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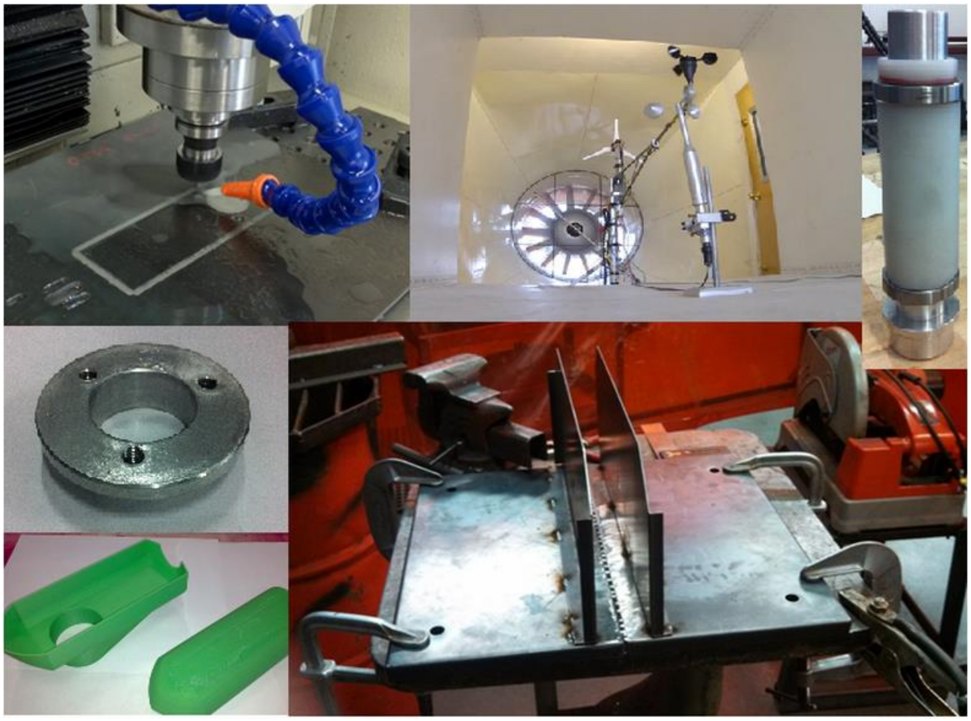

Sponsored by the Department of Energy

Submitted towards partial fulfillment of the requirements for

The Design Review Subcontest

NORTHERN
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FLAGSTAFF

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Nomenclature

a' Angular induction factor	a Axial induction factor
C_d Coefficient of Drag	A_c Cross-sectional swept area of the turbine blades.
C_T Coefficient of Thrust	C_l Coefficient of Lift
F_T Thrust Force	C_p Power coefficient
F_D Drag Force	m Mass
r Blade Profile length	Re Reynolds number
λ_r Tip Speed at blade increment	U Wind velocity
r Blade Profile length	λ Tip Speed Ratio (TSR)
φ Angle of Relative Wind	ω Rotational Velocity
$\theta_{p,0}$ Section Pitch angle	ρ Air density
α Angle of attack	σ_d Solidity

Memo:

To: Dr. Tom Acker

From: DOE Wind Competition Blade Design Team

Subject: Project Proposal

Date: December 11, 2013

cc: David Willy, Karin WadSack, Frank Spitznogle

Dr. Acker,

The efforts of multiple concept generations and engineering analysis considerations has led us to our current project proposal design for the Collegiate Wind Competition. Calculated blade geometries were implemented into a Blade Element Momentum Theory (BEM) code using FAST software to determine if the wind profile meets competition guidelines. Using this computational information allowed the team to compare the analytical results to the computational results taken from the BEM code and FAST.

The turbine was designed using the assigned generator sent from the Department of Energy. In summary a downwind turbine design with three polycarbonate blades designed for a tip speed ratio of 7 generates up to 14 W at 18 m/s.. This final design meets the design constraints of the business plan and competition.

Abstract

This Capstone project is part of the Department of Energy's (DOE) Collegiate Wind Competition (CWC) that is held at the American Wind Energy Association (AWEA) conference. In two full semesters the NAU team constructed a micro-wind turbine, developed for emergency power generation for post disaster situations. The team's design went through many iterations to find out which design was the best at generating power, cut-in wind speed and torque production. The design needed to be compatible with the mandated generator to meet the needs of the DOE Rules and Regulations Document. A business plan, designed for the competition will also be presented to the judges where the NAU design team must follow the specifications that are deemed by the Company Team SPINergy. The proposed design is three-bladed downwind system that operates at 4270 rpm and produces 14 W at 18 m/s. Wind tunnel testing performed to meet generator specifications as well as the testing procedures that will occur on competition day. The blade design is optimized for the business plan to produce sufficient power and operate within the defined wind regime.

Chapter 1: Introduction

1.1 Introduction of client and problem

The Department of Energy is a government-funded agency that is working to ensure America's energy future, scientific & technological leadership, and nuclear security. The DOE CWC is a forum for students to showcase innovative ideas for the wind industry. The primary clients are: Instructor and technical advisor David Willy, Principle Investigator Dr. Tom Acker, Team Manager Karin Wadsack, and Entrepreneur in Residence Frank Spitznogle. Our goal for these clients was to design and build a suitable wind turbine for the competition hosted by the United States Department of Energy (DOE) and to match the business plan. The organizers welcome the opportunity to develop competitions that challenge the intellect and ingenuity of the nation's aspiring wind energy industry contributors and colleges that will attend. The DOE seeks to create fair contest rules for determining appropriate measurable outcomes that each team will compete against each other. The DOE CWC consists of three contests: business plan delivery, wind turbine testing and design review, market issues presentation. Within each contest there are multiple tasks that each team will have to perform.

1.2 State of the art research

Beginning this project involved conceptual understanding of general wind turbine design, looking at what was successful in global markets and what technology hasn't had much success. Technical engineering understanding is crucial for successful design, but in meeting the needs of the business team and plan, global understanding of wind turbine systems is necessary. Wind turbine topologies, subsystems, financing, and extent of need for renewable energy was explored. Identifying energy production trends for developing countries, in addition to fighting climate change exemplified the motivation for being successful with the team's design. Installed capacity, coefficient of power, capacity factors, and wind resources were well explained. Wind resource understanding contributes to the turbine design as well devising how the system will be financed as the trends of wind energy systems continue to decline but nonetheless exceed current fossil fuel generation costs. Trends in European wind turbine installation compared to U.S. further exemplified our nation's dependence on fossil fuels, which inarguably are exhaustible, whether you study engineering or not.

The concepts of drag and lift operated systems were explored with basic aerodynamic concepts of how these devices operate listing their advantages, disadvantages, and applications. The function and trends in generators, gear boxes, control systems, and tower construction were broadly explored as well. A fixed pitch rotor was determined to be most suitable for the design but the team will leaving pitch control an option to stimulate the concept generation process. Gearbox problems, gear ratios, differences in topologies, as well as importance were explained. Lastly, mechanical and electrical control systems were explored broadly which, for the size of our wind tunnel tested turbine, may include both mechanical and electrical systems even though modern trends look to electrical control systems. The most important concepts learned in this, mostly non-in-depth technical review are that this competition does not limit innovation as well as technology used in wind turbine systems of the past.

Chapter 2: Problem Formulation

2.1 Defining the Problem

Currently, the wind energy market has not explored micro-wind turbines as a cost effective source for capturing and using energy in the wind. The NAU design team decided to have a goal and needs statement for the client to know exactly what our goals and needs are. The goal statement is,

"To design a portable, cost-efficient micro-wind turbine for emergency power generation"

Where the needs statement is,

"Often times, in the event of natural disasters, people require access to power for various reasons such as charging small electronic devices, because their main sources of energy have been destroyed."

Completing these statements will result in a successful design, business plan, and market to be able to take to competition and be able to show our clients how these statements were met.

2.2 Project Objectives:

The team project objectives are to design an efficient wind turbine that operates within the business plan wind regime and CWC competition guidelines. Team objectives are listed in detail in the following table, Table 1. During the designing phases, different parameters must be varied in order to optimize the success of the design.

Table 1: Competition Guidelines

Objective	How Objective is Measured	Units of Measurement
Power Curve Verification Task	$Accuracy\ of\ Power\ Curve$	%
Cut in Wind Speed Task	Wind Speed that the Turbine Cuts in (generates positive current)	Watts
Control at Maximum Power Task	Determine what the actual rated power of each turbine is	W
Durability and Safety Task	Turbine must safely shut down within a certain time period	% of Rated RPM

2.3 Competition Constraints:

Table 2: CWC Rules and Regulations

CWC Rules and Regulations	
1	The blade design will be tested in a 45x45x45 cm^3 testing facility
2	Blade testing wind regime will be 1 $\frac{m}{s}$ intervals $0-17\ \frac{m}{s}$
3	Minimum 10W power for one wind speed in the range of 5-14 $\frac{m}{s}$
4	Blades/rotors must be accessible for the judges
5	Nacelle internals must be accessible for the judges
6	To receive full points, the blades must cut-in before 2.5 $\frac{m}{s}$
7	Cut-in wind speed is defined as producing positive current at an operating 5 volts
8	Tests will be performed in 1 $\frac{m}{s}$ intervals
9	Turbine must be capable of shutdown at any given testing wind speed
10	After a 5 minute test of varying wind speeds the turbine must shut down
11	Must be able to predict within 10% the power curve for a given density

The team was given a small electric motor that will also be used as a generator to produce electrical energy. This motor will dictate what the parameters of the blade design and operating power production. The team will determine how the tip speed ratio (TSR), rotor diameter, wind speed, and shaft speed affect the power extracted from the wind. The team must meet competition rules and regulations in order to be successful at competition. The main requirements and regulations of the CWC are listed in Table 2: Rules and Regulations of the CWC. The following rules will be enforced by a panel of judges at competition.

