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Aerodynamic Performance of the NACA 2412 Airfoil at Low Reynolds Number

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Abstract

This paper shows a project by three honors students in an undergraduate engineering program. Students used a 3D printer to fabricate a wing section of the NACA 2412 airfoil. The section has a chord length of 230 mm and a total assembled width of 305 mm. The wing was printed in three separate, hollow sections including a 25mm wide inner section and two 140mm wide outer sections assembled on each side of the inner section. The inner section contained 36 surface holes that were attached by copper tubes and Tygon tubing connected to a multi-manometer. The experiments were compared with CFD simulations using ANSYS Fluent software. Detailed descriptions of the experimental design, fabrication, set-up, learning process and cost are included in the paper together with links to tutorials to repeat the experimental setup as well as a tutorial of the mesh generation and settings for the CFD simulations. Finally, the paper will provide a description of the outcomes for the project, student involvement and response, and an assessment of the student learning procedure.

Introduction

The experimental setup described in this paper is used for hands-on learning experience in labs for the introduction to engineering, fluid mechanics, and experimental methods courses at the university. Students who complete these labs apply conceptual knowledge that they have gained from multiple undergraduate courses. The point of this experiment is to familiarize students with a few basic aerospace concepts and terms such as Reynold's number, coefficient of lift, and coefficient of pressure[1-4]. Furthermore, it teaches students how to read a multi-manometer[5] and perform and compare calculations obtained from experimental data and theoretical/virtual simulations.

This experimental setup was inspired by a published paper by Dr. John Matsson titled, "A Student Project on Airfoil Performance"[6]. In his experiment, data gathered from LabVIEW software is compared to data obtained from CosmosFloWorks. The experiment detailed in this paper, however, contributes the use of the powerful simulation software ANSYS, as well as data obtained from a student designed multi-manometer, which allows students to observe the real-time effects of the experiment. In addition, the airfoil in this experiment was 3D printed in order to provide more precise results and allow for additional measurement points.

The wing used in this experiment is an extrusion of the NACA 2412 airfoil. The wing was 3D printed in three hollow sections and joined together by two aluminum spars that spanned the width of the three sections. The locations for the surface holes were precisely placed in the SOLIDWORKS model and were created during the printing process using an Objet24 printer.

The multi-manometer was designed and constructed by the honors students. The model was conceived in SOLIDWORKS before being fabricated in the university machine shop. It contains thirty-six separate tubes joined together on a board. The board is hinged to a base and is capable of resting at 30, 35, 40, 45, and 50 degrees above the horizontal base. Polycarbonate tubing is used for the straight section of each of the individual manometers. Tygon tubing connects the top ends of the polycarbonate tubing to the surface holes along the wing. Tygon tubing is also used to connect the bottom ends of the polycarbonate tubes to a colored-water filled container. (A detailed explanation of the design and fabrication of the multi-manometer can be found in the appendix.)

ANSYS software was used for virtual testing of the aerodynamics of the NACA 2412 airfoil. Using the Fluid Flow (Fluent) solver[7], the coordinates of the NACA 2412 airfoil were rotated against the wind velocity vector to simulate varying angles of attack. Then, the theoretical coefficients of drag and lift were calculated at varying levels of mesh quality to compare with the experimental results.

The NACA 2412 airfoil is part of the NACA 4 digit series of airfoil classification[8]. The four digits are determined by the characteristics of the airfoil in the following way:

1. The first digit describes the maximum camber as a percent of the chord.
2. The second digit describes the location of that maximum camber measured from the leading edge in percent of the chord.
3. The final two digits describe the maximum thickness of the airfoil in percent of the chord.

With all percentages given in respect to the length of the chord, the classification of the NACA 2412 determines that the airfoil has a maximum camber of 2% located at 40% from the leading edge, with a maximum thickness of 12%.

The professor desired to experiment with the learning process of the honors students. He provided them with a project and allowed them to learn about the different subjects involved while they worked to complete this project rather than teaching all of the information to them before they attempted the project. He offered instruction throughout the process, but also allowed some learning through failure. The students learned new aspects of SOLIDWORKS, ANSYS, and manufacturing by practical experience during this project.

