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Rocket Fin Test Fixture Development & Exploration of Rotation Inducing Fin Design

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Rocket Fin Test Fixture Development & Exploration of Rotation Inducing Fin Design

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Honors Faculty Advisor (printed)

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Dean, Honors College

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Abstract

The purpose of this senior project was to develop a method of applying rotation inducing rocket fin concepts to rockets for the benefit of the University of Akron Akronauts; the student led rocket design team. The project was performed independently of the team's current efforts as a research and development endeavor for future team projects. Main project goals were divided into three parts: design a fin test fixture for verification testing in the University's wind tunnel, develop a parameter-driven software model that could be used to generate design options with theoretical performance data as an output, and run fluid dynamics analyses to offer additional support to findings. At a higher level, this project was chosen as an opportunity to exercise a few of the many different facets of the engineering process. Over the course of the project, our team received valuable experience with: idea generation and brainstorming, concept vetting, technical software programming, process troubleshooting, rapid prototyping, and aerodynamic-related testing.

Introduction & Background

In the design of rockets, the most important design criterion is stability in flight. Without stability, the only thing that is accomplished by launching a rocket is creating a high speed, unpredictable projectile. Flight stability can be accomplished in two ways; either by creating a center of pressure that is behind the center of gravity, or by adding a spin perpendicular to the direction of flight. Where it is not possible or ideal to force the center of pressure behind the center of gravity an overturning torque develops. The further the center of gravity is in front of the center of pressure, the more stability the rocket has; conversely the further the center of pressure is in front of the center of gravity, the more inherently unstable the rocket.

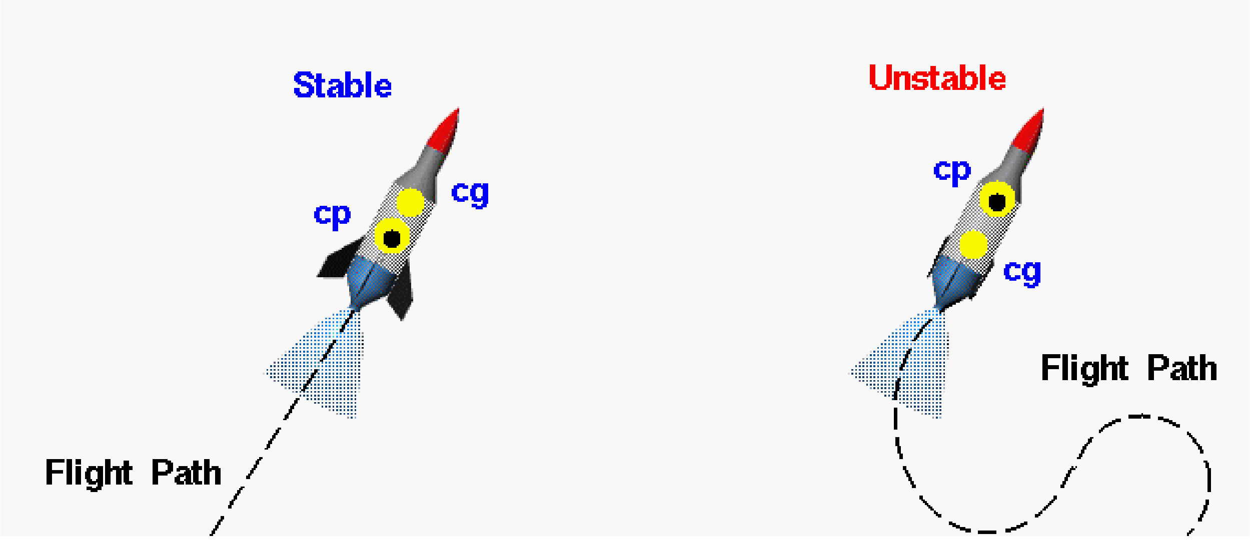


Figure 1: Infographic of stable and unstable centers of pressure and gravity designs [1].

The center of gravity can be calculated by the following equation:

$$C_G = \frac{\int X \cdot m(x) \cdot dx}{\int m(x) \cdot dx} \qquad (1)$$

Where “m” is the mass of each component and “X” is the distance from either end of the rocket that the mass of that component acts on.

The center of pressure can be calculated in a similar manner, with the area terms replaced with mass terms; such that:

$$C_p = \frac{\int \quad X \cdot p(x) \cdot dx}{\int \quad p(x) \cdot dx} \qquad (2)$$

It is important to note that bodies move about their center of gravity, and aerodynamic forces act about centers of pressure.

Where it is not practical or otherwise possible to set the center of gravity behind the center of pressure, spin must be introduced to create a dynamic stability.

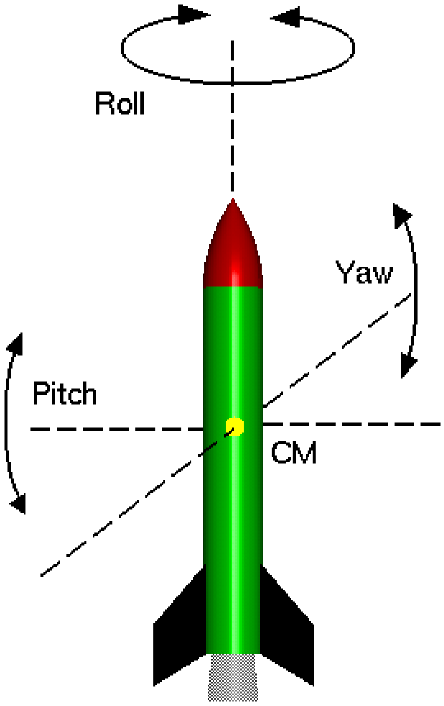


Figure 2: Infographic of rocket axes of motion [1].

As the rocket spins on its principle axis, it has angular momentum about that axis. The principle axis of a rocket is indicated in Figure 2 as the axis about which the roll movement is indicated (note how each axis of rotation passes through the center of gravity). This angular momentum about the principle axis creates a restoring force along the body of the rocket, keeping it on its planned trajectory even when outside forces such as winds buffet the sides of the rocket. This acts in a manner similar to how a gyroscope can remain upright while spinning even when outside forces attempt to tip it over. In both cases the spinning body is able to remain on trajectory (in the case of the rocket), or upright (in the case of the gyroscope) can be explained by Newton's Second Law. Newton's Second Law gives the right-hand rule, which states that if the axis of rotation is held in one's right hand and the fingers are rotated in the same direction as the rotation, then the thumb will point in the direction of the angular velocity. This angular velocity is the restoring force that helps to mitigate outside forces.

The entire purpose of fins on a rocket is to provide stability during flight, to keep the rocket on the intended course through inducing rotation. This rotation is induced by the lifting forces generated by each fin.

The common misconception of how wings or fins generate lift is that the contours of the wing or fin have a "longer" top surface than the bottom surface. This difference in length forces the air moving over the top surface to move faster in order to meet back up with the same particles that went along the bottom of the wing, this faster air leads to a lower pressure, thus create pressure differentials between the top and bottom surfaces. This pressure differential over the surface area of the wing generates the lifting force.

There are many flaws associated with this theory, such as how would an airplane fly upside down, or how did the Wright brothers' plane generate lift when its wings were almost flat (and the plane traveled at a relatively slow speed)? Furthermore, Figures 3a and 3b from the University of Cambridge show that the air from the top of the wing does not meet back up with the air from the bottom of the airfoil.