Chapter 3: Proposed Design

The proposed design is three-bladed downwind system that operates at 4270 rpm and produces 14 W at 18 m/s. Going through multiple methods of choosing the right design, the team was able to find an optimal design that would be used in the competition. First the team studied wind energy engineering and started looking at the types of smaller wind turbines that are on the market today. Wind turbines have multiple designs and functions that are used in certain wind regimes, landscapes, and markets. These types include, downwind and upwind turbines which are oriented either up/downwind of the freestream wind velocity. Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) were other types of wind turbines which are displayed in Figure 1.

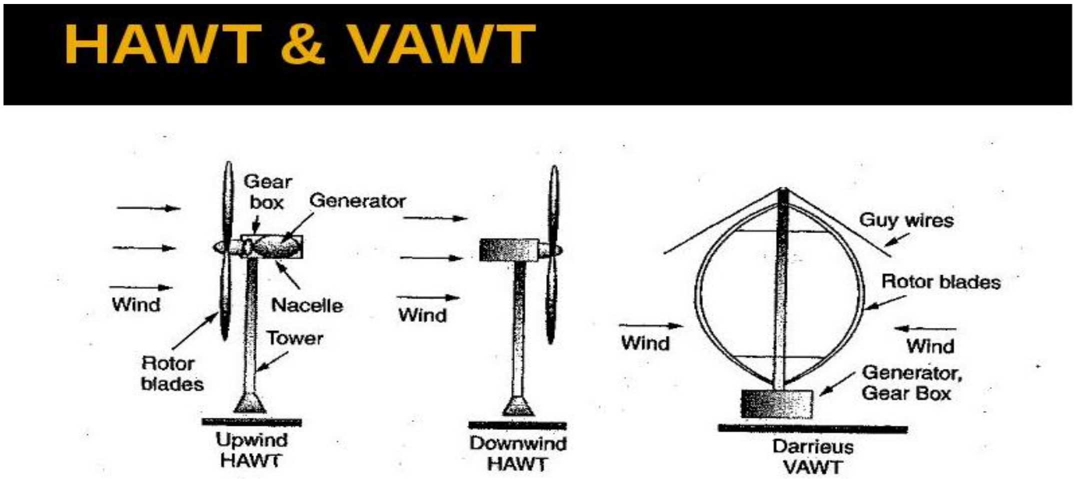

Figure 1: Differences between HAWT and VAWT

3.1 Designing the Rotor

3.1.1: Final Blade Design

Working with such a small rotor diameter, the Reynolds number of the proposed wind turbine blade is ultra-low. This made it very hard to model an accurate blade shape because little data exists for wind turbines and airfoils for flow of such low Reynolds numbers. Testing was completed in an open circuit subsonic wind tunnel to obtain lift and drag data of a flat plate at ultra-low Reynolds numbers and determine the stall characteristics. A flat plate, having a chord length of 0.5 inches and a span of 10 inches, was designed with a slight camber for testing. Normal and axial forces acting on the thin airfoil were measured while flow velocity was steadily increased and varying angles of attack. This data was recorded in a LabVIEW program, then the total lift and drag force of the thin airfoil were calculated.

This information provided the knowledge to be able to utilizing the Blade Element Momentum (BEM) theory code to obtain an optimized blade shape [1]. This blade shape was derived from optimum twist and chord length using the an xy code found in appendix C. A slight camber is also applied to the airfoil so that the blades will obtain enough torque to cut in. The final airfoil chosen was the S834, with optimum geometry because the manufacturing process utilized was not restrictive. From this airfoil, the blade design was optimized using two different software packages and the Blade Elemental Momentum (BEM) theory for wind regimes defined by the business plan and competition. Initially two, three, four, and six bladed systems were considered for competition; however, a three bladed system was chosen for the final design because of its ability to cut in at low wind speeds and run at a high tip speed ratio. The two programs used, BLADED and FAST, determined the forces that are acting on certain blade sections. The final blade profile and root are demonstrated in figure 2 and 3.

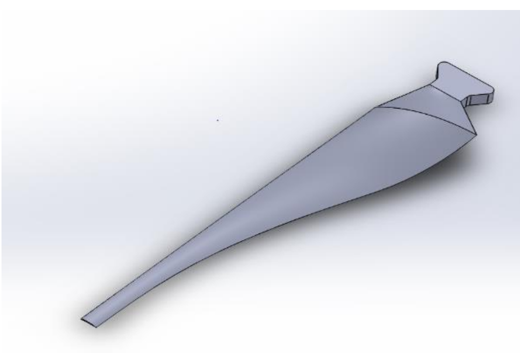

Figure 2: Blade Profile

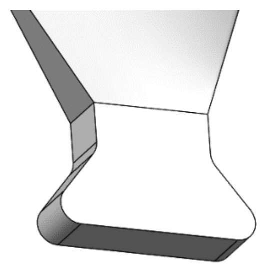

Figure 3: Blade Root

These blades utilized a special blade root design, which was constrained by the hub through three symmetric geometric connections that does not require any fixtures such as through-bolts. With manufacturing tolerances accurate enough to have planar connection reducing normal stresses caused by centripetal acceleration with a larger contact surface. The specific geometry also eliminates the possibility for incorrect blade installation in real life use.

3.2: Final Hub Design

The final intentions of the final hub design required connection between the blade root and gearbox using a collet. Connecting all of the components using a small collet that came with the prescribed gearbox fit through the middle hole of the hub onto the output shaft and was able to withstand the axial forces. The collet was tightened with a small bolt, a few washers, and a hub plate to ensure a compression fit. The final hub design and assembly are seen in figure 4 and figure 5.

Figure 4: Final Hub Design

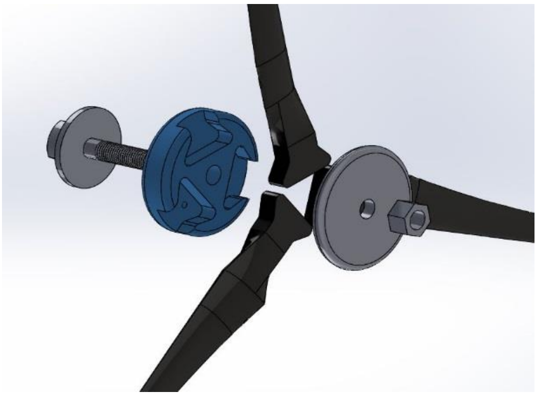

Figure 5: Exploded View of the Rotor

3.3: Calculations

Several equations were used to develop the forces used during FEA. The flap wise force came from the BEM code found in appendix B and is shown in equation 1 . The inputs used for the flap wise forces were TSR=7, wind speed=17 (m/s), no pitching angle, a radius of .225 m with the first blade section occurring 0.05 m into the blade, 10 blade sections, 3 blades, and using the s834 airfoil throughout the blade. The equation represents the total flap wise force on all the blades, so the equation is normalized by the number of blades for analysis.

$$\sum F_{flapwise} = \sum_{Blade\ Sections} C_t \rho U_\infty^2 A \Delta r \quad (1)$$

The torque generated was also obtain from the BEM code using the same inputs as the flap wise force. Because the torque is so small, it was neglected from FEA but is important in determining how well the turbine will perform as the torque must be larger than the cogging torque of the generator. The torque equation can be seen in Equation 2 and is the sum of all the blades.

$$Q = \sum_{Blade\ Sections} \frac{(\sigma_d \pi \rho U_\infty^2 (1-a)^2 (Cl \sin\varphi - Cd \cos\varphi))}{\sin\varphi^2} r^2 \Delta r \quad (2)$$

The radial force is found using Equation 3. The inputs used were a mass of 17.9 g, a RPM of 4270, and a center of mass occurring at one third of the blade radius.

$$F_r = m\omega^2 r_{center\ of\ mass} \quad (3)$$

3.4.1 FEA on the Blades using ANSYS

The forces applied to the blade were 10 N in the flap wise direction and 270 N in the radial direction. The blade root was constrained to be fixed along the 4 main faces that the blade root touches the hub. Analysis revealed that the maximum deflection the blades would experience was 0.048 m (see Figures 8-11).

The blades were difficult to mesh in ANSYS because of their complex geometry and the fact that stresses at the root were most likely to fail. The root hub and edges of the blade contained more elements as the analysis for those sections is the most essential. The simplified blade root utilized about 29192 nodes and 16319 elements. The blades were modeled with both a thrust force and the radial force, with fixed point bounded at surfaces that met the hub. The blade root mesh concentrations are shown in Figures 6 and 7. These concentrated meshes tell the FEA software to perform a more accurate analysis at the root.

The minimum factor of safety for Polycarbonate blades was 2.01 with conservative materials property values. The analysis of the blades confirmed assumptions regarding the location and magnitude of the stress concentrations.