Theory

The pressure distribution over the surface of the airfoil is described by the dimensionless parameter known as the coefficient of pressure

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho_\infty V_\infty^2} = \frac{p - p_\infty}{p_0 - p_\infty} = 1 - \left(\frac{V}{V_\infty}\right)^2 \qquad (1)$$

where the velocity ratio is defined by,

$$\frac{V}{V_\infty} = \sqrt{\frac{p_0 - p}{p_0 - p_\infty}} \tag{2}$$

where V_∞ is the freestream fluid velocity, p_0 is the stagnation pressure[9] that is assumed to be constant through the whole flow-field, p_∞ is the freestream static pressure, ρ_∞ is the density of air, p is the pressure at a specific point along the surface of the airfoil, and V is the fluid velocity at the same point.

The freestream fluid velocity is determined from Bernoulli's equation,

$$p_0 = p_\infty + \frac{1}{2}\rho_\infty V_\infty^2 \tag{3}$$

$$V_\infty = \sqrt{\frac{2(p_0 - p_\infty)}{\rho_\infty}} \tag{4}$$

The pressure difference $p_0 - p_\infty$ is determined by,

$$p_0 - p_\infty = \rho_w g \Delta h_v \tag{5}$$

$$\Delta h_v = \Delta h_{measured} sin(\alpha) \tag{6}$$

where ρ_w is the density of water, g is the gravitational acceleration constant, Δh_v is the vertical height difference, $\Delta h_{measured}$ is the measured change in height of the water in the multi-manometer, and α is the angle the multi-manometer makes with the horizontal base.

The density of air ρ_∞ is found using the ideal gas law,

$$\rho_\infty = \frac{p_{atm}}{RT} \tag{7}$$

where p_{atm} is the atmospheric pressure measured in Pascals, T is the temperature measured in Kelvin, and R is the universal gas constant, measured in J/kg*K. For dry air,

$$R = 287.058 \ \frac{J}{kg*K} \tag{8}$$

Assuming negligible friction, a thin airfoil, and a small angle of attack, a relationship between the coefficient of lift C_L and coefficient of pressure C_p can be derived,

$$C_L = \frac{1}{c}\int_0^c \left(C_{p,L} - C_{p,U}\right)dx \tag{9}$$

where c is the length of the chord, and $C_{p,L}$ and $C_{p,U}$ are the pressure coefficients on the lower and upper surfaces of the airfoil respectively. The coefficient of lift is the area enclosed by the difference in coefficients of pressure.

We define the Reynolds number based on the free stream velocity and the chord length

$$Re = \frac{V_\infty c \rho_\infty}{\mu} \tag{10}$$

where μ is the dynamic viscosity of the air.

Design

The NACA 2412 airfoil was designed and printed as three separate parts. The central part is mostly hollow, containing two slots which a metal bar acting as a spar runs through to connect the three parts. On the surface of the central part, there are 36 small holes that are distributed strategically across the top and bottom of the airfoil. On either side of the central part are two larger outer parts that complete the wing. These sections act chiefly as support, but still maintain the contour of the NACA 2412. Both outer parts are mostly hollow, with only two slots for the spars to connect the entire model. These outer parts contain a larger hole so the Tygon tubing can exit the wing. Hollow metal bars also extrude from the large holes so the wing may be suspended in the wind tunnel. After a 3D printer fabricated the wing, thirty-six copper tubes with the same outer diameter as the surface holes were inserted into the surface holes in the central part. Tygon tubing was then connected to the copper tubes and numbered with respect to the holes' locations. All three parts of the wing were assembled with the Tygon tubes fitting through the aforementioned metal bars (Figure 1), and then the wing was suspended in the wind tunnel.

