehensible manner. This is expected as the information is of a non-technical nature and should rely more on students paying attention to the presentation rather than clarity of communication on behalf of the presenter.

The next question was possibly the most conceptually difficult on the survey. Students were asked if airfoils generated lift because the air traveling over the top surface of the wing was forced to traverse a greater distance in a shorter amount of time than the air on the bottom surface, as dictated by the flawed Principle of Equal Transit Times. This principle was explained in the presentation and told

![Who is credited with inventing the first wind tunnel?](image)

Figure XXIV: Wind Tunnel Inventor Survey Results

18
to be flawed, not outright incorrect. The presenter then explained how Newton’s Second Law can be used to explain the phenomenon of lift as the air on the trailing edge of the wing is forced to change direction, inducing an accelerative force on the airfoil. This concept is extremely difficult to convey in simple terms and the potential for student confusion is high. This seems to be reflected in the results, shown in Figure XXV. The students seemed to retain the information from the first explanation, disregarding the admonition that it was a flawed theory. Since the Principle of Equal Transit Times is simpler, it is thus more likely to be remembered or comprehended. If the Newtonian method of lift was not described in comprehensible terms, students may not have listened to the entirety of the section, if not outright dismissing it. A recapitulation of the information on another slide may have better cemented the information, or eliminating the Principle of Equal Transit Times discussion from the presentation entirely may have reduced the confusion that the data seems to indicate, as the number of students indicating that the Principle of Equal Transit Times is true increased from 19 to 22 rather than the expected decrease.

Question 7 of the survey was founded in basic understanding of forces and identifying lift as a force. The question presented the students with four units of measure and asked students to identify the units of lift. The results of this question are shown in Figure XXVI. The initial results show that most students were able to identify lift as a force and identify the units of force, but some identified it as having mass, velocity, or distance units. After the presentation only 1 student marked the incorrect answer, leaving their answer in units of mass. These results support that the portion of the lessons regarding the forces of flight was able to accurately convey information to the students and that the information was understandable to middle school students. This is as expected, since the complexity of the lesson was fairly low.

The next question is taken from the same portion of the presentation and asks students to identify the...
item listed that is not one of the four forces of flight: lift, drag, gravity, and thrust. The results for this question are shown in Figure XXVII. A majority of students answered correctly on the preliminary survey, the most common mistake listed gravity as not being among the four forces. Thrust was the second most common incorrect answer, followed by a single student marking lift as the answer. Following the presentation, only 1 student marked an incorrect answer, indicating that lift was not one of the four primary forces of flight. This lends further support that the section of the lesson plan that instructed students in the primary forces of flight was able to convey the information in a readily understood manner and that students were able to retain the information.

Question 9 moved on to the section of the presentation that dealt with airfoil geometry and flight. The question asked students to determine if a symmetric airfoil (same in shape on both upper and lower surface) would be able to generate lift and fly. The results of this survey question are shown in Figure XXVIII. The number of students who indicated the statement was true was slightly greater than the number of students who indicated that the statement was false. This shows that the DMS students were not familiar with airfoil geometry, specifically symmetry and its relevance to flight performance. After the presentation, there was still a group of students who marked that symmetric airfoils are not capable of flight, though the number who were able to identify the question as false increased from 15 to 19, creating a majority of responses. The issue for the question may lie in the discussion of symmetric airfoils generating lift was inherently bound to the discussion of the Newtonian explanation of lift which has already been determined to be the least effectively conveyed lesson in the demonstration. This may have led to additional student confusion regarding the performance of symmetric airfoils. Separating the concepts or specifically iterating the
statement that symmetric airfoils are capable of generating enough lift for sustained flight may have increased the number of correct answers in the post-presentation survey. The net increase in correct answers shows that the lesson was at least partially successful, but not as successful as other portions of the presentation.

The succeeding question asked students to identify a non-geometrical flight parameter that directly affects airfoil performance, i.e. the angle of attack. Students were asked to identify the name of the angle at which an aircraft flies with respect to the free stream. The results of this survey question are given in Figure XXIX. In the initial survey, a majority of students were not familiar with the terminology for this particular parameter. There was a fairly even distribution amongst 3 of the incorrect answers, all generating greater numbers of responses than the correct answer. After the presentation, a majority of students marked the correct answer with each incorrect answer still receiving at least one response. The answer was left blank on both surveys by 1 student. This may have been a result of the instruction on the survey sheet asking students to leave questions to which they did not know the answer blank. The overall results of the survey question show that students were able to glean the correct information from the presentation and understand the fundamental definition of the angle of attack.

The final question asked students to identify the airfoil that would produce the most lift. These airfoil choices are shown in Figure XXX. The blue arrows indicate the direction of airflow over the airfoil. The results for this question are shown in Figure XXXI. The initial results show that the students recognize the general shape of an airfoil, but do not seem to recognize proper orientation. The logic may have been that the sharp leading edge shown in option D in Figure XXX would cut through the air better and then the flow would smoothly expand over the trailing edge. The correct answer, option C, was the second most common answer with a small number of students choosing options A and B. Following the presentation, only one student did not, in some capacity, mark the correct answer. An invalid answer was recorded on the post-presentation survey when a student marked both options C and D. It is unknown if one was a preferred answer, so the submission was discarded as an invalid response. The results to this question show that the students were able to recognize the most effective airfoil from a selection after instruction in the geometry and overall shape of an airfoil. This may have been due in part to the visual examples of different airfoil types that find applications in different types of aircraft, from large passenger planes to military jets to single engineer civilian aircraft. If so, this would indicate that future
presentations should include takeaway graphics as a method of cementing the desired information in the students observing the presentation. Overall, the presentation was an effective method in teaching students to recognize effective airfoil shapes.

V. CONCLUSION

The efforts of UAH MAE students operating under the support of WID have produced a number of tools for K-12 classrooms dedicated to the support of STEM education and the promotion of STEM fields. During the design of the product, the UAH students learn essential skills such as communication, teamwork, problem solving, and analysis skills that are invaluable in the engineering industry. With the generous support of WID, one such team was able to produce a mobile wind tunnel STEM tool for DMS in Madison Alabama. Detailed analysis of the system has yielded useful results that were invaluable in the design of the most useful product possible before delivery to DMS, the most critical being the determination of the velocity profiles of the test chamber and axial fan. With this information, various parameters such as the volume flow rate of the fan and the change in velocity profile as the test chamber is traversed were calculated, giving valuable insight into the fluid behavior present in the test chamber. This data was then used to identify any areas of stagnation or turbulence that would disrupt the flow and cause harmful interference when DMS students use the wind tunnel to conduct their own experiments.

The results from DMS students on pre- and post-delivery presentation surveys show that the wind tunnel and the lesson material included are effective in instructing students in the principles of wind tunnels and flight, provided the material is simplified sufficiently and delivered in a clear concise manner. Takeaway slides and pictures of concepts seem to better promote retention and comprehension, critical aspects of STEM instruction. The wind tunnel was less effective at encouraging students to pursue STEM education, but multiple factors must be examined before the project can be determined a failure in this regard. Influences such as presenter clarity, presentation complexity, concept complexity, and overall presentation quality should be eliminated as causes of the decrease in interest before the project itself is determined to be the source. As such, when students begin to perform experiments and get true hands-on experience with the tool, interest in the subject may increase.