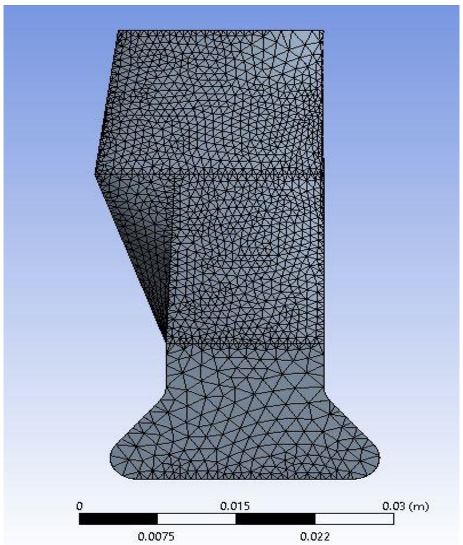

Figure 6: Blade Root Mesh

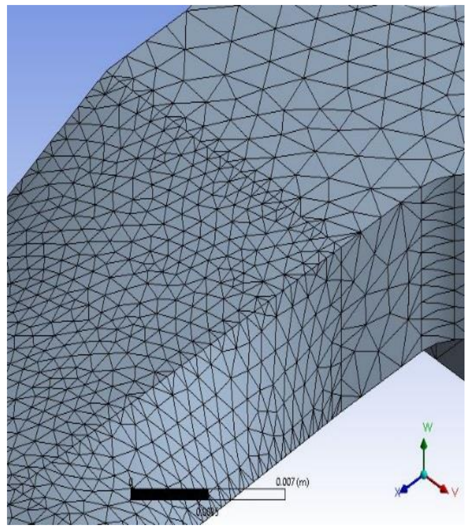

Figure 7: Concentrated Mesh at the root

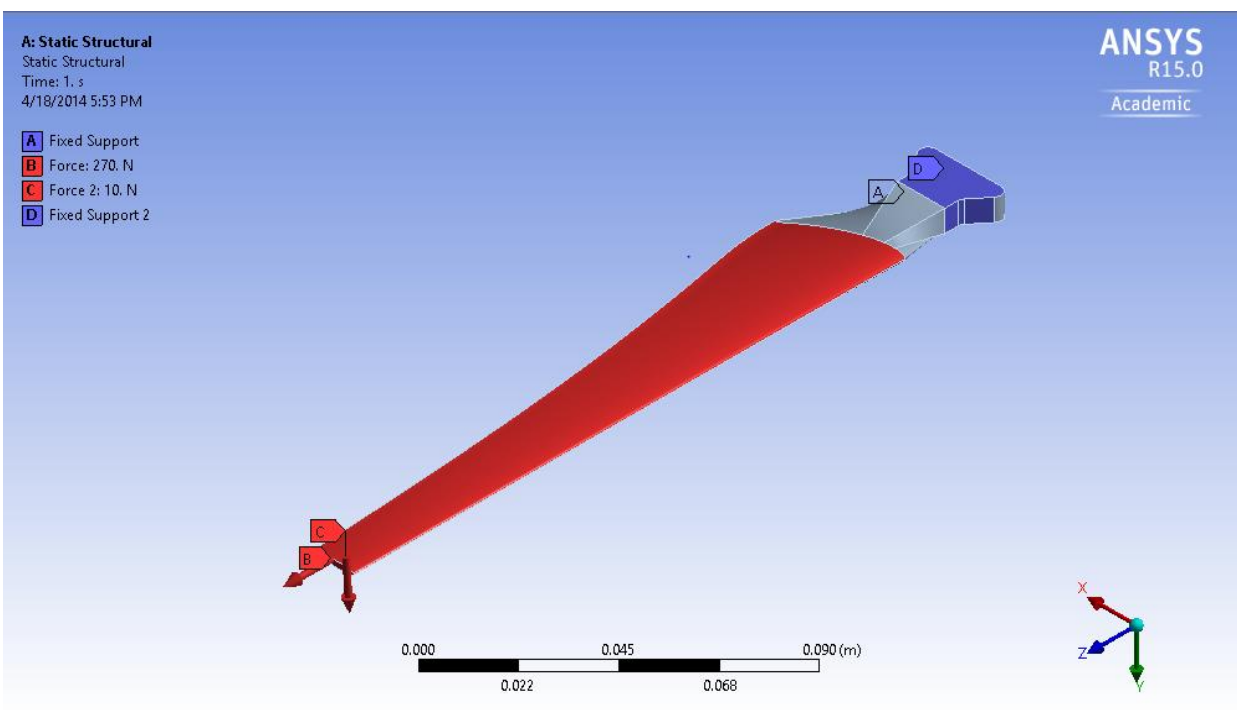

Figure 8: Force Setup

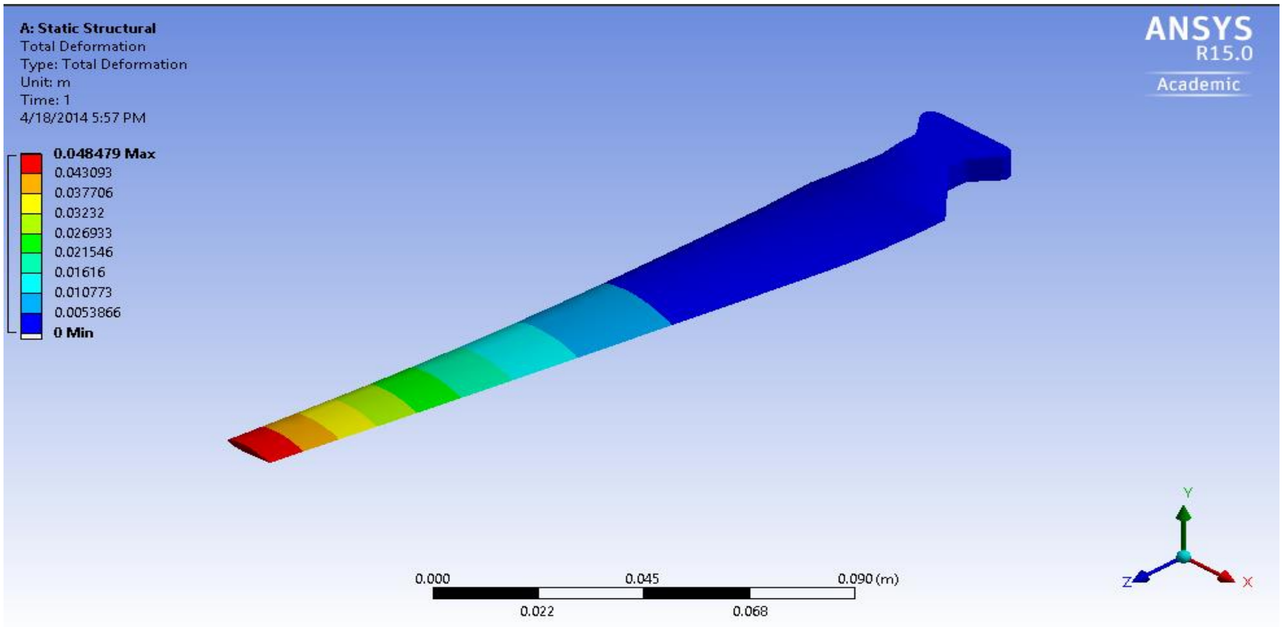

Figure 9: Deformation

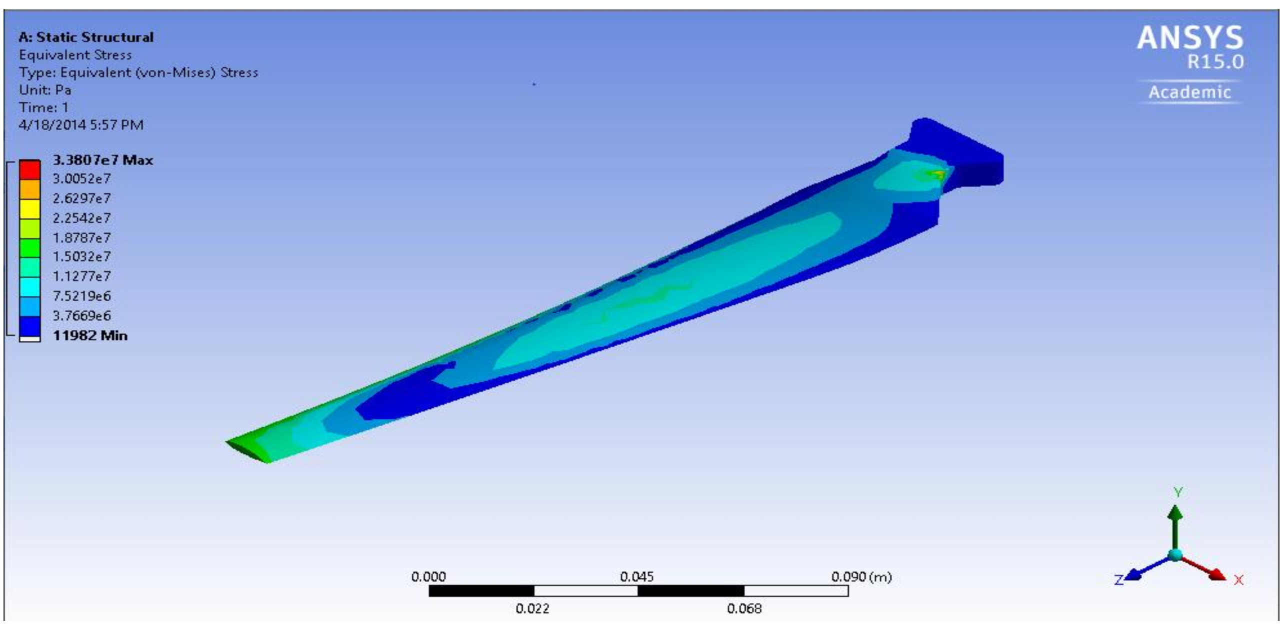

Figure 10: Equilibrium Forces

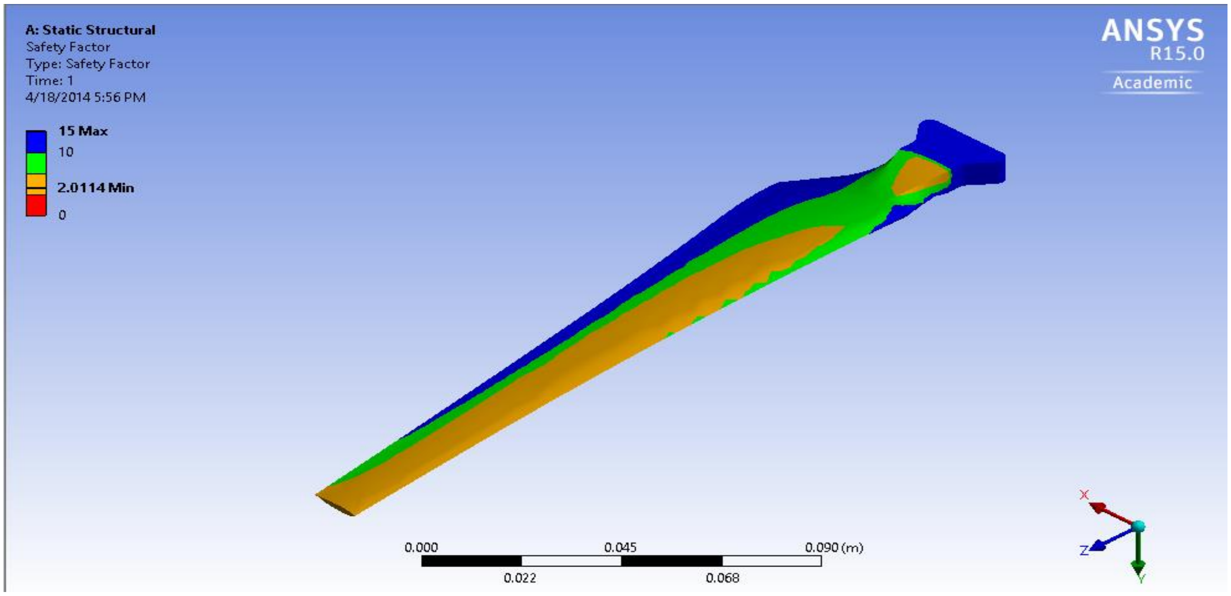

Figure 11: Factor of Safety

3.4.2 FEA on the Hub

For our numerical results, SolidWorks 2013 was utilized to model a simplified blade root and our turbine hub. The CAD files were then exported in IGES format to DesignModeler of ANSYS Workshop. Actual analysis was completed in the Mechanical ANSYS workshop program. For the hub, the mesh was created using program controlled triangular elements. The hub mesh contained roughly 25,849 nodes and 15,072 elements. The forces that were most concerning was the 471 N radial force that would create shear out of the blade root connection with the hub.

The mesh of the hub and empirical solution for forces acting are displayed in Figure 12 and Figure 13. This displays how fine the elements are analyzed and what nodes need to be focused on because they might have high stress concentrations. The