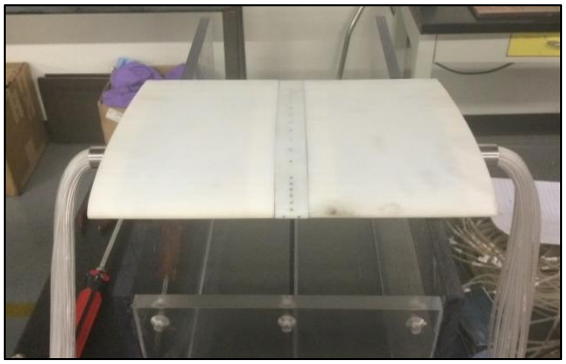

Figure 1: Assembled airfoil with tubing

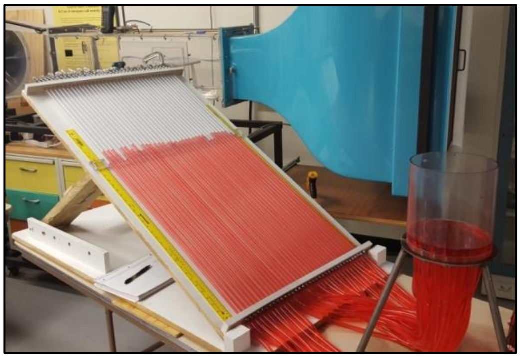

Figure 2: Multi-Manometer

A multi-manometer was used to measure the pressure distribution of the airfoil. The Tygon tubes were connected to larger Tygon tubes using vacuum connectors. The larger Tygon tubes then connected to the multi-manometer, which was built from scratch by the students in their university's machine shop. The multi-manometer is composed of tubes filled with colored water that lie against a straight, white backboard. As the airflow around the airfoil produces varying pressure according to the holes' positions, the height of the water varies accordingly (Figure 2). After measuring the heights of the fluid in each of the tubes, the airfoil's pressure distribution may be computed.

ANSYS Calculations

Using several tutorials and the professor’s instruction, one of the students conducted analysis of the NACA 2412’s aerodynamics on ANSYS’s Fluid Flow (Fluent) solver. Rather than rotating the wind velocity’s angle of attack, a formula was derived to rotate the base coordinates of the NACA 2412 by a certain angle Θ. This method ensured the most consistent mesh across all angles that were tested. After importing the airfoil’s rotated coordinates, a mesh was generated that would strategically measure the aerodynamics of the airfoil at key regions. Across all angle measurements, three mesh qualities— course, refined, and fine— were tested to determine which degree of mesh quality produced the most accurate result. After generating the mesh, Fluent simulations with a constant wind velocity $V_\infty = 30$ m/s were run until convergence or 150000 iterations. The numerical coefficients of lift and drag were recorded alongside images of the velocity vectors (Figure 3) and pressure contours (Figure 4). The wind velocity produced the low Reynold’s Number of $Re = 426{,}248$ for all three mesh qualities across ten angles of attack between 0 to 16 degrees, resulting in thirty full simulations.

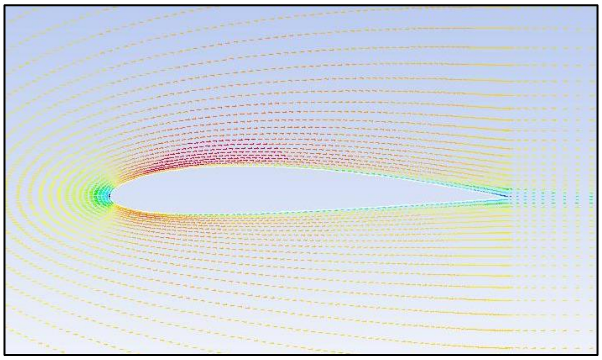

Figure 3: Velocity Vectors ($\Theta = 0°$)

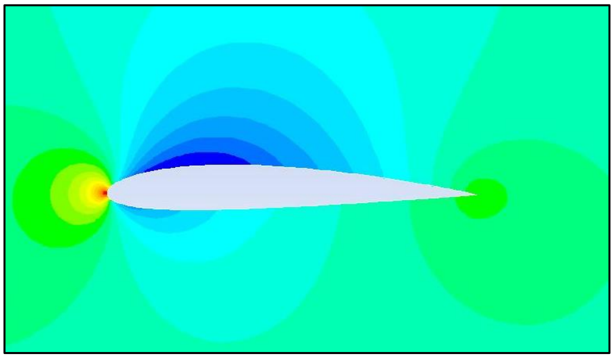

Figure 4: Pressure Contours ($\Theta = 0°$)

In addition, the angle of attack $\Theta = 10°$ was specifically tested across 5 levels of increasing mesh quality. The summary of the tests is displayed in Figure 5 below. This graph’s X values of 1, 2, and 3 correspond to the coarse, refined, and fine mesh qualities, respectively, which all simulations were run with. Only the 10° angle of attack was tested at the mesh qualities 4 and 5, deemed ultra-fine extremely fine, to investigate how ANSYS’s results vary as mesh quality increases.