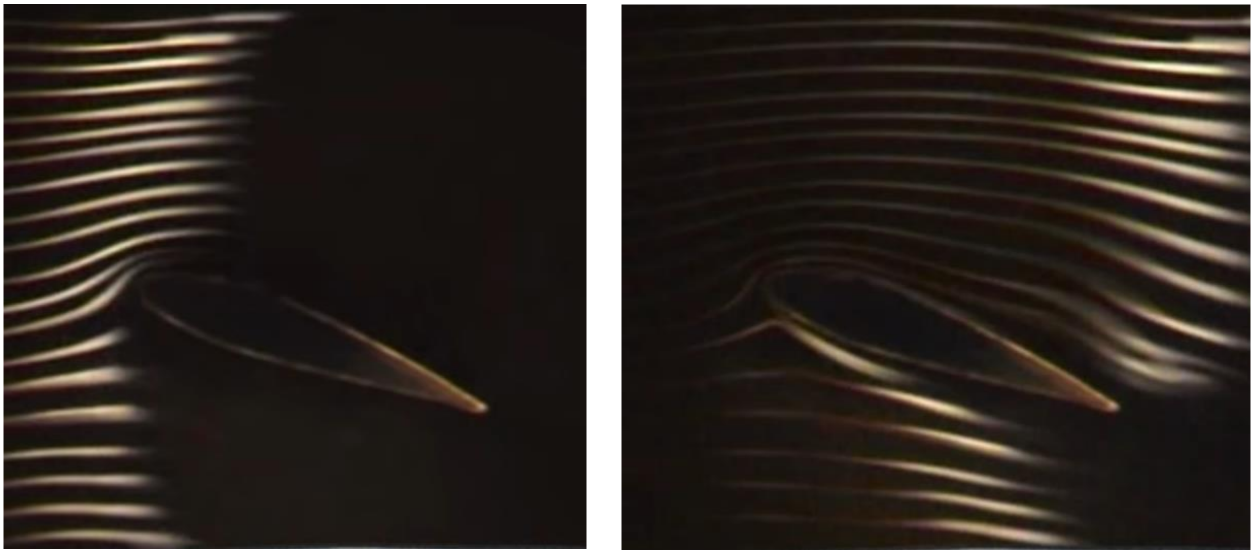


Figure 3a & 3b: Smoke tracing air as it passes over an airfoil [2].

While there is a slight pressure differential that is developed from the fin, the main source of the lift is generated based deflection of air. Newton's Third Law explains that for every action, there is an opposite and equal reaction. In altering the path of the airflow, net forces are developed to provide both lift and drag on the airfoil. The principle of air deflection is demonstrated in figure 4. The blue lines represent the flow of air, the orange represent the lift, and the red represent the drag. The National Advisory Committee for Aeronautics, the predecessor to

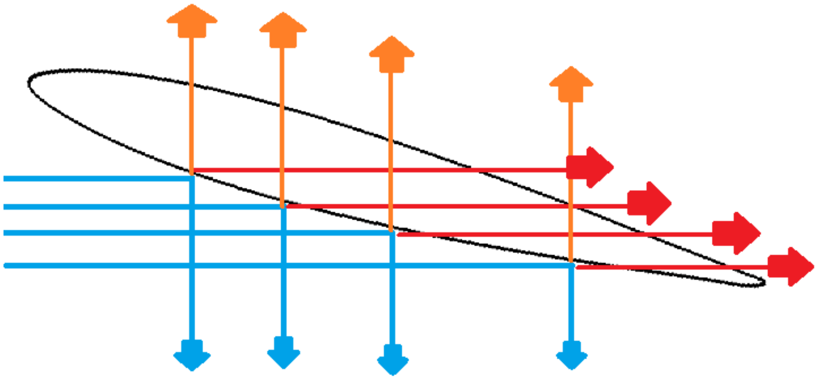


Figure 4: Graphic of aerodynamic forces acting on an airfoil

NASA, developed a system for identifying and creating airfoils. There are several systems, the 4-digit, 5-digit, 6-digit, 7-digit, 8-digit, and 16-digit series; each system has varying benefits and disadvantages. Due to the advantages of the 4-digit series (such as its good stall characteristics, a small center of pressure movement across varying speed ranges, and low effect of roughness on performance), it has become the most frequently used system [3]. As such it was chosen as the system of selection for this project.

List of nomenclature used in theoretical analysis:

C_L= Coefficient of lift, dimensionless

L= Lift, lbf

ρ= Density, slug/ft^3 or slug/in^3

V_∞= Freestream velocity (Airspeed), ft/s

S= Area of fin, ft^2

α= Angle of attack, degrees or radians

Project Goals & Requirements

The initial project purpose according to the team “Design Project Proposal” was to “design and test model rotation-inducing rocket fins under variant conditions such as velocity, angle of attack, and profile.” As the project progressed, it morphed into an effort to develop a wind tunnel test fixture for rotation inducing fins and a method to determine the desired fin profiles to use for a rocket competition application. As stated in the *Abstract*, there were three parts to the project: (1) development of the test fixture, (2) a software tool to plot airfoil profiles and gather useful data about said profiles, and (3) fluid analysis to support findings and develop a better understanding of the test fixture's performance. The *Test Process* below was the overall goal for this project. This document as a whole is a presentation of the work accomplished in the design and development of each of the three parts.

Test Process using Fixture:

- Generate airfoil cross-sectional profile and sizing based on desired lift outcomes per fin
- Model fin and attach in a CAD assembly to the fin mounting prong
- Send to rapid prototype facility manager to be printed. Cut and clean fin support material as required
- Mount fins and bearing assembly to test rocket body.
- Mount in wind tunnel and record video of the rocket test fixture at different speeds to count rotations per specified time amounts; yields rotational velocity.
- Verify rotational velocity in CFD and analyze stabilization effects.
- Define possible percentage efficiency increases because of fins

Methodology

Test Fixture Development

The goal of the test fixture was to allow for easy prototype generation and testing for various types of rocket fins. With this in mind, it would be required that different sets of fins could be secured into the fixture for testing; but would also be easily interchangeable. Conventional manufacturing methods for complex surface geometries quickly become expensive and time-consuming due to the cost of machinery and tooling. As a design team, the Akronauts have a tight budget to allocate towards the development of expensive prototypes. The devised solution was to utilize 3D printing technology to rapidly and cheaply produce complex airfoil shapes while still maintaining a respectable amount of tolerance. Since the University already has a 3D printing lab, it would also keep everything “in house.” The challenge for our team was to develop a mechanical mounting system that was small in size, but robust enough to transfer load from the lift forces generated by the airfoils. The test fixture was to offer the following capabilities/design requirements:

- A method to securely attach fins to the fixture without being permanent
- The test fixture must be mountable to the wind tunnel probe or “sting” using the University provided torque transfer mounting adapter (3/4” OD)
- Must fit into the test section of the University wind tunnel:

Wind Tunnel Test Section Dimensions		
Height	Width	Depth
21.25”	21.75”	27.5”

- A test fixture that would allow for a reasonably undisturbed flow to examine fin performance (verified by CFD)
- The ability for the entire fixture to rotate freely based on lift caused by asymmetric nature of fins