directions of the forces that were applied were placed in the radial and axial directions. These force magnitude came from BEM analysis which showed the torque, moment, normal and axial forces.

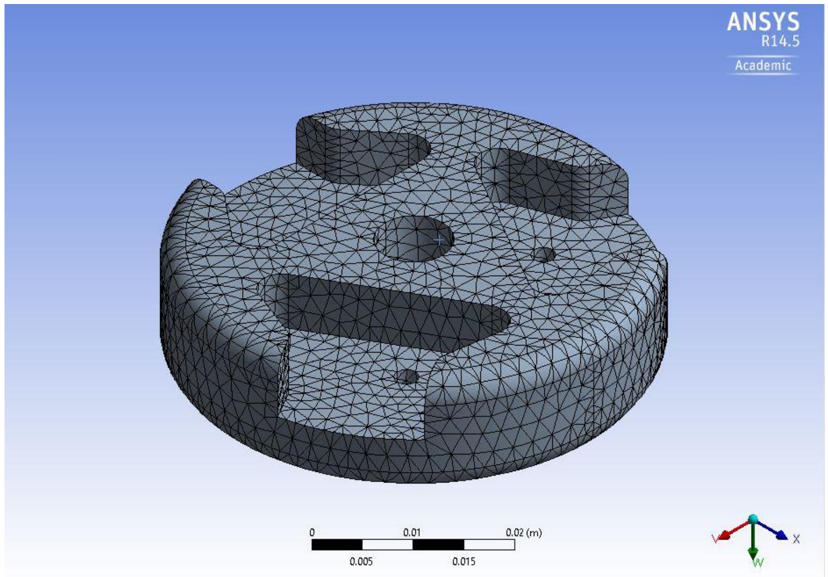

Figure 12: Mesh of Hub

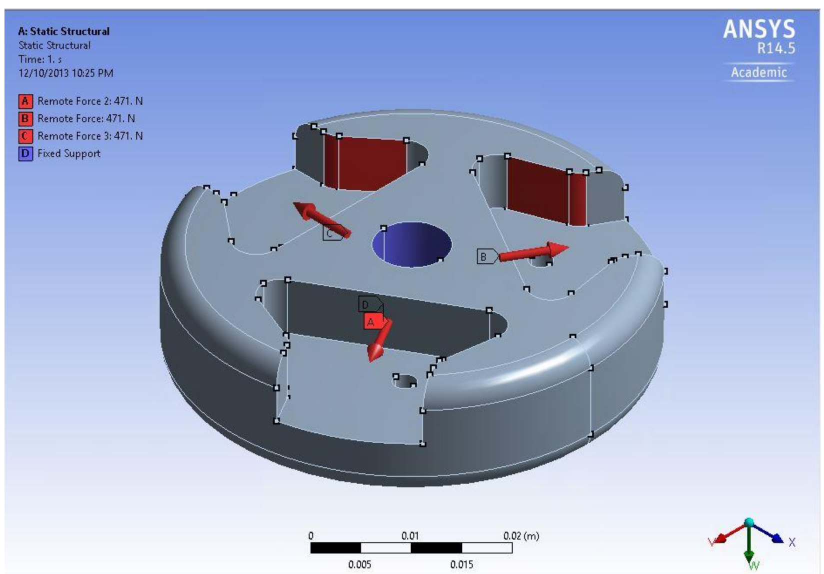

Figure 13: Force Directions and Magnitudes

Through running the FEA software, the team was able to determine a great amount about how the design will react to the forces. First, the team found that the stresses on the hub were all concentrated on the lip of the blade root slot. This is because of the great force that the blades exert when they are spinning around at the rated 4270RPM. This is shown below in Figure 14 and Figure 15.

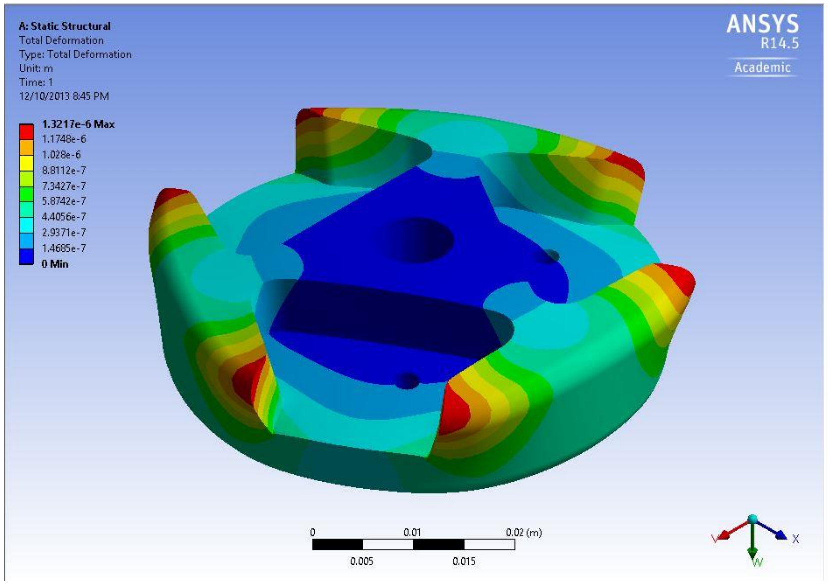

Figure 14: Equivalent Stresses of the Hub Design

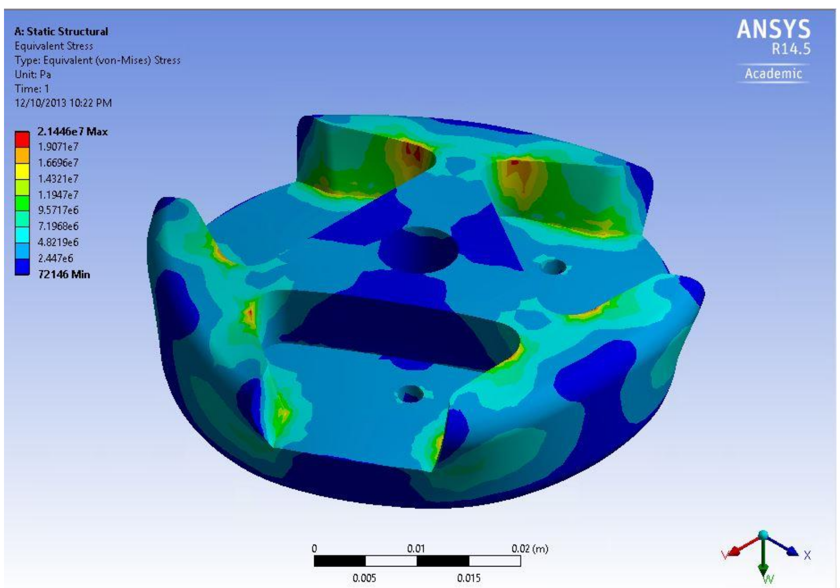

Figure 15: Equivalent Static Stresses

The factor of safety of the hub elements were also analyzed using FEA. Applying the material properties of the hub, which is Aluminum 6061, the software found that the factors of safety throughout the hub. This factor of safety was 11, indicating a strong hub design capable of overcoming radial stresses. This is shown in Figure 16.