ACKNOWLEDGMENTS

The authors would like to thank Women in Defense for their staunch support of STEM education and their support of UAH MAE STEM tool projects. In particular, the authors would like to thank Ms. Deborah Fraley for working closely with the design team and providing invaluable support during the entire design process. The authors would also like to thank Ms. Jane Caudle for her input and support during the preliminary design. The authors would further like to thank Mr. Kelly Archer and Ms. Kelle Moody for their assistance during the final delivery and survey administration. Furthermore, the authors extend their gratitude to the students of Discovery Middle School for their participation and cooperativeness in the design process, as well as all administration and faculty who worked to make the process for delivery as smooth as possible.
VI. REFERENCES


Aerodynamic Analysis for Proposed Airfoils

Contents

- Author: Andrew Machemer
- Class: MAE 490-01/491-01
- Date: 4/13/2013
- Constant Variables for All Airfoils
- Flat Plate Analysis-Textbook
- Flat Plate Analysis - JavaFoil Values
- Symmetrical Wedge Analysis
- Wedge Analysis - JavaFoil Values
- NACA 2410 Analysis
- NACA 0010 Analysis
- NACA 0010 Analysis - JavaFoil Values
- Clark Y Analysis
- NACA 5410 Analysis – JavaFoil Values
- Plot of Max Weight vs Angle of Attack

Author: Andrew Machemer

Class: MAE 490-01/491-01

Date: 4/13/2013

Constant Variables for All Airfoils

```matlab
clc
rho = 0.07962; % air density at sea level for free stream flow in lb/ft^3
b=6; % Wingspan in inches
C = 3; % Average chord length in inches
S = (b*C)*.0069; % Planform Area in ft^2
AR = b^2/(S/.0069); % Aspect Ratio adjusted for units
a=1/(AR)/(AR+2)); %.1; % Lift slope for finite wing
SpeedMin = 9.6*1.467; % Lowest speed generated in wind tunnel (ft/s)
stand=0; %weight of test stand (eliminated in final design)
```

Flat Plate Analysis-Textbook

```matlab
W=.045; % Weight of airfoil/aircraft in lbf
a_stall=7; % Stall angle in degrees
a_zero=0; % Angle of zero lift in degrees
```
figure; plot(Plate(:,3),Plate(:,2),'+'),
title('Flat Plate Coefficient of Lift v. Coefficient of Drag (Re=25000)'),
grid on, xlabel('Coefficient of Drag'), ylabel('Coefficient of Lift')
figure; plot(Plate(:,1),Plate(:,2),'+'),
title('Flat Plate Coefficient of Lift v. Angle of Attack (Re=25000)'),
grid on, xlabel('Angle of Attack'), ylabel('Coefficient of Lift')

CLMax_TB_Plate= a*(a_stall-a_zero) \ %Maximum coefficient of lift for airfoil
VStall_TB_Plate = (sqrt((2*W)/(rho*S*CLMax_TB_Plate)))*.6818 \ %Stall velocity
VLiftoff_TB_Plate = (1.2* VStall_TB_Plate) \ %Velocity required to fly(ft/s)
MaxAddWeight_TB_Plate = (((SpeedMin^2)*rho*S*CLMax_TB_Plate)/2)-stand \ %Maximum weight that can be added to airfoil(lbf)

CLMax_TB_Plate = 0.3500

VStall_TB_Plate = 3.4767

VLiftoff_TB_Plate = 4.1721

MaxAddWeight_TB_Plate = 0.3432
Flat Plate Analysis - JavaFoil Values

\[
\text{CLMax \_ JF \_ Plate} = \max(\text{Plate}(:,2)) \quad \%\text{Maximum coefficient of lift for airfoil}
\]

\[
\text{VStall \_ JF \_ Plate} = (\sqrt{(2*W)/(\rho*S*\text{CLMax \_ JF \_ Plate})})*.6818 \quad \%\text{Stall speed}
\]

\[
\text{VLiftoff \_ JF \_ Plate} = (1.2* \text{VStall \_ JF \_ Plate}) \quad \%\text{Velocity required to fly(ft/s)}
\]

\[
\text{MaxAddWeight \_ JF \_ Plate} = (((\text{SpeedMin}^2)*\rho*S*\text{CLMax \_ JF \_ Plate})/2)\text{-stand}
\]

\[
\text{Weight \_ Percent \_ Diff} = \left| \frac{\text{MaxAddWeight \_ JF \_ Plate} - \text{MaxAddWeight \_ TB \_ Plate}}{\left(\frac{\text{MaxAddWeight \_ JF \_ Plate} + \text{MaxAddWeight \_ TB \_ Plate}}{2}\right)} \right| \times 100
\]

\[
\text{CLMax \_ JF \_ Plate} = 0.4180
\]

\[
\text{VStall \_ JF \_ Plate} = 3.1814
\]

\[
\text{VLiftoff \_ JF \_ Plate} = 3.8177
\]

\[
\text{MaxAddWeight \_ JF \_ Plate} = 0.4099
\]

\[
\text{Weight \_ Percent \_ Diff} = 17.7083
\]

Symmetrical Wedge Analysis

\[
W = .297; \quad \%\text{Weight of airfoil/aircraft in lbf}
\]

\[
a\_\text{stall} = 4; \quad \%\text{Stall angle in degrees}
\]

\[
a\_\text{zero} = 0; \quad \%\text{Angle of zero lift in degrees}
\]

\[
\text{figure; plot(Wedge(:,2),Wedge(:,3),'+'),}
\]

\[
\text{title('Wedge Coefficient of Lift v. Coefficient of Drag (Re=25000)'),}
\]

\[
\text{grid on, xlabel('Coefficient of Drag'), ylabel('Coefficient of Lift')}
\]

\[
\text{figure; plot(Wedge(:,1),Wedge(:,2),'+'),}
\]

\[
\text{title('Wedge Coefficient of Lift v. Angle of Attack (Re=25000)'),}
\]

\[
\text{grid on, xlabel('Angle of Attack'), ylabel('Coefficient of Lift')}
\]

\[
\text{CLMax \_ TB \_ Wedge} = a\cdot(a\_\text{stall}-a\_\text{zero}) \quad \%\text{Maximum coefficient of lift for airfoil}
\]

\[
\text{VStall \_ TB \_ Wedge} = (\sqrt{(2*W)/(\rho*S*\text{CLMax \_ TB \_ Wedge})})*.6818 \quad \%\text{Stall velocity}
\]

\[
\text{VLiftoff \_ TB \_ Wedge} = (1.2* \text{VStall \_ TB \_ Wedge}) \quad \%\text{Velocity required to fly(ft/s)}
\]

\[
\text{MaxAddWeight \_ TB \_ Wedge} = (((\text{SpeedMin}^2)*\rho*S*\text{CLMax \_ TB \_ Wedge})/2)\text{-stand}
\]
%Maximum weight that can be added to airfoil (lbf)
CLMax_TB_Wedge =

0.2000

VStall_TB_Wedge =

11.8158

VLiftoff_TB_Wedge =

14.1790

MaxAddWeight_TB_Wedge =

0.1961
Wedge Analysis - JavaFoil Values

CLMax_JF_Wedge = max(Wedge(:,2)) % Maximum coefficient of lift for airfoil

VStall_JF_Wedge = (sqrt((2*W)/(rho*S*CLMax_JF_Wedge)))*.6818 % Stall speed

VLiftoff_JF_Wedge = (1.2* VStall_JF_Wedge) % Velocity required to fly (ft/s)

MaxAddWeight_JF_Wedge = (((SpeedMin^2)*rho*S*CLMax_JF_Wedge)/2)-stand % Maximum weight that can be added to airfoil (lbf)

Weight_Percent_Diff = abs(MaxAddWeight_JF_Wedge-MaxAddWeight_TB_Wedge)/...((MaxAddWeight_JF_Wedge+MaxAddWeight_TB_Wedge)/2)*100

CLMax_JF_Wedge = 0.2510

VStall_JF_Wedge = 10.5473

VLiftoff_JF_Wedge = 12.6568

MaxAddWeight_JF_Wedge =
Weight_Percent.Diff = 22.6164

NACA 2410 Analysis

W=.333; %Weight of airfoil/aircraft in lbf
a_stall=12; %Stall angle in degrees
a_zero=-.5; %Angle of zero lift in degrees