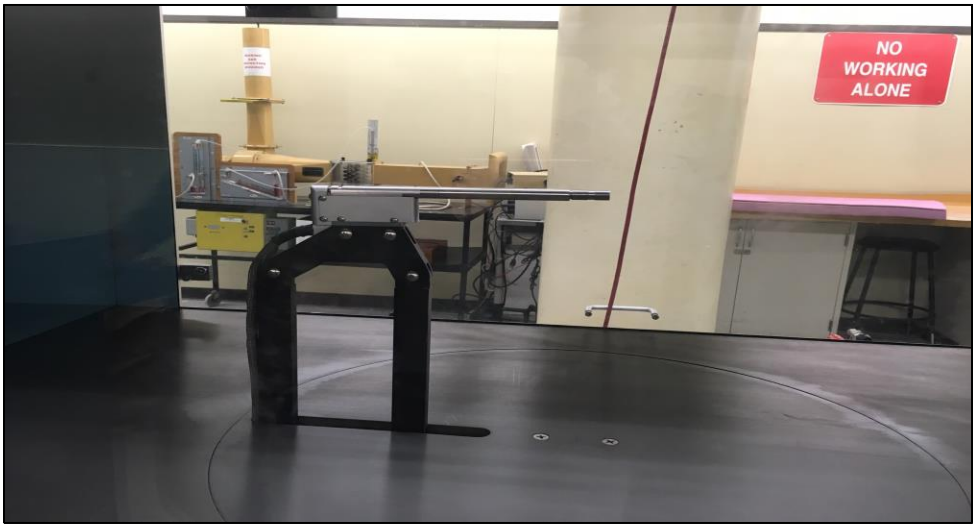


Figure 5: Wind tunnel probe ("sting") for mounting in wind tunnel

After developing these criterion, concept generation took place and an initial design was produced. It was decided that for the rocket fixture, a PVC tube would be used as the rocket body because of the ease at which it could be acquired in various sizes. A low profile nose cone would be 3D printed to cap the front end of the tube. At the rear, three slots were cut at 120 degrees apart for the fins to reside in during tests. A cylindrical section of high density plastic would be inserted into the PVC tubing with corresponding slots cut for the fin bases to securely fit into. At the back of the rocket, a needle roller bearing fit to the PVC inside diameter and the sting adapter outside diameter would mount the test fixture to the wind tunnel probe and axially constrain the entire system.

The desired model size was to be roughly a one-sixth scale model to what a typical sounding rocket size would be and was concurrent with the size of the 2015-2016 team rocket. The team assumed a full-size, one-stage rocket of 9 ft including the nose cone, which scaled to a length of 18 inches for our model. Additionally, the assumed full-size fin chord and span length were 18 inches which scaled down to 3 inches. The diameter of the rocket was not set to a 1:6

scale, but rather it was driven based on the size of the mounting adapter and the resulting required bearing size.

Because the goal was to 3D print airfoils for testing, the fins had to be printed with a mounting feature incorporated into the design. A simple prong system was devised, where the prong of the airfoil would slide into corresponding milled slots on the rear of the fuselage. The prong would bottom out into an interior slot that constrained the prong both radially and axially. The inside face of the airfoil cross-section would sit flush with the outer surface of the rocket fuselage. Below is an initial example of an airfoil with the mounting feature.

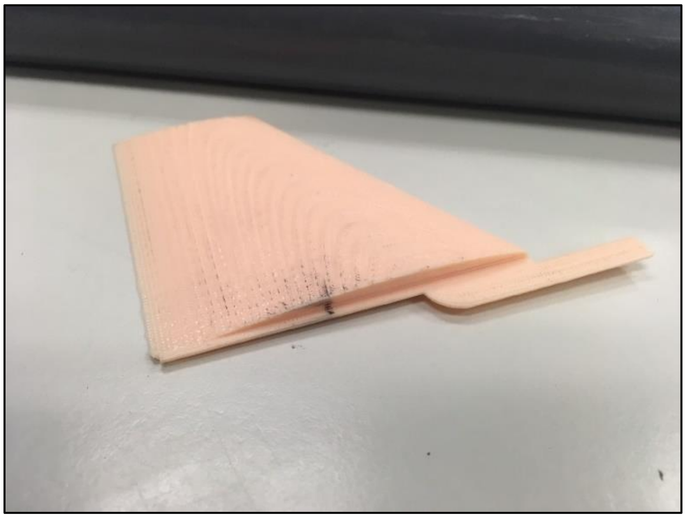


Figure 6: Initial airfoil concept

Figure 7: Test assembly of concept

From the initially printed fin, a few major changes where required. The mounting feature itself needed a substantial increase in thickness because it was flexible in the initial print. Additionally, the length of the feature was initially from the leading edge to the trailing edge of the root chord and would interfere with the installed bearing at the back of the rocket fuselage. Those changes were made and incorporated into an updated design. That design is below:

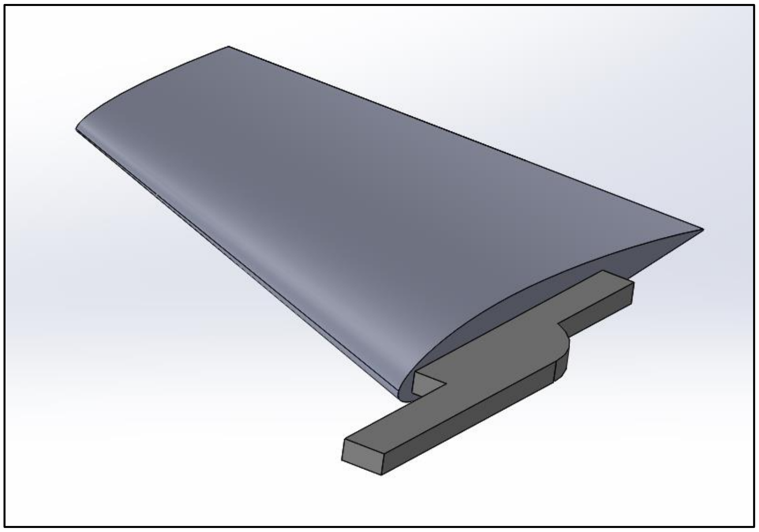


Figure 8: NACA 2412 with updated mounting feature

To verify the validity of the more robust mounting feature, a simple FEA analysis was performed with a force of 35 lbf applied to the underside of the fin simulated a high lift situation above most of the force values the test fixture would see in the wind tunnel. Maximum stress was at *4315 psi*, which is below the tensile yield stress of 7000 psi for ABS plastic [4].

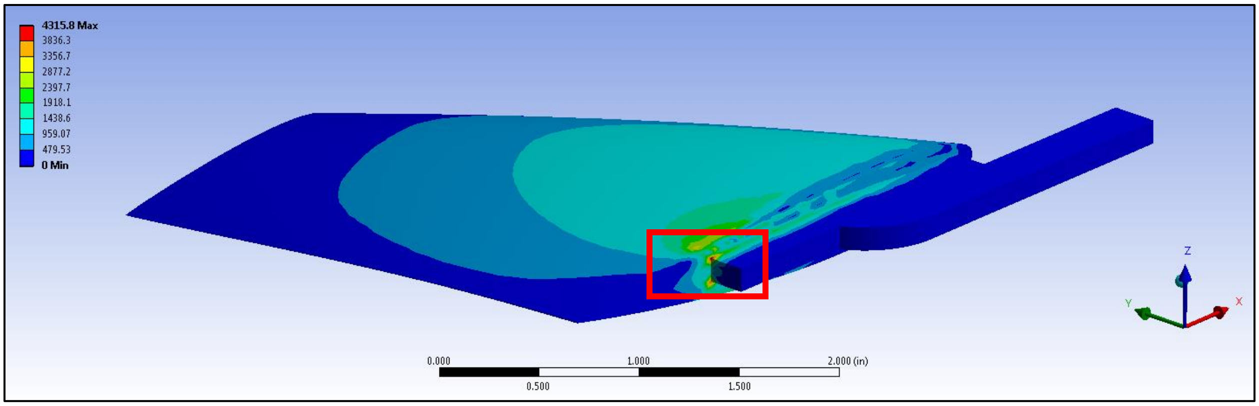


Figure 9: FEA analysis of fin loading

With the fin thickness increased to 0.145” and the shortened mounting feature a snug, reliable fit was able to be obtained. With this design solidified, subsequent airfoil profiles could be easily modeled and assembled in Solidworks, and then printed. Three fins could be printed in one batch on the MakerBots with a set of three taking roughly five hours to complete. This time requirement offers a quick turnaround for the test fixture which was a desired goal of the test process.