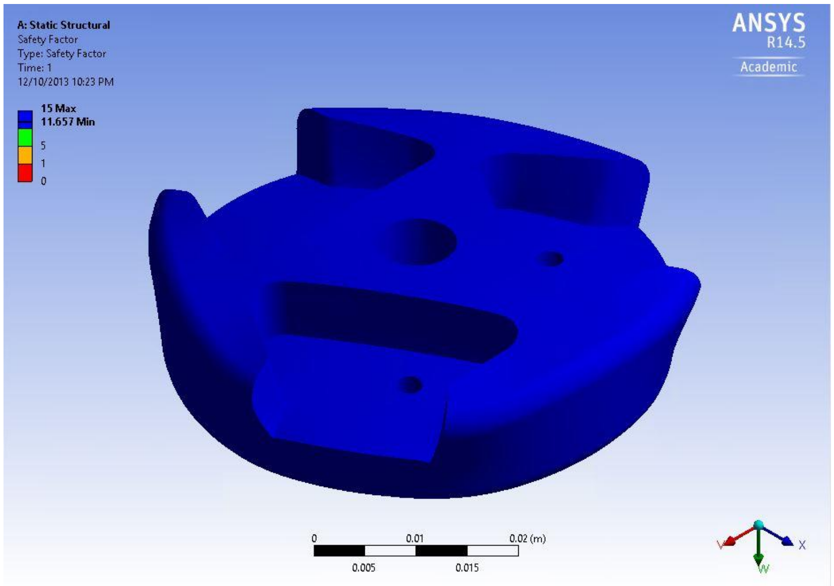

Figure 16: Hub Factor of Safety

Chapter 4: Prototype Manufacturing

4.1: Blade Manufacturing

Rapid prototyping the blades was selected for the ease of manufacturing a complex geometry that would have been beyond the capabilities of the CNC G-code used on the Tormach mills. The rapid prototyped models of the blades were manufactured through the Dimensions in SST 768 Stratasys. It's build size of 10 x 10 x 12 in^3 meant that the blades had to be printed at a slight angle on the base. Several different versions of blades were printed at varying angles and positions, and it was determined that the worst printing positions are directly vertical or horizontal. Further research was done to calculate an optimum angle for printing a blade with acceptable trailing and leading edge. The current blades are made of a Polycarbonate material. These blades were manufactured on the Fortus 400mc by Stratasys. This version of the blades have a much smoother profile due to the thinner (.07 inches) build layers. The software InSight, which generates the layers for Fortus, was able to place parts at a much more specific angles and was able to generate a view of the part before was created showing the edges of final part. Each layer thickness of materials is .01 inches thick, which was determined by the computer software Catalyst. A picture of the manufacturing process is given in Figure 17.

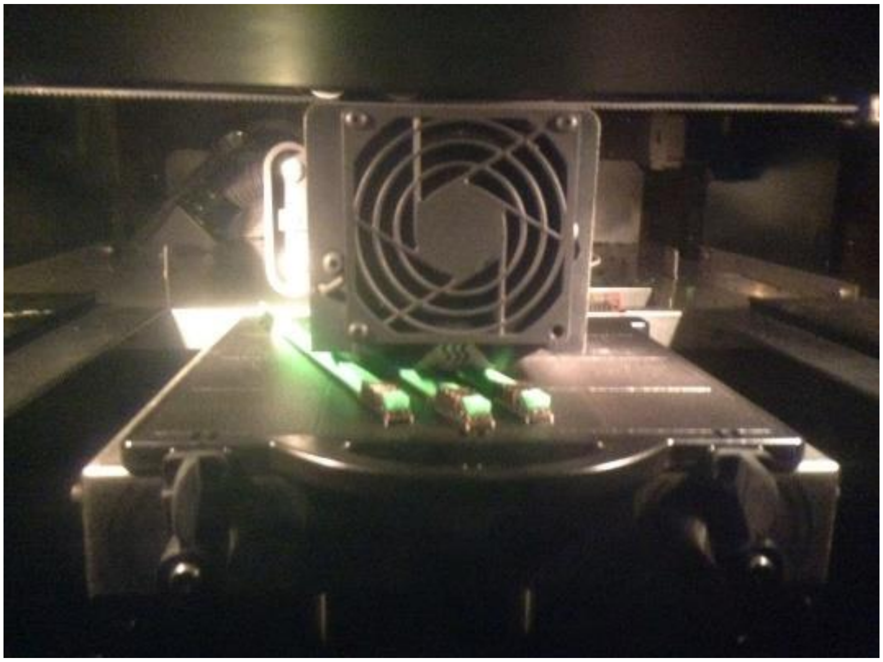

Figure17: Blade Manufacturing Process

4.2: Hub Manufacturing

Manufacturing of the hub was performed from an aluminum round bar stock with a 50.91mm diameter. A horizontal ban saw was used to cut the stock down to a workable 1 ½ inch length. Surfaced milling was performed via a 9/16 inch milling bit to insure it was level during the CNC operation. The stock was placed in a lathe and a center drill marked the position of the center of the stock. Prior to milling on the Tormach CNC the solid works file had been converted to a cad cam works file. From here the appropriated tooling had been selected and G-code developed. Safety concerns later led to the reeducation of feed rates and depth of cuts in the machine. The manufacturing process was simplified by removing all designed fillets and holes for blade orientation indication.

Each height of the four tools required in the manufacturing were measured and zeroed in the mill. The number four center drill and 19/64th inch drill were used in conjunction to develop the through hole of the cullet insert in the hub. This process took approximately three minutes. The pockets that hold the wind turbine blades were made with the .25 in end mill bit to perform initial cutting and a .19 in end mill bit for detailing. Each pocket went through multiple passes at a safe depth of cut with a total approximate manufacturing time of twenty minutes. The program was run again only using the .19 in mill bit to ensure a proper fit. Refer to Figure 18 for a picture of the manufacturing process.

Figure 18: Hub Manufacturing

Figure 3: Manufacturing Process of the hub

The stock was placed in the lathe one additional time to be cut down to its final dimensions. Additionally part of this excess material was used to manufacture a five mm thick hub plate. Later it had been discovered that the cullet opening was too small, so another drill operation was performed on the lathe with a gauge O 0.316 in bit. Weight concerns led to continued milling and turning operations. A new hub plate was reduced to a 2.40 mm thickness and the hub was milled down to its current thickness of 3.50 mm. See Figure 19 for completed hub.

Figure 19: Final Hub Design with Collet

Chapter 5: Testing and Results

5.1 Wind Tunnel Testing (on and off campus)

The team had access to two wind turbines that could help get data for an airfoil design. The one that the team has on campus is an Aerolab wind tunnel that can test airfoil sections and obtain the normal and axial forces. These normal and axial forces can be converted to the lift and drag forces using Equations 4 and 5 and shown in Figure 20. A small airfoil section was designed to get data for the final airfoil design. The designed flat plate, having a chord length of 0.5 inches and a length of ten inches, was designed with a slight camber for testing. Data was recorded for the normal and axial forces acting on the thin airfoil while wind velocity was steadily increasing. This data was recorded automatically in a LabVIEW program, then the total lift and drag force of the thin airfoil was calculated using the normal and axial forces and the angle of attack. The other wind tunnel that the team had restricted access to was from formerly known small wind turbine company, Southwest Wind Power. This wind tunnel was located off campus and the team needed supervision from Professor David Willy, project coordinator.

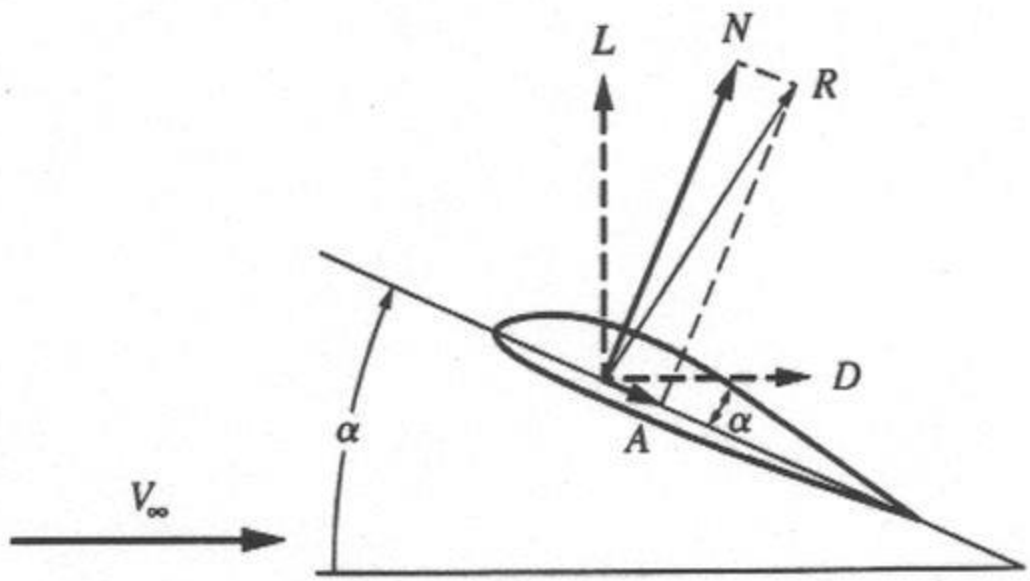

Figure 20: Lift and Drag forces on an airfoil section

$$L = N \cdot cos(\alpha) - A \cdot sin(\alpha) \quad (4)$$

$$D = N \cdot sin(\alpha) + A \cdot cos(\alpha) \quad (5)$$

Where,

α: The angle of attack

A: The axial force acting on the blade

D: The Drag force

L: The Lift force acting on the blade element

The first attempt at recording data from the turbine at south west wind power didn't produce any power under the competition requirements of positive current into a 5V load. This test had a gear box loaded onto the collet and at 17 m/s the turbine was not able to cut in. Without a gear box or generator attached the turbine was able to cut in a 4 m/s. The result of this test concluded that the turbine should not have a gear box in the final design due to the lack of feasibility in overcoming in the cogging torque.