CLMax_TB_2410 = a*(a_stall-a_zero) %Maximum coefficient of lift for airfoil
VStall_TB_2410 = (sqrt((2*W)/(rho*S*CLMax_TB_2410)))*.6818 %Stall velocity
VLiftoff_TB_2410 = (1.2* VStall_TB_2410) %Velocity required to fly(ft/s)
MaxAddWeight_TB_2410 = (((SpeedMin^2)*rho*S*CLMax_TB_2410)/2)-stand %Maximum weight that can be added to airfoil(lbf)

% NACA 2410 Analysis - JavaFoil Values
CLMax_JF_2410 = max(N2410(:,2)) %Maximum coefficient of lift for airfoil
VStall_JF_2410 = (sqrt((2*W)/(rho*S*CLMax_JF_2410)))*.6818 %Stall velocity
VLiftoff_JF_2410 = (1.2* VStall_JF_2410) %Velocity required to fly(ft/s)
MaxAddWeight_JF_2410 = (((SpeedMin^2)*rho*S*CLMax_JF_2410)/2)-stand %Maximum weight that can be added to airfoil(lbf)

Weight_Percent.Diff=abs(MaxAddWeight_JF_2410-MaxAddWeight_TB_2410)/...
((MaxAddWeight_JF_2410+MaxAddWeight_TB_2410)/2)*100

CLMax_TB_2410 = 0.6250
VStall_TB_2410 = 7.0775
VLiftoff_TB_2410 = 8.4930
MaxAddWeight_TB_2410 = 0.6129
CLMax_JF_2410 = 1.0860

VStall_JF_2410 = 5.3692

VLiftoff_JF_2410 = 6.4430

MaxAddWeight_JF_2410 = 1.0650

Weight_Percent_Diff = 53.8866
NACA 0010 Analysis

\( W = 0.332 \); %Weight of airfoil/aircraft in lbf
\( a_{\text{stall}} = 13 \); %Stall angle in degrees
\( a_{\text{zero}} = 0 \); %Angle of zero lift in degrees

figure; plot(N0010(:,2),N0010(:,3),'-+'),
title('NACA 0010 Coefficient of Lift v. Coefficient of Drag (Re=25000)'),
grid on, xlabel('Coefficient of Drag'), ylabel('Coefficient of Lift')

figure; plot(N0010(:,1),N0010(:,2),'-+'),
title('NACA 0010 Coefficient of Lift v. Angle of Attack (Re=25000)'),
grid on, xlabel('Angle of Attack'), ylabel('Coefficient of Lift')

\[ CL_{\text{Max}}_{\text{TB,0010}} = a \cdot (a_{\text{stall}} - a_{\text{zero}}) \] %Maximum coefficient of lift for airfoil
\[ V_{\text{Stall, TB,0010}} = \sqrt{\frac{2 \cdot W}{\rho \cdot S \cdot CL_{\text{Max}}_{\text{TB,0010}}}} \times 0.6818 \] %Stall velocity
\[ V_{\text{Liftoff, TB,0010}} = (1.2 \cdot V_{\text{Stall, TB,0010}}) \] %Velocity required to fly(ft/s)
\[ Max_{\text{AddWeight, TB,0010}} = (1.4 \cdot \text{SpeedMin}^2 \cdot \rho \cdot S \cdot CL_{\text{Max}}_{\text{TB,0010}}) / 2 \] %Maximum weight that can be added to airfoil (lbf)

\[ CL_{\text{Max}}_{\text{TB,0010}} = 0.6500 \]
\[ V_{\text{Stall, TB,0010}} = 6.9297 \]
VLiftoff\_TB\_0010 =
8.3156

MaxAddWeight\_TB\_0010 =
0.6374
NACA 0010 Analysis - JavaFoil Values

\[ CL_{\text{Max, JF_0010}} = \max(N0010(:,2)) \] %Maximum coefficient of lift for airfoil
\[ V_{\text{Stall, JF_0010}} = (\sqrt{\frac{2 \times W}{\rho \times S \times CL_{\text{Max, JF_0010}}}}) \times 0.6818 \] %Stall speed (fps)
\[ V_{\text{Liftoff, JF_0010}} = (1.2 \times V_{\text{Stall, JF_0010}}) \] %Velocity required to fly (ft/s)
\[ \text{MaxAddWeight}_{\text{JF_0010}} = (((\text{SpeedMin}^2) \times \rho \times S \times CL_{\text{Max, JF_0010}})/2) - \text{stand} \]
\[ \text{Weight Percent Diff} = \left| \frac{\text{MaxAddWeight}_{\text{JF_0010}} - \text{MaxAddWeight}_{\text{TB_0010}}}{(\text{MaxAddWeight}_{\text{JF_0010}} + \text{MaxAddWeight}_{\text{TB_0010}})/2} \right| \times 100 \]

\[ CL_{\text{Max, JF_0010}} = 0.8870 \]
\[ V_{\text{Stall, JF_0010}} = 5.9321 \]
\[ V_{\text{Liftoff, JF_0010}} = 7.1185 \]
\[ \text{MaxAddWeight}_{\text{JF_0010}} = 0.8698 \]
Weight_Percent_Diff =

30.8393

Clark Y Analysis

\[ W = 0.334; \text{ Weight of airfoil/aircraft in lbf} \]
\[ \alpha_{\text{stall}} = 14; \text{ %Stall angle in degrees} \]
\[ \alpha_{0} = -4; \text{ %Angle of zero lift in degrees} \]

figure; plot(ClarkY(:,2),ClarkY(:,3),'+'),
title('Clark Y Coefficient of Lift v. Coefficient of Drag (Re=25000)'),
grid on, xlabel('Coefficient of Drag'), ylabel('Coefficient of Lift')
figure; plot(ClarkY(:,1),ClarkY(:,2),'+-'),
title('Clark Y Coefficient of Lift v. Angle of Attack (Re=25000)'),
grid on, xlabel('Angle of Attack'), ylabel('Coefficient of Lift')

CLMax_TB_ClarkY = a*(a_{\text{stall}}-a_{0}) \text{ %Maximum coefficient of lift for airfoil}
VStall_TB_ClarkY = (sqrt((2*W)/(\rho*S*CLMax_TB_ClarkY)))*0.6818 \text{ %Stall velocity}
VLiftoff_TB_ClarkY = (1.2* VStall TB ClarkY) \text{ %Velocity required to fly(ft/s)}
MaxAddWeight_TB_ClarkY = (((SpeedMin^2)*\rho*S*CLMax_TB_ClarkY)/2)-stand \text{ %Maximum weight that can be added to airfoil (lbf)}

CLMax_TB_ClarkY =

0.9000

VStall_TB_ClarkY =

5.9068

VLiftoff_TB_ClarkY =

7.0882

MaxAddWeight_TB_ClarkY =

0.8826
NACA 5410 Analysis - JavaFoil Values

CLMax_JF_ClarkY = max(ClarkY(:,2)) %Maximum coefficient of lift for airfoil
VStall_JF_ClarkY = (sqrt((2*W)/(rho*S*CLMax_JF_ClarkY)))*.6818 %Stall speed (ft/s)
VLiftoff_JF_ClarkY = (1.2* VStall_JF_ClarkY) %Velocity required to fly(ft/s)
MaxAddWeight_JF_ClarkY = (((SpeedMin^2)*rho*S*CLMax_JF_ClarkY)/2)-stand %Maximum weight that can be added to airfoil(lbf)
Weight_Percent.Diff=abs(MaxAddWeight_JF_ClarkY-MaxAddWeight_TB_ClarkY)/...
((MaxAddWeight_JF_ClarkY+MaxAddWeight_TB_ClarkY)/2)*100