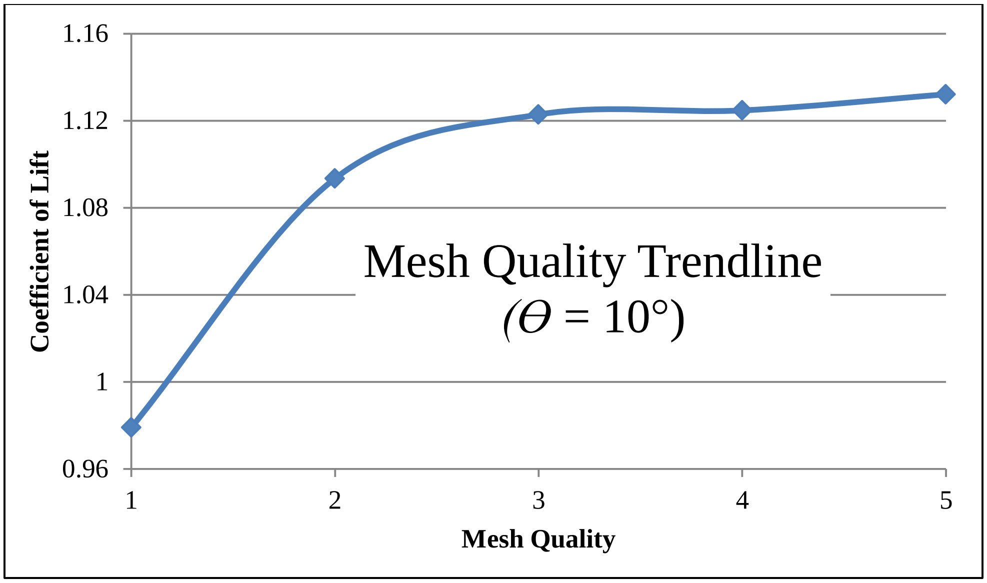

Figure 5: Coefficient of Lift vs. Mesh Quality

Seen in Figure 5, as the mesh quality is increased, ANSYS's calculated coefficient of lift appears to converge. The same is true with the coefficient of drag and the C_L/C_d ratio. In effect, these tests assure that the "fine" quality of mesh, labeled 3 on the x-axis, is of reasonable accuracy to ANSYS's value of convergence and can be trusted as a valid CFD result. ANSYS simulations with the course mesh predict that the airfoil will stall at around 12 degrees, which is indicated by a sudden drop in lift coefficient; however, results from the refined and fine mesh predict a stall angle around 14 degrees. The students were very interested in this slight discrepency, and viewed their experimental data as an important reference to investigate which quality of mesh is the most acurate. Before testing began, based on the trends of ANSYS's results, the honors students predicted the NACA 2412's experimental stall angle to be around 15 degrees.

Experimental Results and Comparison of Data

For the experiment, the airfoil was secured at specified angles of attack[10] in the wind tunnel and exposed to wind traveling at a velocity of 30 m/s, corresponding to Re = 426,248. The airflow created various drops in pressure along the surface of the airfoil, which raised the height of the water in the multi-manometer. The students then measured the change in height for each manometer for experiments conducted at 0, 2, 4, 5, 6, 8, 10, 12 (Figure 6), 14, and 16 degree angles of attack. Each angle was tested multiple times and the data was averaged to provide more precise results.