Modifications were made to the mainframe where a test of direct drive was performed. In this set up a new shaft was designed to fit over the generator, through the frame of the gearbox used for support purposes, and out of the mainframe where the collet would clamp onto. The test results in Figure 21 demonstrate how the turbine was able to cut in at 9.6 m/s and at just under 18 m/s the turbine ramped up from 2000 rpm up to 6000 rpm. When the wind tunnel was ramped down the turbine design continued rotating until 4 m/s. Although these results had been progressive from the prior test, cut in wind speeds were nowhere near the desired 2.5 m/s.

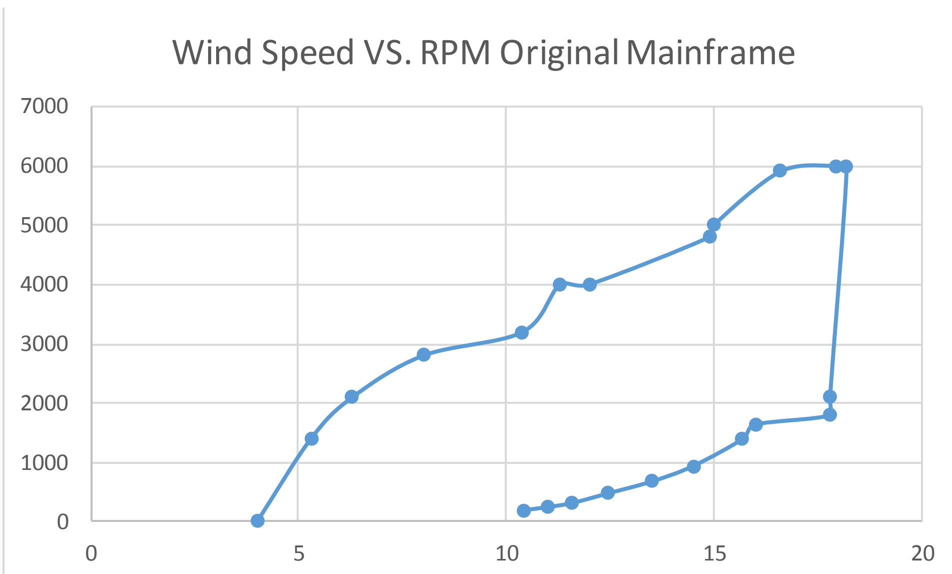

Figure 21: Wind Speed VS. RPM Original Mainframe

Further alterations were made to the mainframe. To ensure the generator was securely fixed in place a ridged structure piece was implemented to hold the generator, shaft and rotor. A new rectifier had also been equipped into the rpm sensor. A design concept for a three blade adapter, manufactured out of PVC pipe, was developed to be retrofitted the polycarbonate blades.

For purposes of observing how the turbine would perform with the mainframe adjustments, the 3 bladed polycarbonate blade system was tested once again. For concept check the blades were tested in both an upwind and downwind orientations. Improvements in performance, as well as a close correlation of results between upwind and downwind orientation, had been observed. The downwind setup produced 12.88 watts at 18.5 m/s and the upwind set up was able to produce 13.68 watts at 18.2 m/s, see Figure 22 for full results. Although the 6 blade concept was able to cut in at 6.8 m/s, rpms values from initial test were significantly reduced, see Figure 23 for results.

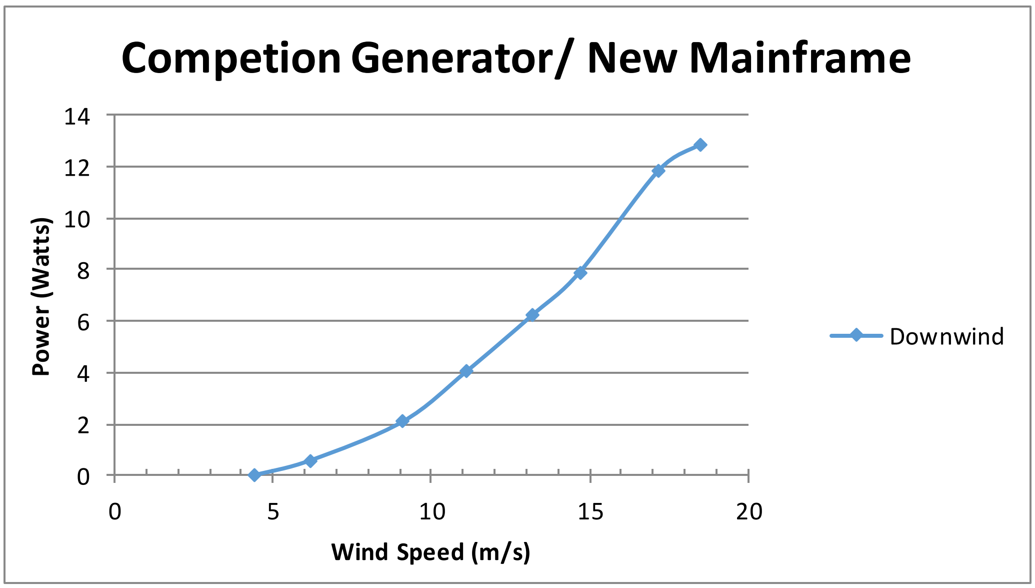

Figure 22: Competition Generator/ New Mainframe

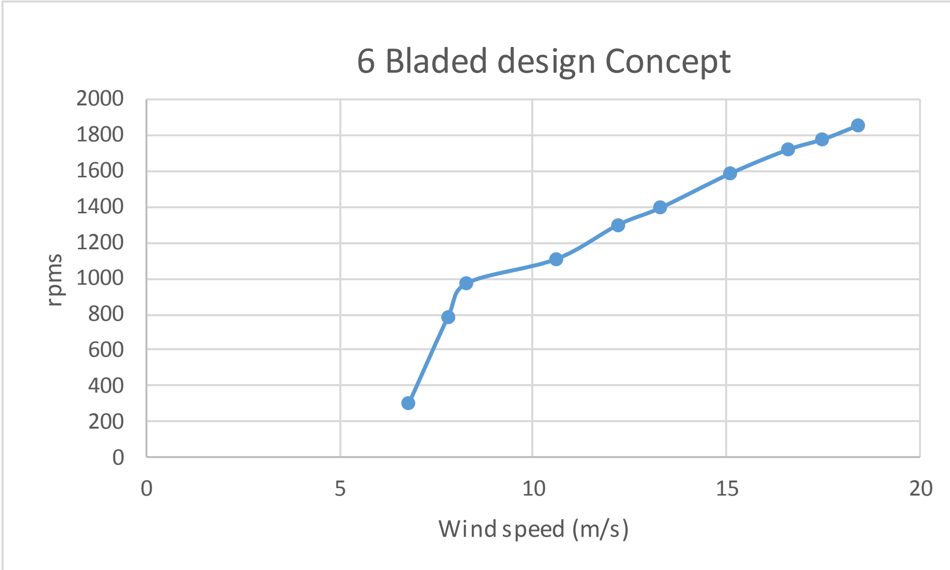

Figure 23: 6 Bladed design Concept

After several wind tunnel tests had been performed it had been observed that the generator DOE assigned the team as a design constraint was not the best fit for the competition requirements. Collaboration with other schools participating in this wind energy competition confirmed the lack of suitability the assigned generator had in meeting the expectations of competition. From this an idealized generator was scoped out, tested and incorporated into the business plan. A generator was found with an improved kv rating and increased number of poles to help with the cogging torque issue. Testing of the new generator had proved the incompetency of the DOE selected generator. Testing of a direct drive system with the three bladed polycarbonate system demonstrated a 6.7 m/s cut in wind speed and a max power output of about 44.5 watts, see figure 24 for results.

