

AAE 415 – Aerodynamic Design

Prof. John P. Sullivan

Aerodynamic Design of a Large Horizontal-Axis Wind Turbine

Final Project Report

Ted Light & Jeffrey Robinson

December 19th, 2003

I. Introduction

This report describes the aerodynamic design project undertaken to analyze and optimize the performance of a large horizontal-axis wind turbine. The analysis began with the modeling of an existing wind turbine with documented geometry and performance, and then continued with the variation of several geometric characteristics in order to improve its performance. This process enabled an understanding of some of the fundamentals of wind turbine design. By changing these aerodynamic properties, an improved design was reached.

II. Background

For thousands of years, the wind has provided energy to mankind. The wind has allowed ships to sail from place to place, and it has turned windmills which allowed the grinding of grain and the pumping of water. The first windmills were primitive and caught as much air as they could pointing in only one direction and using simple, straight, non-aerodynamic blades; nonetheless, they did what no other machines had done before.

However, actual power generation using windmills did not occur until the end of the 19th century. The advancement

of this technology was slow, especially with the rapid industrialization taking place in Europe and the United States. As oil prices fell in the 20th century, wind energy became a less attractive energy source. As such a new technology, wind turbines were expensive to develop and build,



and even though the wind itself was free, wind power was still too unreliable to take the place of fossil fuels.

Not until the Oil Crisis of the 1970s, when gasoline and other petroleum products were very limited and expensive, did serious interest in wind turbine technology once again emerge. Since then, wind power has become one of the fastest growing energy sources in the world. Constant improvements in aerodynamics, structures, and generators have led to more efficient wind turbines outputting more power than ever.

Their use is not only limited to large-scale, commercial energy production. Some small wind turbines are used in homes, for pumping water, or powering satellite and telecommunications dishes. Sometimes they are even used in connection with diesel generators, batteries, and solar power systems. Systems such as these are known as hybrid wind systems and typically are found in remote locations where outside electric power cannot be utilized.³

However, it is in these large, commercial utility wind turbines that much technological improvement has taken place. In addition to individual turbine improvements, changes in the wind turbine's size and the total number being used have increased dramatically over recent years. Today's large wind turbines are sometimes more than a hundred meters in diameter and could be only one of tens or hundreds of wind turbines, all being used together to form a "wind energy power plant."

Size is only one design consideration for wind turbines. The number of turbine blades varies between wind machines, along with the blade's aerodynamic properties, such as taper, twist, and cross-sectional shape. Other advances in wind turbine technology continue today, leading to more powerful and more efficient wind turbines, which will be used to power more of the world in coming years.

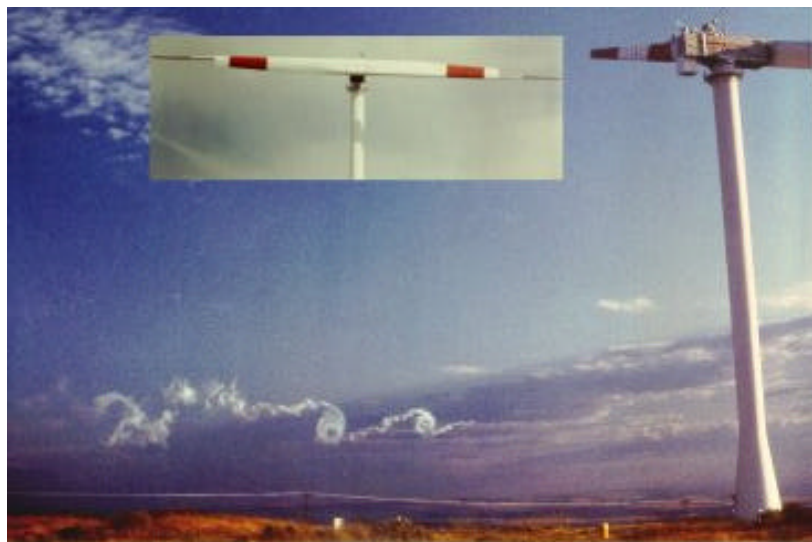
III. Procedure

The problem undertaken is the aerodynamic design of a large horizontal-axis wind turbine. To serve as a baseline for comparison purposes, a turbine with established geometry and performance data was found. This turbine was the Mod-2 wind turbine, built by Boeing in the late 1970s. Table 1 gives the geometry and operational data of the turbine, while Figure 1 is a photograph of the Boeing Mod-2 wind turbine.