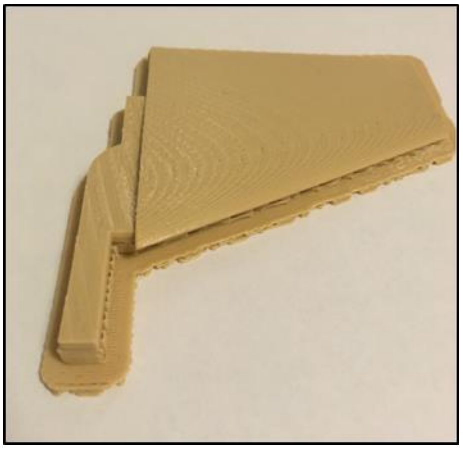


Figure 10: CAD mock-up of fin mounting system

The initial design with the 18” rocket body was fully manufactured and the fin fits were verified. The CAD model was used as a reference for dimensions during the build and helped in the entire manufacturing process. With a completed model, it was time to begin design verification in the wind tunnel. However, prior to gaining access, the team had to present images and functionality of the model to the wind tunnel facility managers for approval. This is an often overlooked, but extremely important step that protects test assets from damage.

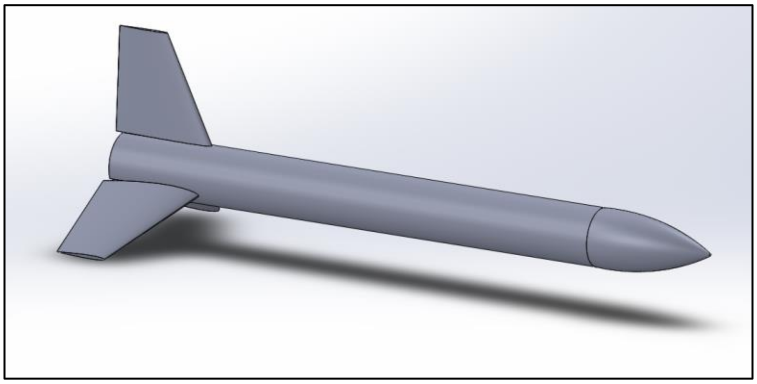


Figure 11: Initial 18" Model

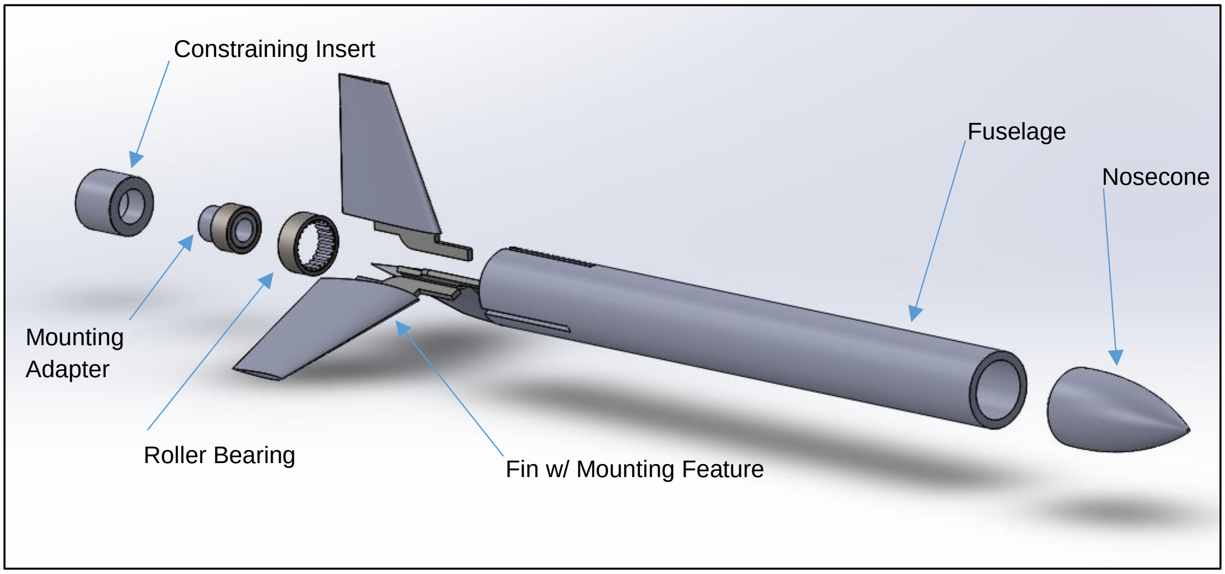


Figure 12: Exploded view of 18" test fixture assembly

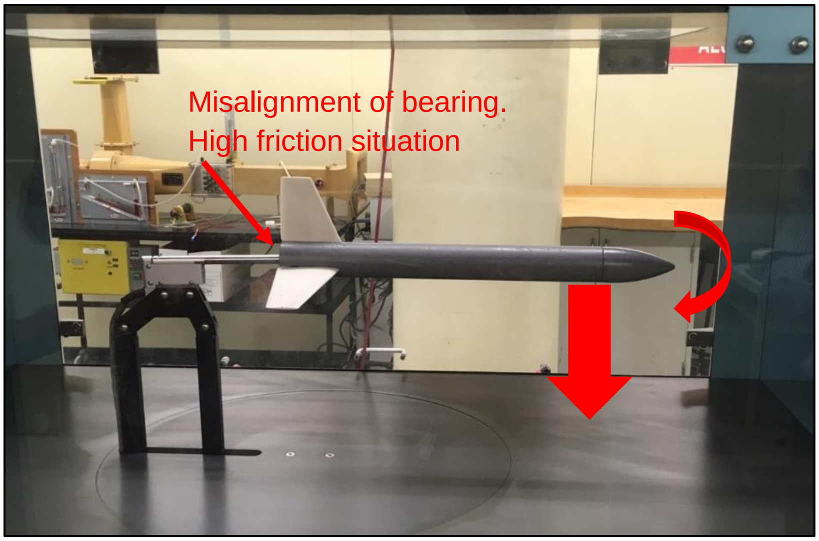


Figure 13: Initial test fixture design mounted in wind tunnel

Figure 14: Rolling issue with mounting adapter

When the test fixture was mounted, it quickly became apparent that the rocket body was too long to perform in the wind tunnel as desired. Because of its overall length and the amount of weight being applied at a significant moment arm distance from the mounting point, the rocket would not rotate. Additionally, the initial bearing choice did not offer a viable freely rotating system because the cylindrical rollers would catch on the slots in the mounting adapter surface.

Redesign activities were performed to mitigate these two issues realized during the initial test. For the bearing issue, a new bearing system was purchased under consultation from engineers at the Akron Bearing Company. Unlike the initial bearing, the new system had both and inner and outer race so that the rollers would have a smooth, enclosed surface to roll on. Additionally, a 3/16” washer that corresponded to the OD of the outer race of the new bearing was epoxied to one end to inhibit the rocket fixture from sliding off the inner race due to drag. For the first problem, the rocket body was made shorter by 50% to yield an overall length of 10.5

inches including the nosecone. By eliminating the weight at those further locations, the entire moment was reduced thus decreasing bearing misalignment and the resulting friction.