CLMax_JF_ClarkY =
1.3080
VStall_JF_ClarkY =
4.8997
VLiftoff_JF_ClarkY =
5.8796
MaxAddWeight_JF_ClarkY =
1.2827
Weight_Percent.Diff =
36.9565

Plot of Max Weight vs Angle of Attack

a=[-15:1:15];
W_ClarkY = (((SpeedMin^2)*rho*S*ClarkY(:,2))/2)-stand;
W_N0010 = (((SpeedMin^2)*rho*S*N0010(:,2))/2)-stand;
W_N2410 = (((SpeedMin^2)*rho*S*N2410(:,2))/2)-stand;
W_Plate = (((SpeedMin^2)*rho*S*Plate(:,2))/2)-stand;
W_Wedge = (((SpeedMin^2)*rho*S*Wedge(:,2))/2)-stand;
plot(a, W_Plate,'g', a,W_Wedge,'b',a,W_N0010,'k',a,W_N2410,'c',...
a,W_ClarkY,'r')
legend('Plate','Wedge','NACA 0010','NACA 2410','Clark Y','Location',...'
'NorthWest')
grid on
title('Maximum Total Weight of Airfoil vs. Angle of Attack')
xlabel('Angle of Attack (degrees)')
ylabel ('Total Weight (lbm)')
Maximum Total Weight of Airfoil vs. Angle of Attack

- Plate
- Wedge
- NACA 0010
- NACA 2410
- Clark Y
Honors Thesis Volumetric Flow Rate Calculation for 24" Drum Fan

Andrew Machemer
University of Alabama in Huntsville
Summer/Fall 2013
In Conjunction with MAE-491 Product Realization
Sponsored by Dr. Christina Carmen

Contents

- Synopsis
- High Speed Setting
- Data Manipulation for High Speed Setting
- Surface Generation for High Speed Setting
- Coefficients for High Speed Setting
- Calculating Volumetric Flow Rate for High Speed Setting
- Data Manipulation for High Speed Setting after Chauvenet's Criterion
- Surface Generation for High Speed Setting
- Coefficients for High Speed Setting
- Calculating Volumetric Flow Rate for High Speed Setting
- Low Speed Setting
- Data Manipulation for Low Speed Setting
- Surface Generation for Low Speed Setting
- Coefficients for Low Speed Setting
- Calculating Volumetric Flow Rate for Low Speed Setting
- Data Manipulation for Low Speed Setting after Chauvenet's Criterion
- Surface Generation for Low Speed Setting
- Coefficients for Low Speed Setting
- Calculating Volumetric Flow Rate for Low Speed Setting
- Fan with Cowling
- High Speed Setting With Cowling
- Data Manipulation for High Speed Setting with Cowling
- Surface Generation for High Speed Setting with Cowling
- Coefficients for High Speed Setting with Cowling
- Calculating Volumetric Flow Rate for Low Speed Setting with Cowling
- Data Manipulation for High Speed Setting with Cowling after Chauvenet's Criterion
- Surface Generation for High Speed Setting with Cowling
- Coefficients for High Speed Setting with Cowling
- Calculating Volumetric Flow Rate for High Speed Setting with Cowling
- Low Speed Setting With Cowling
- Data Manipulation for Low Speed Setting with Cowling after Chauvenet's
- Surface Generation for Low Speed Setting with Cowling
Synopsis

This script calculates the volumetric flow rate in cubic feet per minute by calculating a three-dimensional surface equation fit to experimentally obtained velocity data. It then integrates this function across the circular cross section of the fan that is planned to be used in the final product, namely a small-scale wind tunnel. The process was repeated after applying Chauvenet's Rejection Criterion for each set of values on the same radius, assuming that the fan is designed to be radially symmetrical.

High Speed Setting

Data Manipulation for High Speed Setting

Data is converted into the necessary units.

\[ x_{ft} = \frac{x_{\text{coord}}}{12}; \quad y_{ft} = \frac{y_{\text{coord}}}{12}; \quad \text{velocity}_f_{pm}\_\text{hi} = \text{velocity}_\text{hi} \times 88; \]

Surface Generation for High Speed Setting

sftool is used to fit surface to data. Best fit achieved with a fifth-order polynomial for both x and y.

\[ \text{sfit} = \text{sftool}(x_{ft}(::), y_{ft}(::), \text{velocity}_f_{pm}\_\text{hi}(::)); \]

Coefficients for High Speed Setting

Below are the coefficients of the fifth-order polynomial surface calculated by sftool.

\[
\begin{align*}
p_{00} &= -36.51; \\
p_{10} &= 126.1; \\
p_{01} &= 104.7; \\
p_{20} &= 2743; \\
p_{11} &= -580.2; \\
p_{02} &= 2979; \\
p_{30} &= -526; \\
p_{21} &= 381; \\
p_{12} &= -5.041; \\
p_{03} &= -101.6;
\end{align*}
\]
Calculating Volumetric Flow Rate for High Speed Setting

%Analyzing double integral of function given by sftool converted back into cylindrical coordinates

%Regression eqn
fun_hi = @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

%Regression plot
figure; ezsurf(fun_hi, [-1 1 -1 1])
xlabel('X-position (feet)')
ylabel('Y-position (feet)')
zlabel('Velocity (feet per minute)')
title('Velocity Regression Plot for High Speed Setting')

% Converting back to polar
polarfun = @(theta,r) fun_hi(r.*cos(theta),r.*sin(theta)).*r;

%Performing double integral of velocity profile over surface area
v_flow_hi = quad2d(polarfun,0,2*pi,0,1);

%v_flow is in cubic feet per minute
v_flow_hi

v_flow_hi =
2.9084e+003
Data Manipulation for High Speed Setting after Chauvenet’s Criterion

% Data is converted into the necessary units
x_ft_hc=x_hi_corrected/12; % Converts inches to feet
y_ft_hc=y_hi_corrected/12; % Converts inches to feet
velocity_fpm_hi_corrected = velocity_hi_corrected * 88; % Converts mph to feet/min

Surface Generation for High Speed Setting

sftool is used to fit surface to data. Best fit achieved with a fifth-order polynomial for both x and y

%sftool(x_ft_hc(:,),y_ft_hc(:,),velocity_fpm_hi_corrected(:)); % Activates surface tool

% Tool does not properly display in published document,
% code included for reference

Coefficients for High Speed Setting

% Below are the coefficients of the fifth-order polynomial surface
% calculated by sftool
p00 = -36.34;
p10 = 117.4;
Calculating Volumetric Flow Rate for High Speed Setting

```matlab
%Analyzing double integral of function given by sfctool converted back into cylindrical coordinates

%Regression eqn
fun_hi = @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

%Regression Plot
figure; ezsurf(fun_hi, [-1 1 -1 1])
xlabel('X-position (feet)')
ylabel('Y-position (feet)')
zlabel('Velocity (feet per minute)')
title('Velocity Regression Plot for High Speed Setting After Applying Chauvenets Rejection Criterion')

%Converting back to polar
polarfun = @(theta,r) fun_hi(r.*cos(theta),r.*sin(theta)).*r;

%Performing double integral of velocity profile over surface area
v_flow_hi_corrected = quad2d(polarfun,0,2*pi,0,1);

%v_flow is in cubic feet per minute
v_flow_hi_corrected
```

\[ v_{\text{flow hi corrected}} = 2.9192 \times 10^3 \]
Low Speed Setting

Data Manipulation for Low Speed Setting

% Data is converted into the necessary units
x_ft = x_coord/12; % Converts inches to feet
y_ft = y_coord/12; % Converts inches to feet
velocity_fpm_low = velocity_low * 88; % Converts mph velocity to feet/min