Table 1: Mod-2 Wind Turbine Information

Diameter [m]	91.4
No. of Blades	2
Airfoil Section	NACA 23024
Tip Pitch [deg]	-4.0
Root Pitch [deg]	2.55
Tip Chord [m]	1.43
Root Chord [m]	3.45
Wind Speed, V_0 [m/s]	12.5
Rotational Rate [rpm]	17.5
Power Output [MW]	2.5

Figure 1: Photograph of the Boeing Mod-2 Wind Turbine



This turbine's geometry was modeled using CMARC, and then further modified to attain improved performance. The diameter, rotational rate, wind speed, and number of blades were kept constant, however, to keep the comparisons similar. The turbines were also considered to be constant-speed turbines, since our analysis required a constant rotational rate. Since many turbines in use today are constant-speed turbines, this was not an unreasonable assumption.

The objective of design improvements was therefore to increase the power output by the wind turbine. The power output of the turbine is given by the simple equation,

$$(\text{Power}) = (\text{Torque about rotational axis}) \cdot (\text{Rotational Rate}) \quad (1)$$

The rotational rate was kept constant at 17.5 rpm and the moment about the rotational axis was calculated by the 3D analysis tool CMARC. Research was conducted to formulate ideas on how to improve upon the geometry of the wind turbine. These are discussed below.

An expression for the optimal chord length was given by Reference 2. It gives the optimal chord length based upon the number of turbine blades B , their radius R , and the tip speed ratio λ , which is the linear speed of the blade tips divided by the wind speed. The expressions for chord length and tip-speed ratio are given as Equations (2) and (3), respectively.

$$c = \frac{16p R(R/r)}{9I^2 B} \quad (2)$$

$$\lambda = R\Omega/V_0 \quad (3)$$

Taking five equally spaced control points located at the root, $0.25R$, $0.50R$, $0.75R$, and at the tip, the optimal chord distribution as defined in Equation (2) was calculated; this distribution is given in Table 2.

Table 2: Ideal Chord Lengths

r/R	Ideal Chord (m)
0.00	15.00
0.25	11.40
0.50	5.70
0.75	3.80
1.00	2.85

Note that the Equation (2) is not valid for the first control point where $r/R = 0$, so what was thought to be a reasonable value was substituted.

Reference 1 also gives expressions for optimal wind turbines based upon Glauert's optimal rotor theory. Here the optimal blade layout is given product of the chord c and sectional lift coefficient c_l .

$$\left(\frac{B\Omega}{8\rho V_0} \right) (c c_l) = \left[\frac{(4a-1)}{(1-2a)} \right] \sqrt{(1-a)(1-3a)} \quad (4)$$

In Equation (4) above, a is the axial interference factor, which can be approximated by the following power series as a function of the local speed ratio, $x = r\Omega/V_0$.

$$a = \left(\frac{1}{3} \right) - \left(\frac{2}{81x^2} \right) + \left(\frac{10}{729x^4} \right) - \left(\frac{418}{59049x^6} \right) + \dots \quad (5)$$

These relations were the basis for many of the design changes. The chord and twist values that were used for the design iterations are tabulated below in Table 3 and Table 4, respectively.