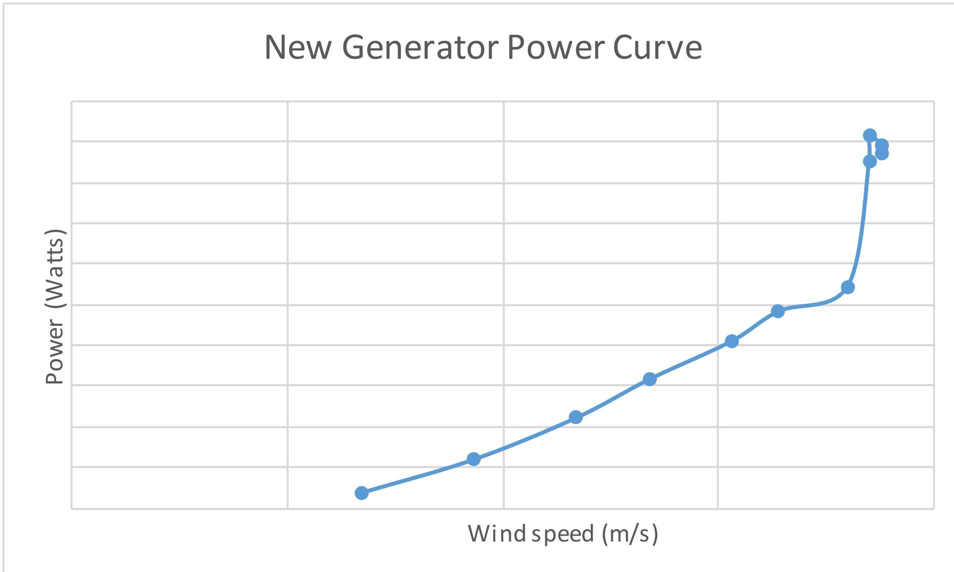

Figure 24: New Generator Power Curve

Chapter 6: Cost Analysis/ Acknowledgement

Through the generosity of NAU and external organizations, manufacturing the rotor came from donated materials and labor. The project must acknowledge the support of the NAU machine shop, NAU mechanical engineering department, NAU business department, Novakinetics associates, and Southwest Windpower. Specifically, Chris Bennett, Emerson Jones, Nick Jurik, Tom Cothrun, Kevin Montoya, and Perry Wood from NAU machine shop assisted in many manufacturing processes as well as manufacturability. David Calley and other Southwind associates helped in concept generation and provided access to wind tunnel testing. Jim Corning from Novakinetics helped guide concept generation as well. In summary, the aid of these generous individuals allowed for low cost development. In practice, the business calls for injection molding processes for the blades while cast aluminum is required for the hub manufacturing.

Chapter 7: Conclusions

The team developed a micro wind turbine in an effort to meet the business plan. As presented earlier, this turbine was designed to operate in coastal and central plain regions of the U.S. A design power of 14 W at 18 m/s was originally designed and proven possible through wind tunnel testing. Following initial testing, a new generator was chosen by the electrical team to better meet the constraints of the business plan while still using the same final rotor design. This design will be capable of charging small electronics with use of a battery. In the end, there are limitations for the implementation of this design in the wind energy industry. Nonetheless, this project developed a new market for wind turbines, and allowed students to explore aerodynamics, multidisciplinary design theory, numerical engineering solutions for stress and aerodynamic analysis, and team communication.

7.1: References

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[2] Spera, D.A. (ed.) (2009) Wind Turbine Technology: Fundamental Concepts in Wind Turbine Engineering, 2nd edn, ASME Press.
[3] Corning, Jim. Personal Interview/Field Trip. December 6th, 2013
[4] Gipe, P., *Wing Power: Renewable Energy for Home, Farm, and Business*, Chelsea Green Publishing, ISBN: 978-1931498142, 2004.
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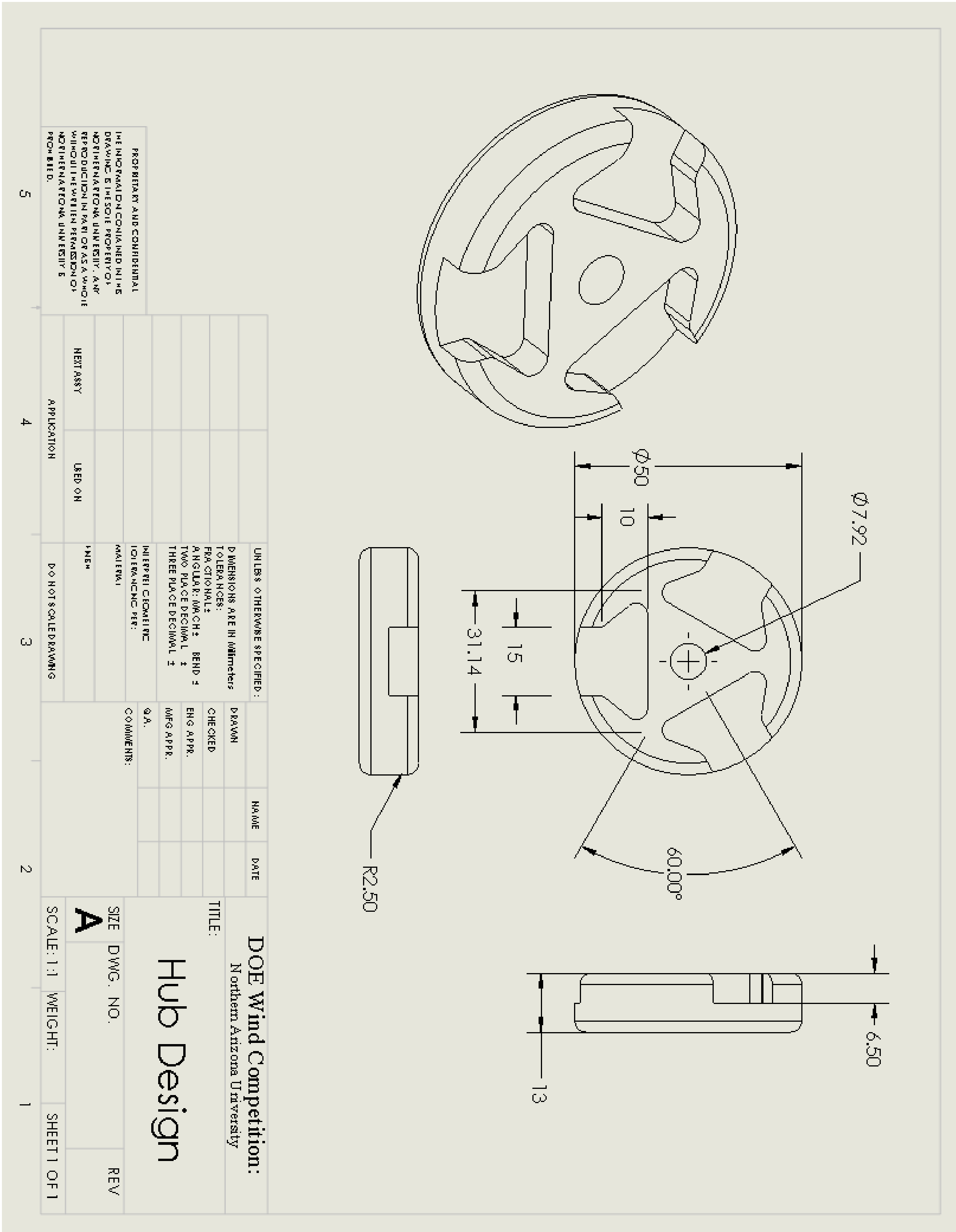
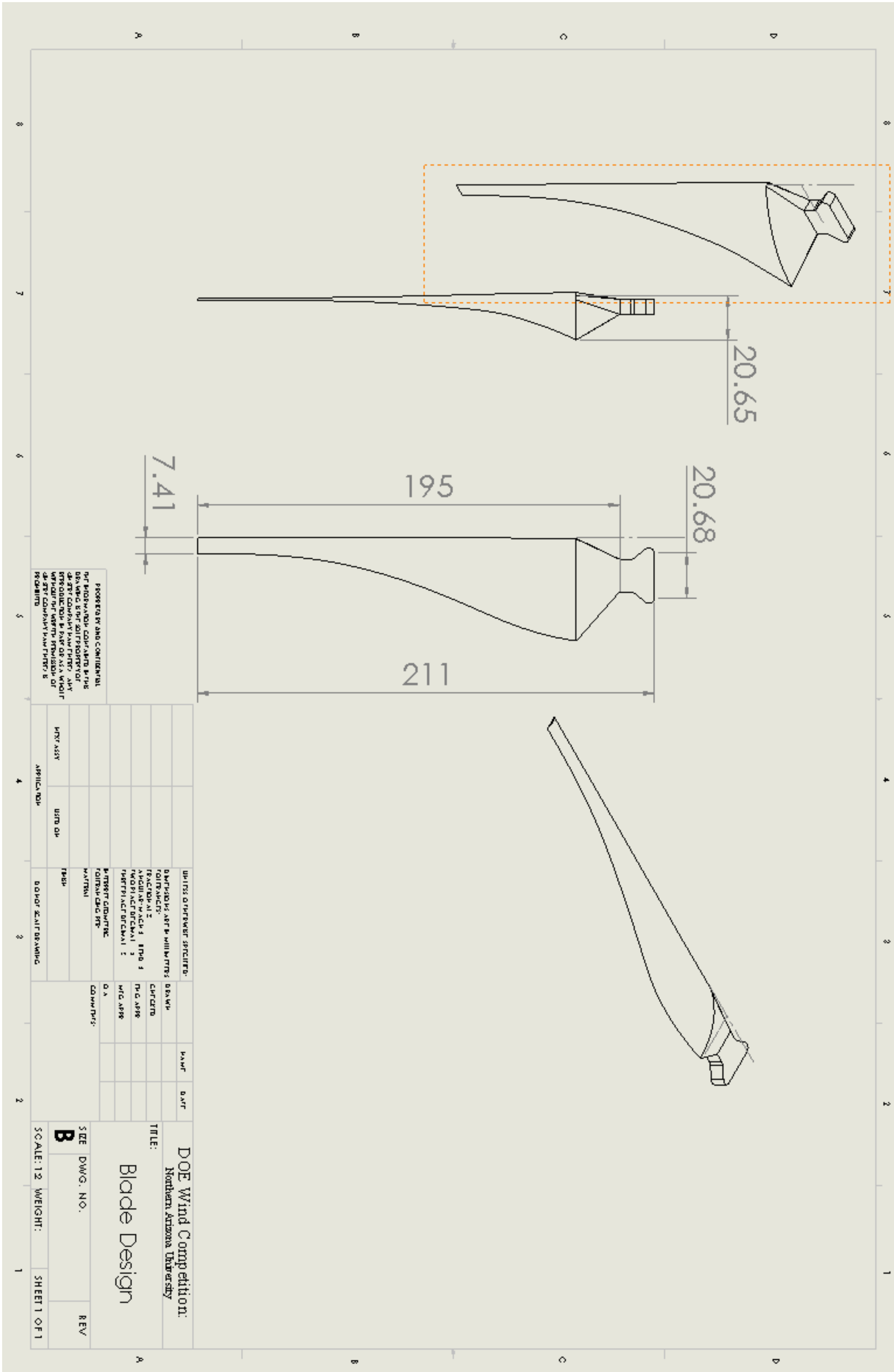
Appendix A