Surface Generation for Low Speed Setting

%sftool is used to fit surface to data. Best fit achieved with a
%fifth-order polynomial for both x and y
%sftool(x_ft(:),y_ft(:),velocity_fpm_low(:)); % Activates surface tool

% Tool does not properly display in published document,
% code included for reference

Coefficients for Low Speed Setting

% Below are the coefficients of the fifth-order polynomial surface
% calculated by sftool
p00 = -63.03;
p10 = 187.5;
p01 = 183.4;
Calculating Volumetric Flow Rate for Low Speed Setting

% Analyzing double integral of function given by sftool converted back into cylindrical coordinates

% Regression eqn
fun_low = @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

% Regression Plot
figure; ezsurf(fun_low, [-1 1 -1 1])
xlabel('X-position (feet)')
ylabel('Y-position (feet)')
ztlabel('Velocity (feet per minute)')
title('Velocity Regression Plot for Low Speed Setting')

% Converting back to polar
polarfun_low = @(theta,r) fun_low(r.*cos(theta),r.*sin(theta)).*r;

% Performing double integral of velocity profile over surface area
v_flow_low = quad2d(polarfun_low,0,2*pi,0,1);

% v_flow is in cubic feet per minute
v_flow_low

v_flow_low =

2.3382e+003
Data Manipulation for Low Speed Setting after Chauvenet’s Criterion

% Data is converted into the necessary units
x_ft_lc = x_low_corrected / 12; % Converts inches to feet
y_ft_lc = y_low_corrected / 12; % Converts inches to feet
velocity_fpm_low_corrected = velocity_low_corrected * 88; % Converts mph to feet/min

Surface Generation for Low Speed Setting

%sftool is used to fit surface to data. Best fit achieved with a fifth-order polynomial for both x and y
%sftool(x_ft_lc(:),y_ft_lc(:),velocity_fpm_low_corrected(:)); % Activates surface tool

% Tool does not properly display in published document, code included for reference

Coefficients for Low Speed Setting

% Below are the coefficients of the fifth-order polynomial surface calculated by sftool
p00 = 6.747;
p10 = 47.48;
p01 = 226.5;
Calculating Volumetric Flow Rate for Low Speed Setting

%Analyzing double integral of function given by sftool converted back into cylindrical coordinates
%Regression eqn
fun_low = @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

%Regression plot
figure; ezsurf(fun_low, [-1 1 -1 1])
xlabel('X-position (feet)')
ylabel('Y-position (feet)')
zlabel('Velocity (feet per minute)')
title('Velocity Regression Plot for Low Speed Setting after Applying Chauvenets Rejection Criterion')

%Converting back to polar
polarfun_low = @(theta,r) fun_low(r.*cos(theta),r.*sin(theta)).*r;

%Performing double integral of velocity profile over surface area
v_flow_low_corrected = quad2d(polarfun_low,0,2*pi,0,1);

%v_flow is in cubic feet per minute
v_flow_low_corrected

v_flow_low_corrected =
2.8177e+003
Fan with Cowling

The following data and calculations reflect the addition of a sheet metal diffuser to the inlet face of the fan.

High Speed Setting With Cowling

Data Manipulation for High Speed Setting with Cowling

% Data is converted into the necessary units; unlike previous, these data were left in polar because an external program found a better fit curve using polar data
x_ft=x_coord/12; % Converts inches to feet
y_ft=y_coord/12; % Converts inches to feet
cowling_fpm_hi = cowling_hi * 88; % Converts mph velocity to feet/min

Surface Generation for High Speed Setting with Cowling

sftool is used to fit surface to data. Best fit achieved with a fifth-order polynomial for both x and y

sftool(x_ft,:),y_ft,:),cowling_fpm_hi,:); % Activates surface tool
% Tool does not properly display in published document,
Coefficients for High Speed Setting with Cowling

Below are the coefficients of the fifth-order polynomial surface calculated by sftool:

- \( p_{00} = 128.7 \)
- \( p_{10} = 89.81 \)
- \( p_{01} = -239.2 \)
- \( p_{20} = -185.8 \)
- \( p_{11} = -440.7 \)
- \( p_{02} = -242.6 \)
- \( p_{30} = -465.3 \)
- \( p_{21} = 993.1 \)
- \( p_{12} = -1408 \)
- \( p_{03} = 816.2 \)
- \( p_{40} = 1137 \)
- \( p_{31} = 319.3 \)
- \( p_{22} = 2031 \)
- \( p_{13} = 375 \)
- \( p_{04} = 1153 \)
- \( p_{50} = 421.5 \)
- \( p_{41} = -803.5 \)
- \( p_{32} = 1408 \)
- \( p_{23} = -1592 \)
- \( p_{14} = 1410 \)
- \( p_{05} = -590.7 \)

Calculating Volumetric Flow Rate for Low Speed Setting with Cowling

Analyzing double integral of function given by sftool converted back into cylindrical coordinates.

Regression eqn; Regression found external to MATLAB:

\[
\text{fun_hi} = @(x,y) p_{00} + p_{10}x + p_{01}y + p_{20}x^2 + p_{11}x\cdot y + p_{02}y^2 + p_{30}x^3 + p_{21}x^2\cdot y + p_{12}x\cdot y^2 + p_{03}y^3 + p_{40}x^4 + p_{31}x^3\cdot y + p_{22}x^2\cdot y^2 + p_{13}x\cdot y^3 + p_{04}y^4 + p_{50}x^5 + p_{41}x^4\cdot y + p_{32}x^3\cdot y^2 + p_{23}x^2\cdot y^3 + p_{14}x\cdot y^4 + p_{05}y^5;
\]

Regression plot:

\[
\text{figure; ezsurf(\text{fun_hi}, [-1 1 -1 1])}
\]

\[
\text{xlabel('X-position (feet)')}
\]

\[
\text{ylabel('Y-position (feet)')}
\]

\[
\text{zlabel('Velocity (feet per minute)')}
\]

\[
\text{title('Velocity Regression Plot for High Speed Setting With Cowling')}
\]

Converting back to polar:

\[
\text{polarfun_hi} = @(\theta,r) \text{fun_hi}(r\cdot\cos(\theta),r\cdot\sin(\theta)).\cdot r;
\]

\[
\text{cowling\_v\_flow\_hi} = \text{quad2d(polarfun_hi,0,2*pi,0,1)};
\]

\[
\text{\%v\_flow is in cubic feet per minute}
\]

\[
\text{cowling\_v\_flow\_hi}
\]

\[
\text{cowling\_v\_flow\_hi} = 39
\]
**Data Manipulation for High Speed Setting with Cowling after Chauvenet's Criterion**

```matlab
% Data is converted into the necessary units
x_ft_hc=x_cowling_hi_corr/12; % Converts inches to feet
y_ft_hc=y_cowling_hi_corr/12; % Converts inches to feet
v_fpm_cowling_hi_corrected = v_cowling_hi_corrected * 88; % Converts mph velocity to feet/min
```

**Surface Generation for High Speed Setting with Cowling**

sftool is used to fit surface to data. Best fit achieved with a fifth-order polynomial for both x and y.

```matlab
@sftool(x_ft_hc(:),y_ft_hc(:),v_fpm_cowling_hi_corrected(:)); % Activates surface tool
```

% Tool does not properly display in published document, % code included for reference

**Coefficients for High Speed Setting with Cowling**
Calculating Volumetric Flow Rate for High Speed Setting with Cowling

%Analyzing double integral of
%function given by sftool converted back into cylindrical coordinates

%Regression eqn
fun_hi = @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + ... + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + ... + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + ... + p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

%Regression Plot
figure; ezsurf(fun_hi, [-1 1 -1 1])
xlabel('X-position (feet)')
ylabel('Y-position (feet)')
zlabel('Velocity (feet per minute)')
title(['Velocity Regression Plot for High Speed Setting'; 'With Cowling after Applying Chauvenets Rejection Criterion'])