Table 3: Chord Distributions for Design Iterations

Chord Changes (values in meters)			
r/R	(1)	(2)	(3)
0.00	15.00	14.00	10.00
0.25	11.40	11.40	8.00
0.50	5.70	7.00	6.00
0.75	3.80	3.80	4.00
1.00	2.85	2.85	2.00

Table 4: Twist Distributions for Design Iterations

Twist Changes (values in deg from wind axis)			
r/R	(1)	(2)	(3)
0	6.1	6.0	5.5
0.25	66.7	27.8	83.5
0.5	83.4	49.5	89
0.75	93.8	71.3	90
1	111.6	93.0	92

Our best turbine, which had the highest power output, included the chord distribution listed as Chord Change (3) above, as well as the twist change listed as Twist Change (1) above. Chord Change (3) was a linear taper approximately over a range of values given by the optimal chord length equations above. Twist Change (1) was found by substituting the same chord distribution into Equation (4) above, and assuming a lift curve slope equal to $2p$. One can see that in this twist distribution, the blade's tip actually twists back beyond the plane of rotation by more than 20 degrees. It seems suspicious that this distribution resulted in the highest calculated power output. This is due to the fact that the blade has a pitch greater than 90 degrees, and it will actually work against the rest of the rotor by lifting in the opposite direction and take power out of the entire wind turbine system. The surprising result obtained from CMARC raised the question as to whether CMARC itself was an accurate analysis tool.

IV. Analysis of Results

Beginning with the Mod-2 baseline model, several modifications were made. With each change, the moment about the rotational axis was computed and used to calculate the power output in kilowatts. This respective power output was then compared to the baseline model in order to establish if the modification was beneficial or not. Table 5 gives the results of all of the design iterations. For each model, the model number is given, with a brief description of the modification, as well as with the power output its relative change from the baseline.

Table 5: Design Iteration Results

Model #	Description	Power (kW)	D from Baseline
Mod-2	Baseline Model	5816	---
Mod-A	Airfoil Changed to NACA 65 ₁ -012	5516	-12%
Mod-B	Airfoil Changed to NACA 65-410	6179	15%
Mod-C	Airfoil Changed to Althaus AH 93-W-145	2551	-131%
Mod-D	Chord Change (1) from Mod-B with no sweep	8914	124%
Mod-E	Chord Change (2) from Mod-B with no sweep	8442	105%
Mod-F	Chord Change (3) from Mod-B with no sweep	7872	82%
Mod-G	Chord Change (3) from Mod-B with sweep	9380	143%
Mod-H	Twist Change (1) from Mod-G	10367	182%
Mod-I	Twist Change (2) from Mod-G	7849	81%
Mod-J	Twist Change (3) from Mod-G	7735	77%
Mod-2 Rating	Published Power Rating	2500	

After several modifications to specific elements (i.e., airfoil shape, chord distribution, etc.), the best design was kept and used in later models. An example of this method is shown when several different airfoils were tested in the models Mod-A through Mod-C. Of these options, the NACA 65-410 was chosen to be the best airfoil section, based on power output values in the Table 5. This was then chosen to be the airfoil used in subsequent modifications, and ultimately it was chosen for the final design.

After the airfoil shapes were tested and the best kept for further testing, the chord distribution was altered in hopes that a more optimal design could be found. As was discussed in the previous section, the initial chord distribution was obtained using Equation (2). The chord distribution was modified twice more; the distributions are shown in Table 5. Again, the best chord distribution was kept and used for later modifications.

Finally, the twist distribution was modified in a similar fashion to that of the airfoil section and the chord distribution. Twisting the blade along the length allowed the angle of attack to be optimized, depending on the relative wind that a given portion of the blade would “see.” Also, by changing the angle of attack, the lift was maximized, increasing the rotational moment and ultimately the power output.

Using these modifications, a highly optimized, final wind turbine blade design could be made. This blade design used the NACA 65-410 airfoil section, was approximately 45.7 meters long,

with a chord length of 10 meters at the root, tapering linearly to 2 meters at the tip. The blade was highly twisted, with the root directed into the natural wind direction and the tip approximately aligned with the plane of rotation; the blade underwent a major initial change in pitch—60 degrees in pitch in the first 25% of the blade length.

This design created a moment about the rotational axis of 2.83×10^6 N-m. Substituting this value into Equation (1), along with the given rotation rate of 17.5 rpm (1.833 rad/sec), the power output was computed to be 10367 kW.