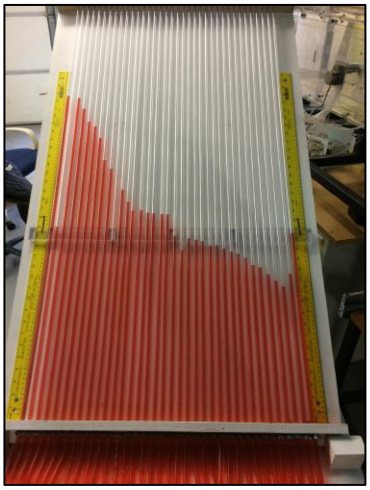

Figure 6: $\Theta = 12°$

The change in height of each tube was applied to the equations put forth in the theory section yielding coefficients of pressure, $(p - p_\infty)/(p_0 - p_\infty)$, which were used to calculate the coefficient of lift. The coefficient of pressure for each tube was plotted against the tubes' respective positions on the airfoil, determined by percent of chord length (Figure 7). For the purpose of clarity and understanding, the Y-axis of this graph is inverted to place the upper section of the wing on top with the lower section of the wing beneath it. There were two outlying data points assumedly due to some of the connections inside the airfoil being clogged, so those data points were replaced with the average of the surrounding holes' values to provide more accurate results. Using Excel, curves of best fit were generated based from the experimental results of 0, 5, and 10 degrees angles of attack (Figure 7).

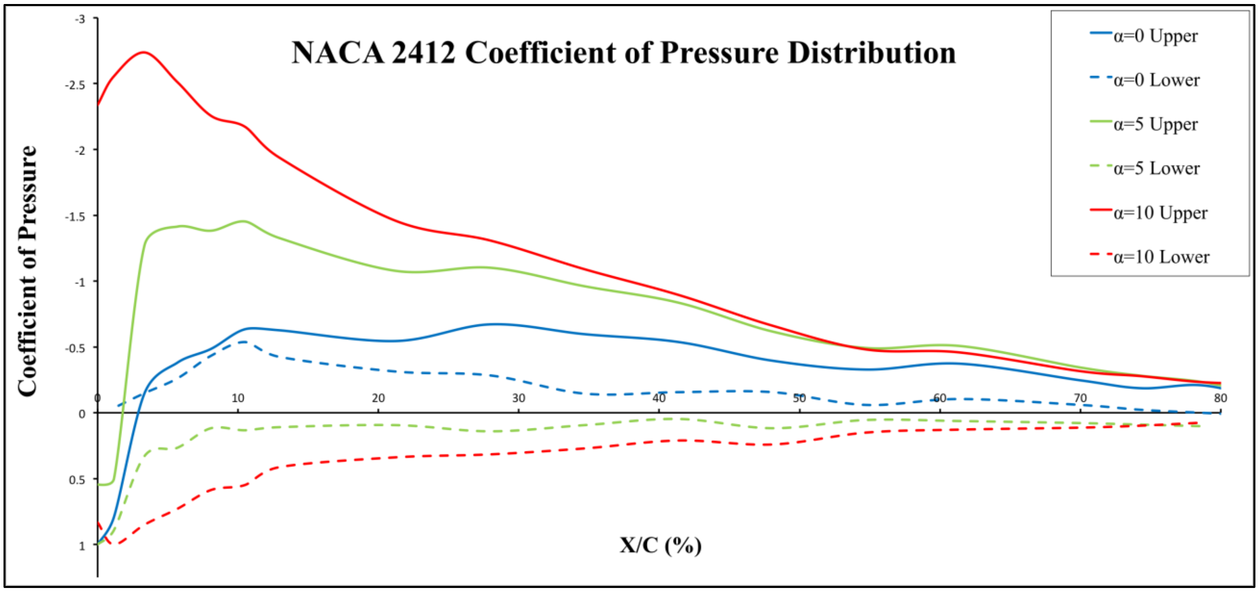

Figure 7: Coefficient of Pressure vs. Percent Chord Length

In accordance with Bernoulli's principle, as the airflow velocity increases along the surface of the wing, the pressure along the surface of the wing decreases. Similarly, an increase in the angle of attack will increase the separation between the airfoil's upper and lower sections' coefficient of pressure (Figure 7). In the same way that an airplane wing gets more lift as it increases its angle of attack, the NACA 2412 airfoil receives drastically more pressure loss as the angle of attack increases, producing a strong lifting force. Furthermore, the curves appear to resemble each other, validating the precision of this experiment's methods.