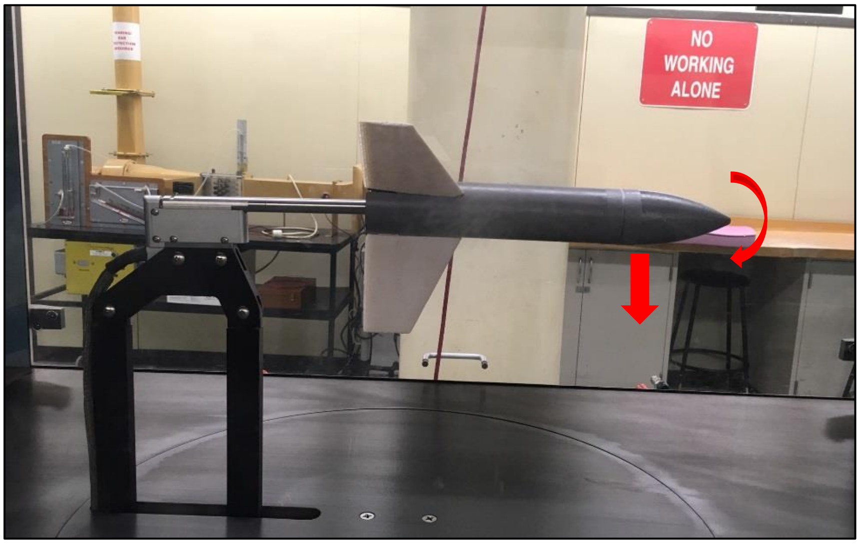


Figure 15: Redesigned Test Fixture

With these changes, the test fixture is extremely close to being fully functional. There are still small issues with friction because of the insert that is installed behind the bearing assembly. These issues will hopefully be eliminated with some additional fine tuning of the interface between the insert, the fuselage, and the bearing.

3D Fluid Model Analysis

Separate from the CFD analysis that will be done on the tested airfoil profiles, an analysis was run to computationally confirm certain aspects of the test fixture design. The exterior features of the test fixture where the focus of these trials; including the nosecone and entire assembled body. Fluent was used to generate these analyses because of a team member's familiarity with the program.

The purpose of a nosecone is very logical in that its primary function is to avoid creating a large stagnation point at the leading end of the entire rocket. The nose cone for the fixture was not designed under any specific equation or requirement other than it had to generate low amounts of vorticity and stagnation. Calculations were run on the proposed shape at 50 m/s; equivalent to 111.8 miles per hour that was chosen because of its proximity to the 120mph max of the University's wind tunnel.

Vorticity is creation of vortexes resulting from fluid rotation or circulation. The less aerodynamic a feature is in a flow, the more opportunity there is for vortexes to develop. This is not good for a rocket because it reduces the amount of smooth flow passing over the wings which decreases lift in the fins and also generates turbulence that could jar the rocket off course. The low vorticity characteristics of the nosecone are presented below.

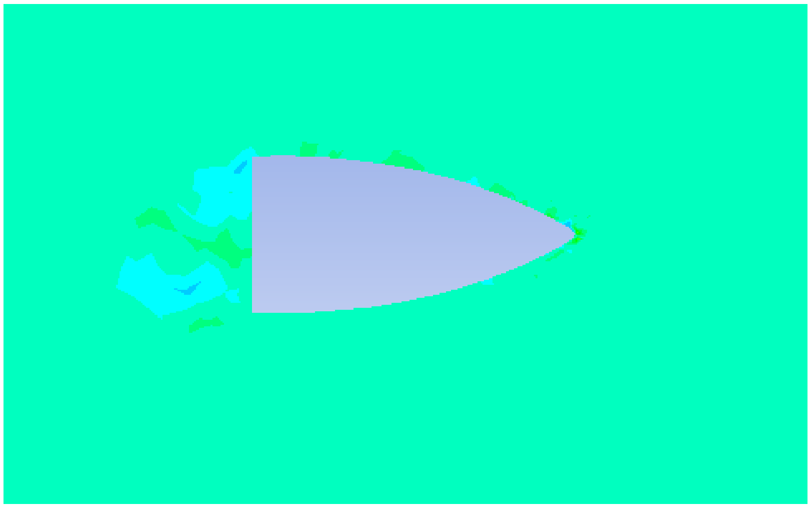


Figure 16: Vorticity resulting from flow over nosecone

The next contour map shows the dynamic pressure levels across the nosecone. The value of dynamic pressure is telling of the corresponding velocities at those locations. Dynamic pressure is an expression of the kinetic energy that resides in a fluid in motion. Where the dynamic pressure is high, the fluid velocity is also high. The map supports the idea that flow over the cone does not disrupt the flow over the fins.

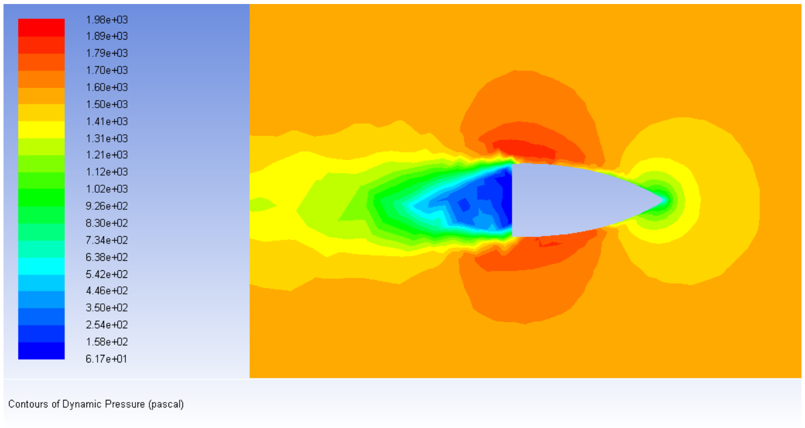


Figure 17: Contour plot of nosecone dynamic pressure

An additional dynamic pressure plot was run on the entire rocket assembly. It shows no major abnormalities at the 111mph free stream velocity that would affect performance.

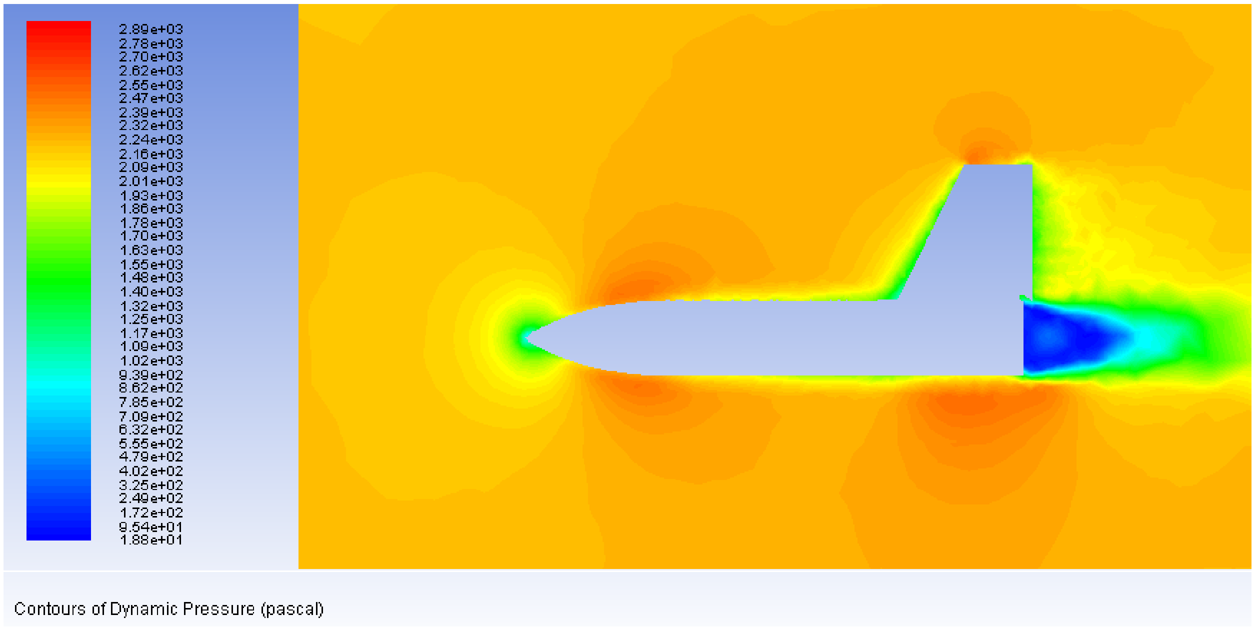


Figure 18: Contour plot of test fixture assembly

Software Model:

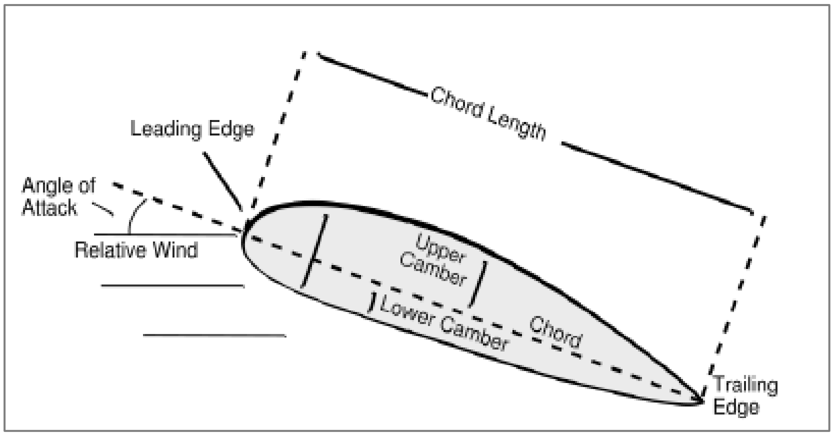


Figure 19: Infographic of basic airfoil terminology

For the software portion of the project, our team employed Matlab to develop an airfoil plotting tool that would also generate coefficients of lift, moment, and pressure based off of the airfoil profile. Under the scope of the project, the team focused on the NACA 4-Digit airfoil series, however, in future use the code could easily be expanded to accommodate additional NACA series'. A 4-digit airfoil has four constraints that define its camber line and overall shape.

The first digit of the airfoil defines the maximum camber of the airfoil in ten percent lengths of the chord. The second digit specifies the position of the maximum camber along the chord also in tenths of chord. The third and fourth digits describe the maximum thickness of the airfoil as a percentage of the chord. The digits are designed as follows:

- Digit 1: Maximum camber as percentage of chord (m)
- Digit 2: Positon of maximum camber along chord (p)
- Digits 3 & 4: Maximum thickness as a percentage of chord length (t)

To illustrate an example, a NACA 2412 airfoil would have an m-value of 20%, a p-value of 40%, and a t-value of 12%. With the input (m, p, & t) and the overall length of the chord as an input, the corresponding airfoil coordinate plots can be solved for using the following equations and process. First, the camber line of the air foil (y_c) is calculated along the chord length from zero to x:

$$y_c = \left(\frac{m}{p^2}\right)(2 * p * x - x^2) \;\; from\; x = 0\; to\; x = p \quad [3]$$

$$y_c = \left(\frac{m}{(1-p)^2}\right)\left((1-2p) + 2 * p * x - x^2\right)\ from\ x = p\ to\ x = c \quad [3]$$

Next, a thickness distribution is calculated for both positive and negative y-coordinates along the chord.

$$\pm y_t = \frac{t}{0.2}\left(0.2969\sqrt{x} - 0.126x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right)$$

$$from\ x = 0\ to\ x = c \quad [3]$$

Finally the x-value, camber y-coordinates (y_c), and thickness y-coordinates (y_t) are used to calculate the upper and lower surface coordinates.

$$x_U = x - y_t sin\theta$$

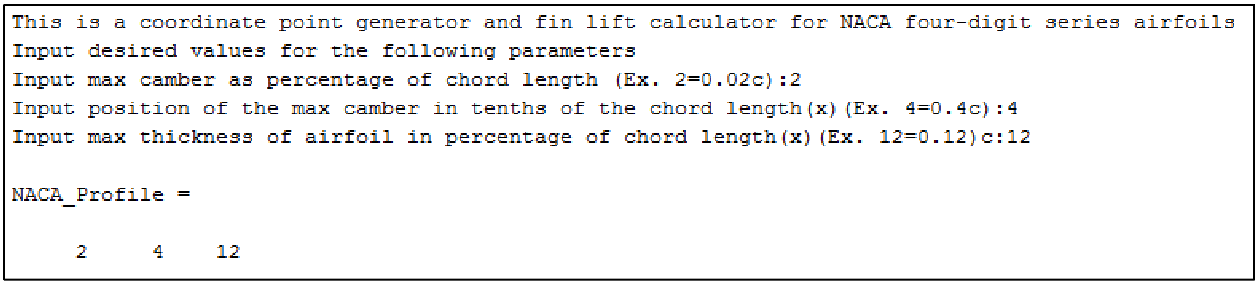
$$y_U = y_c + y_t cos\theta$$

$$x_L = x + y_t sin\theta$$

$$y_L = y_c - y_t cos\theta$$

$$where\ \theta = \arctan(\frac{dy_c}{dx}) \quad [3]$$

This method is the baseline for the code that was developed. The full code is presented in the Appendix, but a demonstration of its capability with explanation is presented below. Upon running the code, the user is prompted to input the desired 4 digits for the airfoil.



```
This is a coordinate point generator and fin lift calculator for NACA four-digit series airfoils
Input desired values for the following parameters
Input max camber as percentage of chord length (Ex. 2=0.02c):2
Input position of the max camber in tenths of the chord length(x)(Ex. 4=0.4c):4
Input max thickness of airfoil in percentage of chord length(x)(Ex. 12=0.12)c:12

NACA_Profile =

     2     4    12
```

Figure 20: Initial input prompts

The code calculates the points for the airfoil and then plots the shape with the camber line included. This plot is merely for reference and verification that a legitimate plot is being used in the rest of the code.

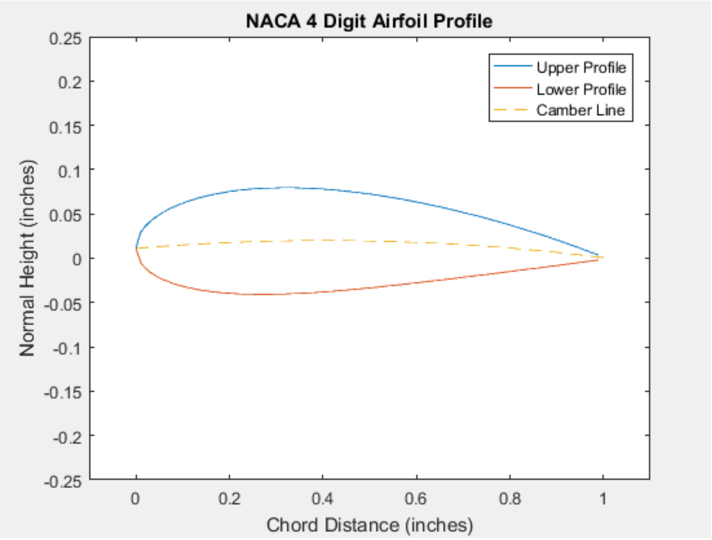
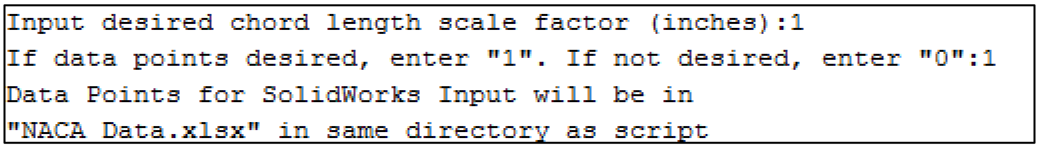


Figure 21: Plot of airfoil based off of inputs

The code then prompts the user to define a desired root chord length for the given application (Note: For the airfoils printed by the project team for the test fixture, a root chord length of 3 inches was used). Then it asks if the user would like the data points to be printed to an excel file for later modeling use in Solidworks.