%Converting back to polar
polarfun = @(theta,r) fun_hi(r.*cos(theta),r.*sin(theta)).*r;

%Performing double integral of velocity profile over surface area
v_cowling_hi_corrected = quad2d(polarfun,0,2*pi,0,1);

%v_flow is in cubic feet per minute
v_cowling_hi_corrected =
1.2398e+003
Low Speed Setting With Cowling

Data Manipulation for Low Speed Setting with Cowling after Chauvenet's

%Data is converted into the necessary units
x_ft = x_coord/12; %Converts inches to feet
y_ft = y_coord/12; %Converts inches to feet
v_fpm_cowling_low = cowling_low * 88; %Converts mph velocity to feet/min

Surface Generation for Low Speed Setting with Cowling

%sftool is used to fit surface to data. Best fit achieved with a
%fifth-order polynomial for both x and y
%sftool(x_ft,y_ft(:,),v_fpm_cowling_low(:)); %Activates surface tool
%Tool does not properly display in published document,
%code included for reference

Coefficients for Low Speed Setting with Cowling

%Below are the coefficients of the fifth-order polynomial surface
%calculated by sftool
    p00 = 14.78;
    p10 = 65.92;
Calculating Volumetric Flow Rate for Low Speed Setting with Cowling

```matlab
%Analyzing double integral of function given by sftool converted back into cylindrical coordinates

%Regression eqn
fun_low = @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5;

%Regression Plot
figure; ezsurf(fun_low, [-1 1 -1 1])
xlabel('X-position (feet)')
ylabel('Y-position (feet)')
zlabel('Velocity (feet per minute)')
title('Velocity Regression Plot for Low Speed Setting With Cowling')

%Converting back to polar
polarfun_low = @(theta,r) fun_low(r.*cos(theta),r.*sin(theta)).*r;

%Performing double integral of velocity profile over surface area
cowling_v_flow_low_corrected = quad2d(polarfun_low,0,2*pi,0,1);

%c_vol is in cubic feet per minute
cowling_v_flow_low =

484.8315
```
Data Manipulation for Low Speed Setting with Cowling after Chauvenet’s

%Data is converted into the necessary units
x_ft_lc = x_cowling_low_corr/12; %Converts inches to feet
y_ft_lc = y_cowling_low_corr/12; %Converts inches to feet
v_fpm_cowling_hi_corrected = v_cowling_low_corrected * 88; %Converts mph
to feet/min

Surface Generation for Low Speed Setting with Cowling

%sftool is used to fit surface to data. Best fit achieved with a
%fifth-order polynomial for both x and y
%sftool(x_ft_lc,y_ft_lc(:),v_fpm_cowling_hi_corrected(:)); %Activates surface
tool

%Tool does not properly display in published document,
%code included for reference

Coefficients for Low Speed Setting With Cowling

%Below are the coefficients of the fifth-order polynomial surface
%calculated by sftool
p00 = 14.46;
p10 = 61.84;
p01 = 55.63;
Calculating Volumetric Flow Rate for Low Speed Setting with Cowling

```
Calculating Volumetric Flow Rate for Low Speed Setting with Cowling

%Analyzing double integral of
%function given by sftool converted back into cylindrical coordinates

%Regression eqn
fun_low_corr = @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

%Regression Plot
figure; ezsurf(fun_low_corr, [-1 1 -1 1])
xlabel('X-position (feet)')
ylabel('Y-position (feet)')
zlabel('Velocity (feet per minute)')
title({'Velocity Regression Plot for Low Speed Setting'; 'With Cowling after Application of Chauvenets Rejection Criterion'})

%Converting back to polar
polarfun_low = @(theta,r) fun_low_corr(r.*cos(theta),r.*sin(theta)).*r;

%Performing double integral of velocity profile over surface area
cowling_v_flow_low_corrected = quad2d(polarfun_low,0,2*pi,0,1);

%v_flow is in cubic feet per minute
cowling_v_flow_low_corrected

cowling_v_flow_low_corrected = 484.8315
```
Velocity Regression Plot for Low Speed Setting
With Cowling after Application of Chauvenets Rejection Criterion
Honors Thesis Volumetric Flow Rate Calculation for 8" Blower Fan

Andrew Machemer
University of Alabama in Huntsville
Summer/Fall 2013
In Conjunction with MAE-491 Product Realization
Sponsored by Dr. Christina Carmen

Contents

- Synopsis
- Inlet Velocity Profile and Flow Rate
- Data Manipulation
- Fit for Inlet
- Calculation of Flow Rate
- Data Manipulation
- Fit Coefficients for Inlet
- Calculation of Flow Rate
- Calculation of Flow Rate through Planes Located Inside Test Chamber
- Plane 6" from Inlet
- Data Manipulation
- Fit Coefficients for Plane 6" From Inlet
- Calculating Flow Rate
- Plane 12" from Inlet
- Data Manipulation
- Fit Coefficients for Plane 12" From Inlet
- Calculating Flow Rate
- Plane 18" from Inlet
- Data Manipulation
- Fit Coefficients for Plane 18" From Inlet
- Calculating Flow Rate
- Plane 24" from Inlet
- Data Manipulation
- Fit Coefficients for Plane 24" From Inlet
- Calculating Flow Rate
- Plane 30" from Inlet
- Data Manipulation
- Fit Coefficients for Plane 30" From Inlet
- Calculating Flow Rate
- Average Flow Rate
- Combined Plot of Surface Fits
- 3D Vector Field
Synopsis

This script calculates the volumetric flow rate in cubic feet per minute by calculating a three-dimensional surface equation fit to experimentally obtained velocity data. It also calculates velocity profiles in six-inch increments along the length of the test chamber, generates a 3D vector field, and plots the streamlines of the flow assuming one directional flow. It then integrates this function across the rectangular cross section of the fan that is planned to be used in the final product, namely a small-scale wind tunnel.

Inlet Velocity Profile and Flow Rate

Calculate the velocity profile and volume flow rate at the inlet to the test chamber

Data Manipulation

Convert into correct units
clc
inlet_x_ft=inlet_x/12; %Converts inches to ft
inlet_y_ft=inlet_y/12; %Converts inches to ft
v_inlet_fpm=v_inlet*88; %Converts mph to ft/min

Fit for Inlet

Below are the coefficients of the surface calculated by external solver sftool(inlet_x_ft,inlet_y_ft,v_inlet_fpm)
p00 = 1042;
p10 = -661.1;
p01 = 994.4;
p20 = 6163;
p11 = 6397;
p02 = -1.244e+004;
p30 = -2.333e+004;
p21 = -1.222e+004;
p12 = -1.244e+004;
p03 = 4.12e+004;
p40 = 3.389e+004;
p31 = 2.473e+004;
p22 = 82.4;
p13 = 1.68e+004;
p04 = -5.589e+004;
p50 = -1.672e+004;
p41 = -2.271e+004;
p32 = 1.081e+004;
p23 = -8718;
p14 = -5563;
p05 = 2.676e+004;

v_in=@(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 ...
+ p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;
A=-.0191163;
B=12.4353;
center_x = 4.666010959240884;
width_x = 2.4406330010092518;
center_y = -2.2283704577954566;
width_y = 22.761135439331071;

% v_in= @(x,y) A*cosh(pi*(x-center_x)/width_x).*sin(pi*(y-center_y)/width_y)+B;

Calculation of Flow Rate

%Calculates the double integral across the inlet
Q_inlet=quad2d(v_in,0,9/12,0,9/12);
Q_inlet
Q_inlet =
593.7779