Based on the equations of the theory section, the students were able to use MATLAB to find the coefficient of lift for each angle of attack measured. They then compared the coefficients of lift found by the experiment to those produced by the ANSYS simulations (Figure 8). The students were pleased to find the results had reasonably low percent differences with a few exceptions (Table 1). Most percent differences may be explained by imperfections in the transfer method of pressure from the airfoil to the manometer, wind speed fluctuations, or slight changes in the angle of attack as the air speed increased. During the 16 degree experiment, the water in the manometer fluctuated even though the airfoil was held firmly in place. Since the pressure distribution of an airfoil past its stall angle of attack will vary with time, the students experimentally concluded that the NACA 2412's stall angle lies between 14 and 16 degrees, which agrees with their original prediction. An approximate multi-manometer height was taken at 16 degrees, probably explaining the large percent difference.

Angle of Attack (degrees)	C_L (Simulated)	C_L (Experimental)	C_L % Difference
0	0.20426017	0.20514	0.43175
2	0.41614148	0.43085	3.47405
4	0.6251167	0.75574	18.9193
5	0.72640153	0.78731	8.04742
6	0.82478389	0.83953	1.77233
8	1.0059511	0.97253	3.37852
10	1.1580771	1.15722	0.07364
12	1.2533316	1.20161	4.21349
14	1.2556093	1.29075	2.75996
16	0.88459214	1.19112	29.5348

Table 1: Comparison between Simulations and Experiments

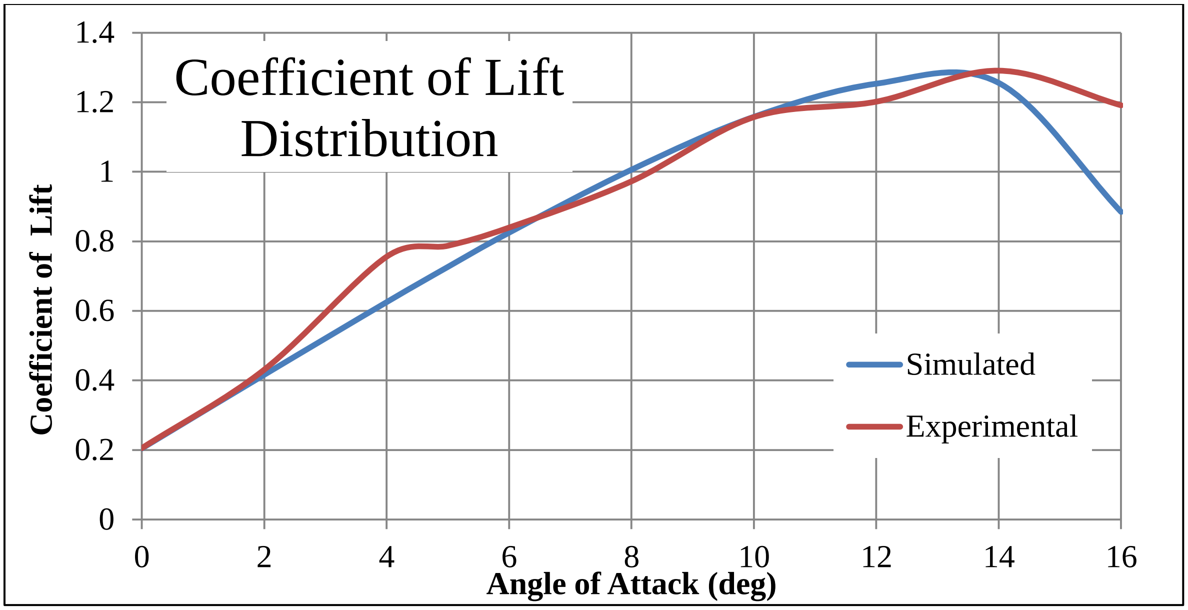

Figure 8: Coefficient of Lift vs. Angle of Attack

Assessment

The honors students acquired new knowledge and skills by creating equipment and testing procedures to provide learning opportunities for future engineering students. Instead of learning information from separate classes where practical applications are often rare, the students were given a hands-on project that required knowledge previously unknown to them. With their professor's instructions and examples, the students gradually and effectively developed the necessary knowledge for implementing their research. This new knowledge includes deeper understanding of SOLIDWORKS, ANSYS, MATLAB, and machining techniques, giving the students real-world skills that will be used in their future engineering endeavors.