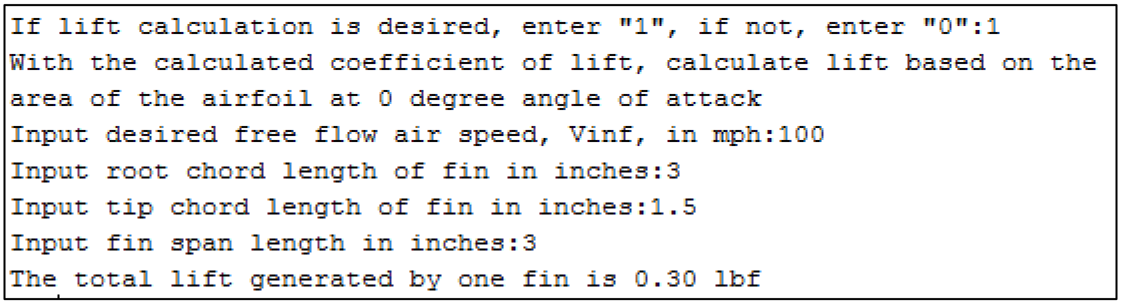


```
Input desired chord length scale factor (inches):1
If data points desired, enter "1". If not desired, enter "0":1
Data Points for SolidWorks Input will be in
"NACA Data.xlsx" in same directory as script
```

Figure 22: Desired root chord length and data export

At the same time that the values are exported, the coeffiecent of lift, drag, moment, and pressure are calculated for the specific airfoil. This is performed using an open source Matlab script that calculates those aerodynamic coeffients based on the airfoil cross-section. (Note: The script is properly identified as unoriginal work in the code). The coefficient of lift, C_l, is utilized in the calculation of the lift generated for a specifically sized airfoil at a specific velocity. Where lift is calculated for one fin using the following equation:

$$Lift = \frac{1}{2}\rho V_{\infty}^{2} S C_l$$



```
If lift calculation is desired, enter "1", if not, enter "0":1
With the calculated coefficient of lift, calculate lift based on the
area of the airfoil at 0 degree angle of attack
Input desired free flow air speed, Vinf, in mph:100
Input root chord length of fin in inches:3
Input tip chord length of fin in inches:1.5
Input fin span length in inches:3
The total lift generated by one fin is 0.30 lbf
```

Figure 16: Airfoil dimensioning and lift calculation

The validity of the coefficient of lift calculation is illustrated in the appendix. Experimental data for a NACA 2412 [5] is compared to the code plot over a range of alpha, α.

Conclusions

The results of this project include the design and development of a useful student design team test fixture and a complementary Matlab software program. The hope is that it will be incorporated into future Akronauts projects for the development of an innovative and high-performing rocket. Our team was able to design, test, and prove out a concept while making any needed adjustments along the way. Although the initial project goals where not fully realized, the team did indeed gain a plethora of experience with the engineering design process. Practical applications of FEA, CFD, and technical programming were exercised over the course of the project that directly demonstrated the skills learned by the involved students over the past 4 years of coursework. The third portion of the project goals involving CFD analysis of the overall stabilization of the rocket due to rotation will be accomplished in the Spring 2017 semester by the team member who is graduating during that semester. This will round out the entirety of the project.

References

[1] "Rocket Stability Condition." NASA. NASA, n.d. Web. 05 Dec. 2016. https://spaceflightsystems.grc.nasa.gov/education/rocket/rktstabc.html

[2] "How Wings Really Work." University of Cambridge. N.p., n.d. Web. 05 Dec. 2016. http://www.cam.ac.uk/research/news/how-wings-really-work

[3] “The NACA Airfoil Series.” *University of Clarkson.* N.p., n.d Web 05 Dec. 2016. http://people.clarkson.edu/~pmarzocc/AE429/The%20NACA%20airfoil%20series.pdf

[4] "Thermoplastics - Physical Properties." Thermoplastics - Physical Properties. N.p., n.d. Web. 05 Dec. 2016. http://www.engineeringtoolbox.com/physical-properties-thermoplastics-d_808.html

The textbook used throughout the entire development of this project:

[5] Anderson. Fundamentals of Aerodynamics Fourth Edition. ..: McGraw-Hill Education, 2009. Print.