Data Manipulation

%Convert into correct units
blower_outlet_x_ft=blower_outlet_x/12; %Converts inches to ft
blower_outlet_y_ft=blower_outlet_y/12; %Converts inches to ft
v_outlet_fpm=v_outlet*88; %Converts mph to ft/min

Fit Coefficients for Inlet

%Below are the coefficients of the surface calculated by external solver
%sftool(blower_outlet_x_ft,blower_outlet_y_ft,v_outlet_fpm)
p00 = -340.5;
p10 = 7.861e+004;
p01 = 907;
p20 = -6.822e+005;
p11 = -3.292e+005;
p02 = 1.949e+005;
p30 = 2.985e+006;
p21 = 1.295e+006;
p12 = 8.544e+005;
p03 = -1.26e+006;
p40 = -6.235e+006;
p31 = -2.936e+006;
p22 = -9.283e+005;
p13 = -1.476e+006;
p04 = 3.091e+006;
p50 = 4.954e+006;
p41 = 2.437e+006;
p32 = 6.164e+005;
Calculation of Flow Rate

% Calculates the double integral across the inlet
Q_outlet = quad2d(v_out, 0, 5.25/12, 0, 5.25/12);
Q_outlet

Q_outlet =

465.4015

Calculation of Flow Rate through Planes Located Inside Test Chamber

This portion of the script calculates the volumetric flow rate at a plane located a specific distance from the inlet

Plane 6" from Inlet

Data Manipulation

inlet_x_ft = inlet_x / 12; % Converts inches to ft, coordinates same as inlet
inlet_y_ft = inlet_y / 12; % Converts inches to ft, coordinates same as inlet
v_6_fpm = v_6 * 88; % Converts mph to ft/min
sftool(inlet_x_ft, inlet_y_ft, v_6_fpm)

Fit Coefficients for Plane 6" From Inlet
p00 = 145;
p10 = 1.06e+004;
p01 = -3610;
p20 = -3.554e+004;
p11 = -1.39e+004;
p02 = 3.139e+004;
p30 = 5.916e+004;
p21 = 4.617e+004;
p12 = -3.673e+004;
p03 = -7.134e+004;
p40 = -5.521e+004;
p31 = -2.15e+004;
p22 = -4.23e+004;
p13 = 1.202e+005;
p04 = 6.202e+004;
p50 = 1.798e+004;
p41 = 1.873e+004;
p32 = -1.731e+004;
p23 = 1.968e+004;
p14 = -7.744e+004;
p05 = -1.933e+004;

%Regression Function
v_6_fit= @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + ... + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + ... + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + ... + p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

Calculating Flow Rate

Q_6=quad2d(v_6_fit,0,9/12,0,9/12);
Q_6
Q_6 =
483.9381

Plane 12" from Inlet

Data Manipulation

inlet_x_ft=inlet_x/12; %Converts inches to ft, coordinates same as inlet
inlet_y_ft=inlet_y/12; %Converts inches to ft, coordinates same as inlet
v_12_fpm=v_12*88; %Converts mph to ft/min
%sftool(inlet_x_ft,inlet_y_ft,v_12_fpm)

Fit Coefficients for Plane 12" From Inlet

p00 = 73.87;
p10 = 8282;
p01 = -2107;
p20 = -2.778e+004;
p11 = -1.34e+004;
\[ p_{02} = 4.174e+004; \]
\[ p_{30} = 4.18e+004; \]
\[ p_{21} = 5.586e+004; \]
\[ p_{21} = -2.859e+004; \]
\[ p_{03} = -1.465e+005; \]
\[ p_{40} = -2.445e+004; \]
\[ p_{31} = -6.833e+004; \]
\[ p_{22} = -4.426e+004; \]
\[ p_{13} = 1.183e+005; \]
\[ p_{04} = 1.893e+005; \]
\[ p_{50} = -2421; \]
\[ p_{41} = 5.436e+004; \]
\[ p_{32} = -2.511e+004; \]
\[ p_{23} = 4.762e+004; \]
\[ p_{14} = -1.01e+005; \]
\[ p_{05} = -8.244e+004; \]

%Regression Function
\[
v_{12\_fit}(x,y) = p_{00} + p_{10}x + p_{01}y + p_{20}x^2 + p_{11}xy + p_{02}y^2 + p_{30}x^3 + p_{21}x^2y + p_{12}xy^2 + p_{03}y^3 + p_{40}x^4 + p_{31}x^3y + p_{22}x^2y^2 + p_{13}xy^3 + p_{04}y^4 + p_{50}x^5 + p_{41}x^4y + p_{32}x^3y^2 + p_{23}x^2y^3 + p_{14}xy^4 + p_{05}y^5;
\]

Calculating Flow Rate

\[
Q_{12} = \text{quad2d}(v_{12\_fit}, 0, 9/12, 0, 9/12);
\]
\[
Q_{12} = 467.8599
\]

Plane 18" from Inlet

Data Manipulation

\[
inlet_x\_ft = inlet_x/12; \quad %\text{Converts inches to ft, coordinates same as inlet}\n\]
\[
inlet_y\_ft = inlet_y/12; \quad %\text{Converts inches to ft, coordinates same as inlet}\n\]
\[
v_{18\_fpm} = v_{18}\_mph \times 88; \quad %\text{Converts mph to ft/min}\n\]
\[
%sftool(inlet_x\_ft, inlet_y\_ft, v_{18\_fpm})
\]

Fit Coefficients for Plane 18" From Inlet

\[
p_{00} = 152.8; \]
\[
p_{10} = 6410; \]
\[
p_{01} = -2701; \]
\[
p_{20} = -2.13e+004; \]
\[
p_{11} = -1.022e+004; \]
\[
p_{02} = 3.863e+004; \]
\[
p_{30} = 5.355e+004; \]
\[
p_{21} = -1.13e+004; \]
\[
p_{12} = 4.092e+004; \]
\[
p_{03} = -1.467e+005; \]
Calculating Flow Rate

Q_18=quad2d(v_18_fit,0,9/12,0,9/12);
Q_18

Q_18 =

445.0970

Plane 24' from Inlet

Data Manipulation

inlet_x_ft=inlet_x/12;  %Converts inches to ft, coordinates same as inlet
inlet_y_ft=inlet_y/12;  %Converts inches to ft, coordinates same as inlet
v_24_fpm=v_24*88;    %Converts mph to ft/min
%sftool(inlet_x_ft,inlet_y_ft,v_24_fpm)

Fit Coefficients for Plane 24' From Inlet

p00 = 1001;
p10 = 3512;
p01 = -1.425e+04;
p20 = -1.121e+04;
p11 = -1560;
p02 = 1.075e+05;
p30 = 3.021e+04;
p21 = -2.314e+04;
p12 = 2.308e+04;
p03 = -3.39e+05;
p40 = -4.685e+04;
p31 = 4.671e+04;
p22 = -1.001e+04;
p13 = -1.849e+04;
p04 = 4.611e+05;
p50 =  2.45e+004;
p41 = -1.672e+004;
p32 = -2.242e+004;
p23 =  2.609e+004;
p14 = -6983;
p05 = -2.249e+005;

%Regression Function
v_24_fit= @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + ...  
+ p30*x.^3 + p21*x.*y.^2 + p12*x.^2.*y + p03*y.^3 + p40*x.^4 + ...  
+ p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + ...  
+ p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

Calculating Flow Rate

Q_24=quad2d(v_24_fit,0,9/12,0,9/12);

Q_24 =

449.9542

Plane 30" from Inlet

Data Manipulation

inlet_x_ft=inlet_x/12; %Converts inches to ft, coordinates same as inlet
inlet_y_ft=inlet_y/12; %Converts inches to ft, coordinates same as inlet
v_30_fpm=v_30*88; %Converts mph to ft/min
%sftool(inlet_x_ft,inlet_y_ft,v_30_fpm)