A particular example of the dynamic learning environment created by this project may be seen in the expansion of the students' knowledge of SOLIDWORKS. The honors students had already learned the basics of the CAD program through a required course, but they did not have all of the knowledge they needed to design the airfoil and the multi-manometer. The nature of creating these two models produced several difficulties that the university's course did not cover. For example, the students searched for several days for a method to input the exact coordinates of the holes along the airfoil's surface. Through trial and error tests, along with the guidance of the professor, the team was able to find a solution that provided the desired result in the SOLIDWORKS model. This gradual and experimental form of learning vastly expanded the students' knowledge of SOLIDWORKS, giving them confidence to complete the rest of the challenges in the project's design process. Additionally, the knowledge gained from the experimental nature of this learning process was more effectively retained than in a common classroom setting.

The manufacturing process of the airfoil and multi-manometer also proved to be a great educational tool to teach various machining techniques. Even with some previous experience in the machine shop, the honors students were highly unqualified for the machining required by this project. By partnering with the professor and machine shop technician, the team of students was able to successfully replicate their SOLIDWORKS designs. The painstaking processes of inserting 36 copper tubes into the airfoil's holes, experimentally finding the optimal position for multi-manometer's base's holes, and determining how to guide pressure flow from the airfoil to the multi-manometer taught students valuable lessons about manufacturing and machining. Many times the honors students realized their initial machining attempts needed revisions because the process could be accomplished more efficiently and accurately through a different method. At the beginning of the project, the students needed almost constant supervision and assistance, but by the completion of their research, the students were almost entirely self-sufficient in the machine shop. The manufacturing process provided the students with a hands-on experience and knowledge about their specific project and general machining procedures that are difficult to impart in a typical classroom setting. After completing the fabrication and testing of the airfoil and multi-manometer, the students viewed their results as verification of CFD software. Designing, building, and testing an airfoil via multi-manometer is a valuable learning experience but is also an expensive and long process. For future engineering endeavors, the honors students will have the experience to confidently use CFD software as an effective alternative to real-world testing. The completion of this project allowed the students to receive practical experience that they will bring into their future careers.

In addition to the individual learning of the honors students, the multi-manometer and 3D printed airfoil will be used in future labs at the university in at least two classes. In the first course, Introduction to Engineering, students will gain a basic understanding of aerodynamics through airfoil and multi-manometer demonstrations. The airfoil's visual example will be coupled with data recorded from the multi-manometer so that the wing's pressure distribution may be calculated. A main goal for this lab is to improve the retention rate for freshmen engineering students by exhibiting an interesting and interactive experiment.

A second course, Fluid Mechanics, has already implemented the experiment outlined in this paper into the curriculum in order to further the students' understanding of the coefficient of lift at varying angles of attack. After solving for the coefficient of lift using the multi-manometer, they construct an ANSYS simulation in order to provide a digital comparison to the experimental data. The honors students created an ANSYS tutorial, available by following the appendix's link, which instructs how to simulate airflow to find the lift coefficients for different Reynold's numbers and angles of attack. In order to improve the lab, current students in the Fluid Mechanics class were asked about their experience with the experiment and if it was able to help them better understand the subject matter. Almost all of the students mentioned that it was helpful to see the real time effects of the pressure difference across a wing. One student mentioned, "It was good to see the practical proof of a lab we've done in SOLIDWORKS multiple times.” Other students said it helped them better understand the theory behind the coefficient of lift and how it relates to angle of attack. A greater understanding of the importance of pressure difference over the top and bottom of the airfoil was also mentioned. Furthermore, the experiment gave all the students a better understanding of how to operate both a wind tunnel and a multi-manometer. Many students stressed that the visual aspect of the multi-manometer was aesthetically pleasing and gave them a greater interest in the subject matter. Overall, the students were grateful for the opportunity to gain hands-on experience and compare real-world data to their computer-simulated data. As a result of this project, many university students will benefit from new, exciting laboratory experiences.