Appendix

Full Matlab Code:

```
%NACA FOUR-DIGIT SERIES AIRFOIL GENERATOR
%
%
%Authored By D. Royak Fall Semester 2016
%(With exception of noted portions that are utilized for academic purpose
%only)
%
%
clc,clear,clf
%
%Program asks for inputs of NACA Parameters
disp('This is a coordinate point generator and fin lift calculator for NACA four-digit series airfoils')
disp('Input desired values for the following parameters')
prompt1='Input max camber as percentage of chord length (Ex. 2=0.02c):';
m= input(prompt1)/100;
prompt2='Input position of the max camber in tenths of the chord length(x)(Ex. 4=0.4c):';
p= input(prompt2)/10;
prompt3='Input max thickness of airfoil in percentage of chord length(x)(Ex. 12=0.12)c:';
t= input(prompt3)/100;
NACA_Profile=horzcat(100*m,10*p,100*t)
%
%
%Define Chord Length (c)as unit chord of 1 inch. Scale if needed later in program.
c=1;
%
%Compute mean camber line coordinates
n=100;
for x_integer = 1:1:n
x=c*(x_integer-1)/n;
if 0<=x<=p
y_camber= (m/p^2)*(2*p*x-x^2);% only up to value for p along chord
elseif p<x<=c
y_camber=(m/(1-p)^2)*((1-2*p)+2*p*x-x^2);
end
y_c(x_integer,:)=[y_camber];
x_c(x_integer,:)=[x];
end
y_c;
x_c; %x for all intents and purposes
c_points=linspace(0,c,n);
%figure(1)
%plot(c_points,y_c)
%Solve for thickness distribution (y_t) positive and negative
y_t= t/(.2)*(0.2969*sqrt(x_c)-0.12608*x_c-0.3516*(x_c.^2)+0.2843*(x_c.^3)-0.1015*(x_c.^4));
```

```
y_tneg=(-1).*y_t;

%Airfoil Coordinates:
%
%Definition of theta
for i=(1:1:n-1);
   dy_c=(y_c(i+1)-y_c(i));
   dx_c=(x_c(i+1)-x_c(i));
   theta_loop=atan(dy_c/dx_c);  %(linspace(0,pi()/2,330);
   theta(i,:)=[theta_loop];
end
theta;
add=theta(n-1);
theta_n=cat(1,theta,add);
%x_upper
x_u=x_c-y_t.*sin(theta_n);
%y_upper
y_u=y_c+y_t.*cos(theta_n);
%x_lower
x_l=x_c+y_t.*sin(theta_n);
%y_lower
y_l=y_c-y_t.*cos(theta_n);
figure(1)
plot(x_u,y_u)
hold on
plot(x_l,y_l)
hold on
plot(c_points,y_c,'--')
xlabel('Chord Distance (inches)')
ylabel('Normal Height (inches)')
title('NACA 4 Digit Airfoil Profile')
legend('Upper Profile','Lower Profile','Camber Line')
%Define axis limits
axis([-.1 1.1 -.25 .25])
%
%Export Coordinates to Excel Sheet for import to SW
prompt4='Input desired chord length scale factor (inches):';
scale=input(prompt4);
%Scaled Upper profile coordinates
x_u_scale=x_u*scale;
y_u_scale=y_u*scale;
%%Get rid of self-intersecting point
x_u_scale=x_u_scale(2:n);
y_u_scale=y_u_scale(2:n);
%Scaled Lower profile coordinates
x_l_scale=x_l*scale;
y_l_scale=y_l*scale;
%Logic for exporting data to excel
prompt5='If data points desired, enter "1". If not desired, enter "0":';
val=input(prompt5);
if val==1;
%Excel Sheet
z=zeros(1,n)';
filename = 'NACA_Data.xlsx';
xlswrite(filename,x_u_scale,1,'A1')
xlswrite(filename,y_u_scale,1,'B1')
```

```
xlswrite(filename,z,1,'C1')
xlswrite(filename,x_l_scale,1,'D1')
xlswrite(filename,y_l_scale,1,'E1')
xlswrite(filename,z,1,'F1')
%
%Define File Location for airfoil profile
disp('Data Points for SolidWorks Input will be in')
disp('"NACA_Data.xlsx" in same directory as script')
elseif val==0;
end
%**Note modified code usage from the following author:**
% Original code by L. sankar, April 1997
%  Modified by D. Royak, 2016 for academic purpose
%
% Assemble the Influence Coefficient Matrix A
%
%
%Angle of Attack range (alpha)
  for i =1:n
       x_l_scale1(n+1-i) = x_l_scale(i);
       y_l_scale1(n+1-i) = y_l_scale(i);
  end
x_l_scale=x_l_scale1';
y_l_scale=y_l_scale1';
%switched order of xl and x upper to fit program
x1=vertcat(x_l_scale,x_u_scale)';
y1=vertcat(y_l_scale,y_u_scale)';
x=x1;
y=y1;
%figure(7)
%plot(x,y)
n=numel(x)-1;
for alf=1:1:21;
alpha=alf-11;
A=zeros(n+1,n+1);
ds=zeros(1,n);
pi=4. * atan(1.0);
%
% Assemble the Influence Coefficient Matrix A
%
 for i = 1:n
   t1= x(i+1)-x(i);
   t2 = y(i+1)-y(i);
   ds(i) = sqrt(t1*t1+t2*t2);
 end
for j = 1:n
 a(j,n+1) = 1.0;
 for i = 1:n
   if i == j
     a(i,i) = ds(i)/(2.*pi) *(log(0.5*ds(i)) - 1.0);
   else
     xm1 = 0.5 * (x(j)+x(j+1));
     ym1 = 0.5 * (y(j)+y(j+1));
     dx  = (x(i+1)-x(i))/ds(i);
     dy  = (y(i+1)-y(i))/ds(i);
     t1  = x(i) - xm1;
```

```
     t2  = y(i) - ym1;
     t3  = x(i+1) - xm1;
     t7  = y(i+1) - ym1;
     t4  = t1 * dx + t2 * dy;
     t5  = t3 * dx + t7 * dy;
     t6  = t2 * dx - t1 * dy;
     t1  = t5 * log(t5*t5+t6*t6) - t4 * log(t4*t4+t6*t6);
     t2  = atan2(t6,t4)-atan2(t6,t5);
     a(j,i) = (0.5 * t1-t5+t4+t6*t2)/(2.*pi);
   end
 end
a(n+1,1) = 1.0;
a(n+1,n) = 1.0;
end
%
% Assemble the Right hand Side of the Matrix system
%
rhs=zeros(n+1,1);
alpha = alpha * pi /180;
xmid=zeros(n,1);
for i = 1:n
  xmid(i,1) = 0.5 * (x(i) + x(i+1));
  ymid = 0.5 * (y(i) + y(i+1));
  rhs(i,1) = ymid * cos(alpha) - xmid(i) * sin(alpha);
end
gamma = zeros(n+1,1);
%
% Solve the syetm of equations
% In MATLAB this is easy!
%
gamma = a\rhs;
cp=zeros(n,1);
cp1=zeros(n,1);
%
% Open a file to write x vs. Cp and the Loads
%
% Change the file name below, to open a new file every time
%
fid=fopen('cp4.dat','w');
fprintf(fid,'   X          CP\n\n');
for i = 1:n
cp(i,1) = 1. - gamma(i) * gamma(i);
cp1(i,1) = - cp(i,1);
xa     = xmid(i,1);
cpa = cp(i,1);
%
% Write x and Cp to the file
%
% The xa- coordinate is the center points of panel 'i'
% Cpa is the Cp value at that point
%
fprintf(fid,'%10.4f %10.4f\n',xa,cpa);
end
%
% Open a new figure and plot x vs. Cp
%
```

```
figure(2);
plot(xmid,cp1);
%
% Compute Lift and Drag Coefficients
%
cy = 0.0;
cx = 0.0;
cm = 0.0;
% We assume that the airfoil has unit chord
% we assume that the leading edge is at i = nl;
for i=1:n
dx = x(i+1) - x(i);
dy = y(i+1) - y(i);
% xarm is the moment arem , equals distance from
% the center of the panel to quarter-chord.
xarm = 0.5 * (x(i+1)+x(i))-x(n/2)-0.25;
cy = cy - cp(i,1) * dx;
cx = cx + cp(i,1) * dy;
cm = cm - cp(i,1) * dx * xarm;
end
%
% Print Lift and Drag coefficients on the screen
%
cl = cy * cos(alpha) - cx * sin(alpha);
cd = cy * sin(alpha) + cx * cos(alpha);
cm;
%
% Write lift and Drag coefficients to a file
%
fprintf(fid,'  CL        CD  CM\n');
fprintf(fid,'%10.4f %10.4f %10.4f\n', cl,cd,cm);
fclose(fid); %****End of code by L. sankar, April 1997***
cl1(alf,:)=[cl];
cd1(alf,:)=[cd];
cm1(alf,:)=[cm];
end
%Matrix results for each lift, drag, and moment coefficients
cl1;
cd1;
cm=-cm1;
aoa=-10:1:10;
figure(3);
plot(aoa,cl1);
title('Coefficient of Lift vs Angle of Attack')
ylabel('Coefficient of Lift (cl)')
xlabel('Angle of attack (degrees)')
figure(4);
plot(aoa,cd1);
title('Coefficient of Drag vs Angle of Attack')
ylabel('Coefficient of Drag (cd)')
xlabel('Angle of attack (degrees)')
figure(5);
plot(aoa,cm1);
title('Coefficient of Moment vs Angle of Attack')
ylabel('Coefficient of Moment (cm)')
xlabel('Angle of attack (degrees)')
```

```
%%%
%With the calculated coefficient of lift, calculate lift based on the area
%of the airfoil
prompt6='If lift calculation is desired, enter "1", if not, enter "0":';
val=input(prompt6);
if val==1;
disp('With the calculated coefficient of lift, calculate lift based on the')
disp('area of the airfoil at 0 degree angle of attack')
clzero=cl1(11);
%Density assumed at 1500 ft(Avg altitude in Northeast Ohio)
density=2.2743*10^-3; %slugs/ft^3
prompt7='Input desired free flow air speed, Vinf, in mph:';
vinf=input(prompt7)*5280/3600; %convert from mph to ft/s
prompt8='Input root chord length of fin in inches:';
rtchord=input(prompt8)/12; %converted to feet
prompt9='Input tip chord length of fin in inches:';
tipchord=input(prompt9)/12; %converted to feet
prompt10='Input fin span length in inches:';
span=input(prompt10)/12; %converted to feet
%calculate area of fin, S
S= tipchord*span+((rtchord-tipchord)*span)/2;
%Calculate lift:
L=0.5*(density)*(vinf^2)*S*clzero;
fprintf('The total lift generated by one fin is %4.2f lbf\n',L);
elseif val==0;
end
```

Comparison of NACA 2412 Cl from code vs. experimental data plot pulled from the text: Fundamentals of Aerodynamics