Fit Coefficients for Plane 30" From Inlet

p00 =  853.3;
p10 =  1096;
p01 = -2.215e+004;
p20 =  2.18e+004;
p11 = -3.775e+004;
p02 =  2.301e+005;
p30 =  -9.2e+004;
p21 =  7.553e+004;
p12 =  2.103e+005;
p03 =  -8.465e+005;
p40 =  1.448e+005;
p31 = -1.038e+005;
p22 = -1.881e+005;
p13 = -2.916e+005;
p04 =  1.264e+006;
p50 = -8.436e+004;
p41 =  5.903e+004;
p32 =  4.174e+004;
p23 =  1.507e+005;
p14 =  1.091e+005;
p05 = -6.624e+005;

%Regression Function
v_30_fit= @(x,y) p00 + p10*x + p01*y + p20*x.^2 + p11*x.*y + p02*y.^2 + p30*x.^3 + p21*x.^2.*y + p12*x.*y.^2 + p03*y.^3 + p40*x.^4 + p31*x.^3.*y + p22*x.^2.*y.^2 + p13*x.*y.^3 + p04*y.^4 + p50*x.^5 + p41*x.^4.*y + p32*x.^3.*y.^2 + p23*x.^2.*y.^3 + p14*x.*y.^4 + p05*y.^5;

Calculating Flow Rate

Q_30=quad2d(v_30_fit,0,9/12,0,9/12);
Q_30

Q_30 = 649.9689

Average Flow Rate

Q_avg=(Q_inlet+Q_outlet+Q_6+Q_12+Q_18+Q_24+Q_30)/7;
Q_avg

Q_avg = 507.9996

Combined Plot of Surface Fits

Surface plots of each velocity plane from inlet to 30 inches into test chamber

set(gca,'XtickLabel',[],'YtickLabel',[]);
[x y]=meshgrid(0:.005:.75,0:.005:.75); %Establish uniform x,y values
s1=mesh(x,y,v_30_fit(x,y)+10000);hold on; %Value added to create offset
s2=mesh(x,y,v_24_fit(x,y)+8000);hold on; %Value added to create offset
s3=mesh(x,y,v_18_fit(x,y)+6000);hold on; %Value added to create offset
s4=mesh(x,y,v_12_fit(x,y)+4000);hold on; %Value added to create offset
s5=mesh(x,y,v_6_fit(x,y)+2000);hold on; %Value added to create offset
s6=mesh(x,y,v_in(x,y));hold on;
set(gca,'XtickLabel',[]);
set(gca,'YtickLabel',[]);
set(gca,'ZtickLabel',[]);
figure;
3D Vector Field

% Generates a 3D vector plot of the velocities measured in the test chamber
% color coding vectors according to magnitude

x = chamber_x;  % Assigning variables
y = chamber_z;  % Note switch between y and z due to naming convention conflict
z = chamber_y;
u = zeros(864,1);
v = v_chamber;
w = zeros(864,1);

% Generate Figure
% quiver3(x(tf), y(tf), z(tf), u(tf), v(tf), w(tf), 'color', [0, 0, 0], 'linewidth', 2);
hold on;
  tf = u < 0;  % Color is different for U<0 and U>=0
  tf = ~tf;
% quiver3(x(tf), y(tf), z(tf), u(tf), v(tf), w(tf), 'color', [0, 0, 0], 'linewidth', .01);
colormap(hot)

% Number of conditions
  cn = 6;  % Number of conditions
  cmap = hot(cn);  % Choose colormap
  tftmpl = false(size(v));  % Create all-false template
for i = 1:cn
tf=tftmpl; %Start with clean tf

if i==1 %Assign color based on value of v
tf(v>1)=true;
elseif i==2
tf(v>=5 & v<10)=true;
elseif i==3
tf(v>=10 & v<15)=true;
elseif i==4
tf(v>=15 & v<20)=true;
elseif i==5
tf(v>=20 & v<25)=true;
elseif i==6
end
quiver3(x(tf),y(tf),z(tf),u(tf),v(tf),w(tf),'color',cmap(i,:)); %Plot field
end

ylabel('Axial Position (Inches)')
xlabel('Horizontal Position (Inches)')
zlabel('Vertical Position (Inches)')
title('Vector Field for Wind Tunnel')

Author’s Note: Orientation of vector field output was adjusted manually to achieve orientation used in Figure
The purpose of this survey is to gauge your knowledge and interest with respect to the various topics the wind tunnel is designed to convey. Answer each question in the column on the right. If you do not know an answer, please leave the answer blank.

Grade: ____ Age: ____ Boy/Girl: ____ African American/American Indian/Asian/Caucasian/Hispanic/other: ____

<table>
<thead>
<tr>
<th>Question</th>
<th>Selection (CIRCLE ONE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are you interested in an education in Science, Technology, Engineering, or Mathematics?</td>
<td>No/Not at all</td>
</tr>
<tr>
<td>Are you familiar with the concept of a wind tunnel?</td>
<td>1</td>
</tr>
<tr>
<td>Are you at all familiar with airfoils?</td>
<td>1</td>
</tr>
<tr>
<td>Are you at all familiar with aerodynamics?</td>
<td>1</td>
</tr>
<tr>
<td>Who is credited with inventing the first wind tunnel?</td>
<td>Frank H. Wenhem</td>
</tr>
<tr>
<td>True or False? Airplanes fly because the air has to travel farther on top of the wing, meaning it moves faster making the pressure lower.</td>
<td>True</td>
</tr>
<tr>
<td>What units is Lift measured in?</td>
<td>Pounds Force/Newton</td>
</tr>
<tr>
<td>Which of these is NOT one of the basic Four Forces of Flight?</td>
<td>Rolling Force</td>
</tr>
<tr>
<td>True or False? An airfoil (airplane wing) that is the same shape on the top as on the bottom will not fly</td>
<td>True</td>
</tr>
<tr>
<td>What is the name of the angle an airplane flies at?</td>
<td>Flight Angle</td>
</tr>
<tr>
<td>Circle the airfoil shape below that will create the most amount of lift (NOTE: the arrows represent the direction of the airflow)</td>
<td></td>
</tr>
</tbody>
</table>
## POST-SURVEY

<table>
<thead>
<tr>
<th>Question</th>
<th>Selection (CIRCLE ONE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are you interested in an education in Science, Technology, Engineering, or Mathematics?</td>
<td>No/Not at all</td>
</tr>
<tr>
<td>Are you familiar with the concept of a wind tunnel?</td>
<td>1</td>
</tr>
<tr>
<td>Are you at all familiar with airfoils?</td>
<td>1</td>
</tr>
<tr>
<td>Are you at all familiar with aerodynamics?</td>
<td>1</td>
</tr>
<tr>
<td>Who is credited with inventing the first wind tunnel?</td>
<td>Frank H. Wenhem</td>
</tr>
<tr>
<td>True or False? Airplanes fly because the air has to travel farther on top of the wing, meaning it moves faster making the pressure lower.</td>
<td>True</td>
</tr>
<tr>
<td>What units is Lift measured in?</td>
<td>Pounds Force/Newton</td>
</tr>
<tr>
<td>Which of these is NOT one of the basic Four Forces of Flight?</td>
<td>Rolling Force</td>
</tr>
<tr>
<td>True or False? An airfoil (airplane wing) that is the same shape on the top as on the bottom will not fly</td>
<td>True</td>
</tr>
<tr>
<td>What is the name of the angle an airplane flies at?</td>
<td>Flight Angle</td>
</tr>
<tr>
<td>Circle the airfoil shape below that will create the most amount of lift (NOTE: the arrows represent the direction of the airflow)</td>
<td><img src="image_url" alt="Airfoil Shapes" /></td>
</tr>
</tbody>
</table>