Conclusion

This paper has shown a research project where the students designed, manufactured, and tested an airfoil section and a multi-manometer, calculating the coefficient of lift across the surface of the NACA 2412 at varying angles of attack. The students’ experimental methods were effective, indicated by the coefficient of lift closely resembling the simulated results predicted by ANSYS.

Because an undergraduate degree in engineering requires a daunting amount of materiel to be learned, students often struggle to obtain practical experience. This project successfully partnered typical classroom learning with real-world applications. Through instruction from the professor and the students’ studies, an extremely effective learning atmosphere was demonstrated.

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10. M-D Building Projects 60cm Digital Level (http://www.mdteam.com/index.php/products/smarttool)

Appendix

Link to public drobox (all blind copy tutorial pdf's):
https://www.dropbox.com/sh/zjofb67qokgjciw/AADcrGb8fyY4CLV8jNDVxMNKa?dl=0

The total cost of the project is $1611.14, excluding the cost of the wind tunnel and computer. A table of costs may be seen on the following page:

Manufacturer	**Item Description**	**Item Number**	**Quantity**	**Unit Price**	**Total**
Professional Plastics Co.	Tygon E3603 Tube 0.250" ID X .375" OD X 50 FT	N/A	1	99.84	99.84
	Tygon E3603 Tube 0.062" ID X .125" OD X 50 FT	N/A	1	49	49
	Tygon E3603 Tube 0.125" ID X .250" OD X 50 FT	N/A	1	58.04	58.04
	Tygon E3603 Tube 0.375" ID X .500" OD X 50 FT	N/A	2	61.11	122.22
Stratasys	3-D Printing Material	N/A	N/A	N/A	545
Tulsa Plastics Co.	Polycarbonate Tubing 0.250” ID X 0.375” OD X 96”	N/A	20	8.398	167.96
	LABOR - Cutting above pipes in half	N/A	N/A	N/A	10
MSC Industrial Supply Co.	Polycarbonate Tubing 5.75" ID 6.00" OD X 12"	63406557	1	31.89	31.89
AutoZone	Hard T Vacuum Tubing Connector 1/8" x 1/8" x1/8" OD	493-052	4	18.99	75.96
	Assorted Vacuum Connectors (2 X 1/8" - 3/16", 2 X 1/4" - 3/16" per pkg)	47308	18	3.99	71.82
	3/8” x 1/4" dia. Hard vacuum tubing connector (10 per pkg)	493-044	4	19.99	79.96
Zoro	Wire Marker Tape w/Dispenser, label width .215", Numbers 0-9	G3472226	1	36.93	36.93
Fishersci	Tygon Tubing 1/16" X 1/8" 50' - 15m/pkg	14-171-129	3	20	60
Home Depot	Plywood Board - 30" X 55" X 1"	N/A	1	~ 20	20
	Plywood Board - 28" X 48" X 1"	N/A	1	~ 20	20
	Wood Beam- 28" X 1.5" X 1"	N/A	2	~ 4	8
	Wood Beam - 25" X 5.5" X 1.5"	N/A	2	~ 7	14
	Wood Beam- 20" X 4" X 1"	N/A	1	~ 5	5
	Wood Beam - 22" X 3" X 0.5"	N/A	2	~ 5	10
	Wood Block - 2.5" X 2" X 1.5"	N/A	2	~ 1	2
	Aluminum Rod - 0.5" Diameter X 32" length	N/A	1	~ 10	10
	Aluminum Hinge Bracket	N/A	4	~ .5	2
	Copper Tubing - 3/8" OD 5/16" ID X 40"	N/A	1	~ 10	10
	Everbilt 3/8” - 7/8” Hose Repair Clamp	N/A	108	$0.94	101.52

Grand Total: $1611.1