DOE Wind Competition:
Northern Arizona University
TITLE:
Hub Design
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN Millimeters
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
Ø50
Ø7.92
10
15
31.14
60.00°
R2.50
6.50
13



20.65
7.41
195
20.68
211
DOE Wind Competition:
Northern Arizona University
TITLE:
Blade Design
SIZE
B
DWG. NO.
REV
SCALE: 1:2 WEIGHT:
SHEET 1 OF 1

Appendix B: BEM code

```
% The following is a BEM code that can build its own blade shape of that
% will take a precisting shape in the form of a matrix.
% All angles are in degrees
% All unites are in metric
% B is number blades
% N is number of sections
% thetap is the starting pitch
% alpha is the angle of attack for the builder only
%Cl is lift coeficant for the builder only
%R is the radis of the blade

function [cp,didntwork]=bem2(lambda,thetap,B,R,N,h)

%below is the function call to make a ideal blade with wake
mm=xlsread('S809_CLN.xls');
cl001=mm(:,2);
cd001=mm(:,3);
alpha001=mm(:,1);
fuck=cl001./cd001;
shit=max(abs(fuck));
bumsin=find(abs(fuck)==shit);
alpha=alpha001(bumsin);
Cl=cl001(bumsin);
cd=cd001(bumsin);
```

```
[c,a,ap,theatt,r,lambdar,sigpd]=bladewake(R,N,lambda,alpha,thetap,B,Cl,h);



%storage for outputs
Fstore=zeros(1,length(r));
astore=zeros(1,length(r));
apstore=zeros(1,length(r));
phistore=zeros(1,length(r));
Cl1store=zeros(1,length(r));
Cdstore=zeros(1,length(r));
alphastore=zeros(1,length(r));
ctstore=zeros(1,length(r));



wtf=0; %counting vairable:number of iterations
  didntwork=0;%counting vairable, how many times did it not converge
  alpha001=round(alpha001);



for ii=1:length(r) %loop for each section
    for jj=1:9000 %iterater begins

        %calculate angle of relitive wind
        phi=atand((1-a(ii))/((1+ap(ii))*lambdar(ii)));
                 %calculate alpha
         alpha1=phi-theatt(ii)-thetap;
```

```
        %edit here to insert cl function or lookup

        hi=find(alpha001>=alpha1);

        hell=find(alpha001<=alpha1);


        low=cl001(hell(end));

        high=cl001(hi(1));

        percentage=(alpha1-alpha001(hell(end)))/(alpha001(hi(1))-
alpha001(hell(end)));


        Cl1=percentage*(high-low)+low;





        sigp=sigpd(ii);


        %edit here to insert cd function or lookup

        Cd1=percentage*(-cd001(hell(end))+cd001(hi(1)))+cd001(hell(end));


        %tip loss to be change depending on if ideal on not

            %not ideal

        F=(2/pi)*acos(exp(-1*((B/2)*(1-r(ii)/R)/((r(ii)/R)*sind(phi)))));

            %ideal

        %F=1;
```

```
%calculate thrust coefficent
ct=sigp*(1-a(ii))^2*(Cl1*cosd(phi)+Cd1*sind(phi))/((sind(phi))^2);

%normal case, means a<4
if ct <= .96
    %use normal a eqaution to calculate new a
    anew=1./(1+(4*F*sind(phi)^2/(sigp*Cl1*cosd(phi))));
         %abnormal case a>4
else
    %use the following a equation for anew
    anew=(1/F)*(.143+sqrt(.0203-.6427*(.889-ct)));

end
%calculate ap new
apnew=1./((4*F*cosd(phi))./(sigp*Cl1)-1);

%find the differance between the two
z=abs(apnew-ap(ii));
x=abs(anew-a(ii));

%reset a and ap to the new values
a(ii)=anew;
ap(ii)=apnew;
wtf=wtf+1;

%find out if we are done iterating
```

```
        if z<=.01 && x<=.01

            %storage
            Fstore(ii)=F;
            astore(ii)=a(ii);
            apstore(ii)=ap(ii);
            phistore(ii)=phi;
            Cl1store(ii)=Cl1;
            Cdstore(ii)=Cd1;
            alphastore(ii)=alpha1;
            ctstore(ii)=ct;
            %end while loop
            break
        elseif wtf ==1999
            didntwork=didntwork+1;
          %count the number of times it failed


        end
    end
end
didntwork
%below is the just a for loop to do the intergurl (also can be done with
%sum()
cpsave=0;
%cpstore=[];
for zz=1:length(r)
```

```
 cp1=Fstore(zz) * sind( phistore(zz) )^2 * (cosd( phistore(zz) ) - ...

     lambdar(zz) * sind( phistore(zz) )) * ( sind( phistore(zz) )...

     + lambdar(zz) * cosd( phistore(zz) )) * (1-(Cdstore(zz)/Cl1store(zz))...

 / tand( phistore(zz) )) * lambdar(zz)^2;



 cpsave=cpsave+cp1;

 end

%outputs

%cpsec=(8/(lambda*N))*cpstore;

dr=(R-h)/N;

dfn=ctstore.*.5.*1.225.*17^2.*2*pi.*r.*dr;

Fn=sum(dfn/B)

dQ=sigpd.*pi.*1.225.*(17^2.*(1-
a).^2/(sind(phistore)).^2).*(Cl1store.*sind(phistore)...

     -Cdstore.*cosd(phistore)).*r.^2.*dr;

Q=sum(dQ./(B))

disp([r',c', theatt', astore'])

cp=(8/(lambda*(N+1)))*cpsave;

end


%below is the fuction to build an ideal blade with wake

function
[c,a,ap,theatt,r,lambdar,sigpd]=bladewake(R,N,lambda,alpha,thetap,B,Cl,h)

dr=(R-h)/N;

r=h:dr:R-dr;

r=r+.5*dr;


lambdar=lambda*r/R;
```

```
phi1=(2/3)*atand(1./lambdar);


theatt=phi1-alpha-thetap;

c=8*pi.*r.*(1-cosd(phi1))./(B*Cl);

sigpd=B*c./(2*pi*r);

a=1./(1+(4*sind(phi1).^2)./(sigpd.*Cl.*cosd(phi1)));

ap=(1-3*a)./(4*a-1);

end
```

Appendix C: XY coordinate generation

```
function [dx]=xy(lambda,thetap,B,R,N,h)


m=textread('s818xy.txt'); %airfoil data x/c , y/c

mm=xlsread('S818_2703.xls'); %lift drag data

cl001=mm(:,2);  % retrive data

cd001=mm(:,3);

alpha001=mm(:,1);

liftdragmax=cl001./cd001; %find the highest lft/drag and locate it

highestvaule=max(abs(liftdragmax));

location=find(abs(liftdragmax)==highestvaule);

alpha=alpha001(location);

Cl=cl001(location);

cd=cd001(location);


%below is the function call to make blade shape

[c,a,ap,theatt,r,lambdar,sigpd]=bladewake(R,N,lambda,alpha,thetap,B,Cl,h);


%multiply by cord and convert to mm

xc=m(:,1);

yc=m(:,2);

x=xc*c*1000;

y=yc*c*1000;


%factor in the twist

for ii=1:length(c)

y(:,ii)=y(:,ii).*cosd(theatt(ii))+x(:,ii).*sind(theatt(ii));
```

```
x(:,ii)=x(:,ii).*cosd(theatt(ii))-y(:,ii).*sind(theatt(ii));

end

%create z direction vectors

z=ones(length(xc),1)*r*1000;




%graph it to make sure it worked

dx=surf(x,z,y);


%round to 3 decamiles

y=round(y*1000)/1000;

x=round(x*1000)/1000;

xyz=[];

%put in one matrix

for ii=1:length(c)

     xyz=[xyz,x(:,ii),y(:,ii),z(:,ii)];

end

location=[r;c;theatt];

%outputes

xlswrite('bladedout',location)

xlswrite('outputs818',xyz)

end


function
[c,a,ap,theatt,r,lambdar,sigpd]=bladewake(R,N,lambda,alpha,thetap,B,Cl,h)

dr=(R-h)/N;

r=h:dr:R;
```

```
lambdar=lambda*r/R;

phi1=(2/3)*atand(1./lambdar);


theatt=phi1-alpha-thetap;

c=8*pi.*r.*(1-cosd(phi1))./(B*Cl);

sigpd=B*c./(2*pi*r);

a=1./(1+(4*sind(phi1).^2)./(sigpd.*Cl.*cosd(phi1)));

ap=(1-3*a)./(4*a-1);

end
```