The theoretical limit of the maximum amount of power that can be extracted from a wind turbine is known as the Betz limit and is approximately 60%. Given that limit, an analysis is possible to see if the amount of power that can be extracted from the wind has been overpredicted. The kinetic energy in the wind is given by

$$KE = \frac{1}{2} \rho \left(\frac{P D^2}{4} \right) V_0^2 \quad (6)$$

The power available can then be shown to be equal to the kinetic energy of the wind multiplied by its velocity and the Betz limit.

$$\begin{aligned} P &= 0.6 \cdot V_0 \left(\frac{1}{2} \rho \left(\frac{P D^2}{4} \right) V_0^2 \right) = 0.3 \cdot \rho \left(\frac{P D^2}{4} \right) V_0^3 \\ &= 0.3 \cdot 1.225 \frac{kg}{m^3} \left(\frac{P \cdot (91.4 m)^2}{4} \right) \left(12.5 \frac{m}{s} \right)^3 = 4.709 MW \end{aligned} \quad (7)$$

Therefore, from the above calculation, the maximum theoretical output of a wind turbine, using the final design's given size and wind speed is approximately 4.7 megawatts.

A picture of our final turbine is shown in Figure 2. The changing chord length and twist distribution along the blade can easily be seen.

Figure 2: Final Wind Turbine Blade Design

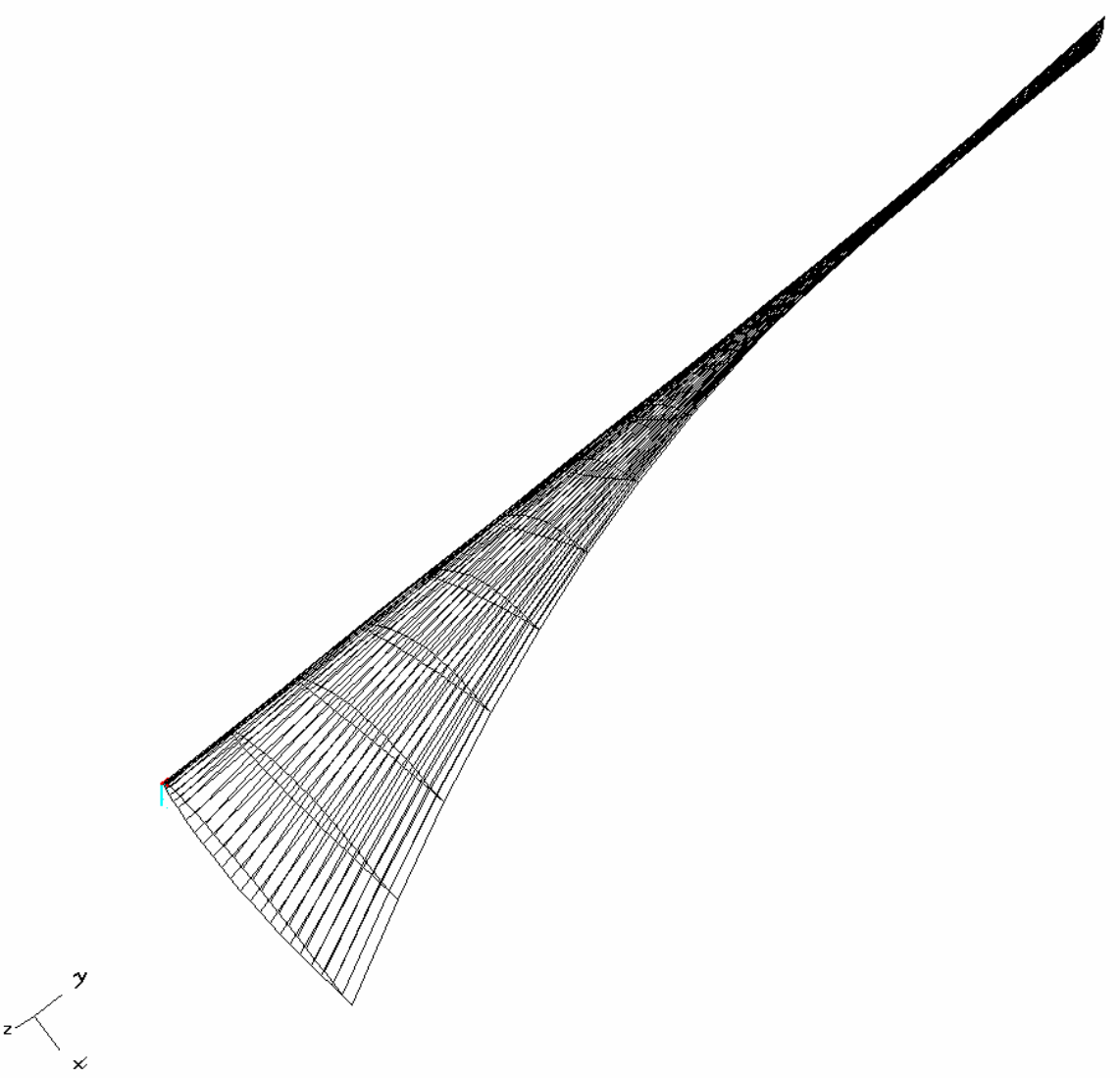
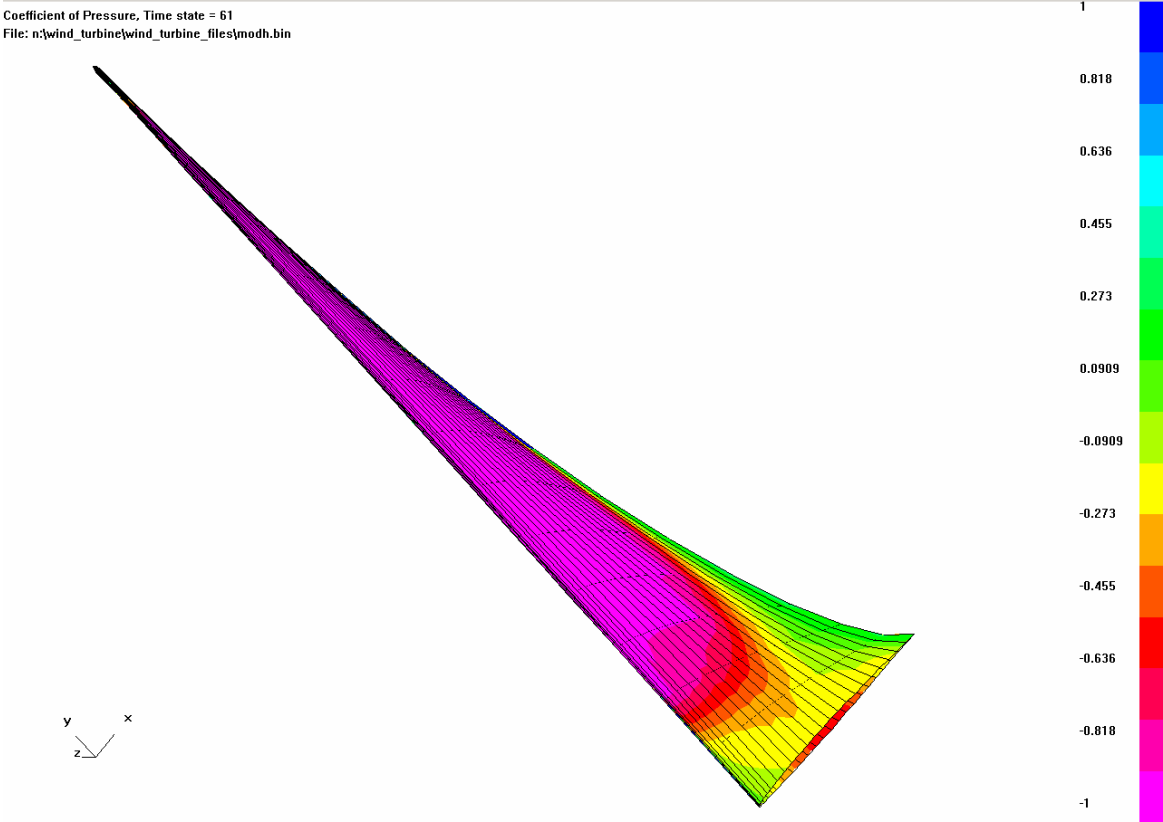


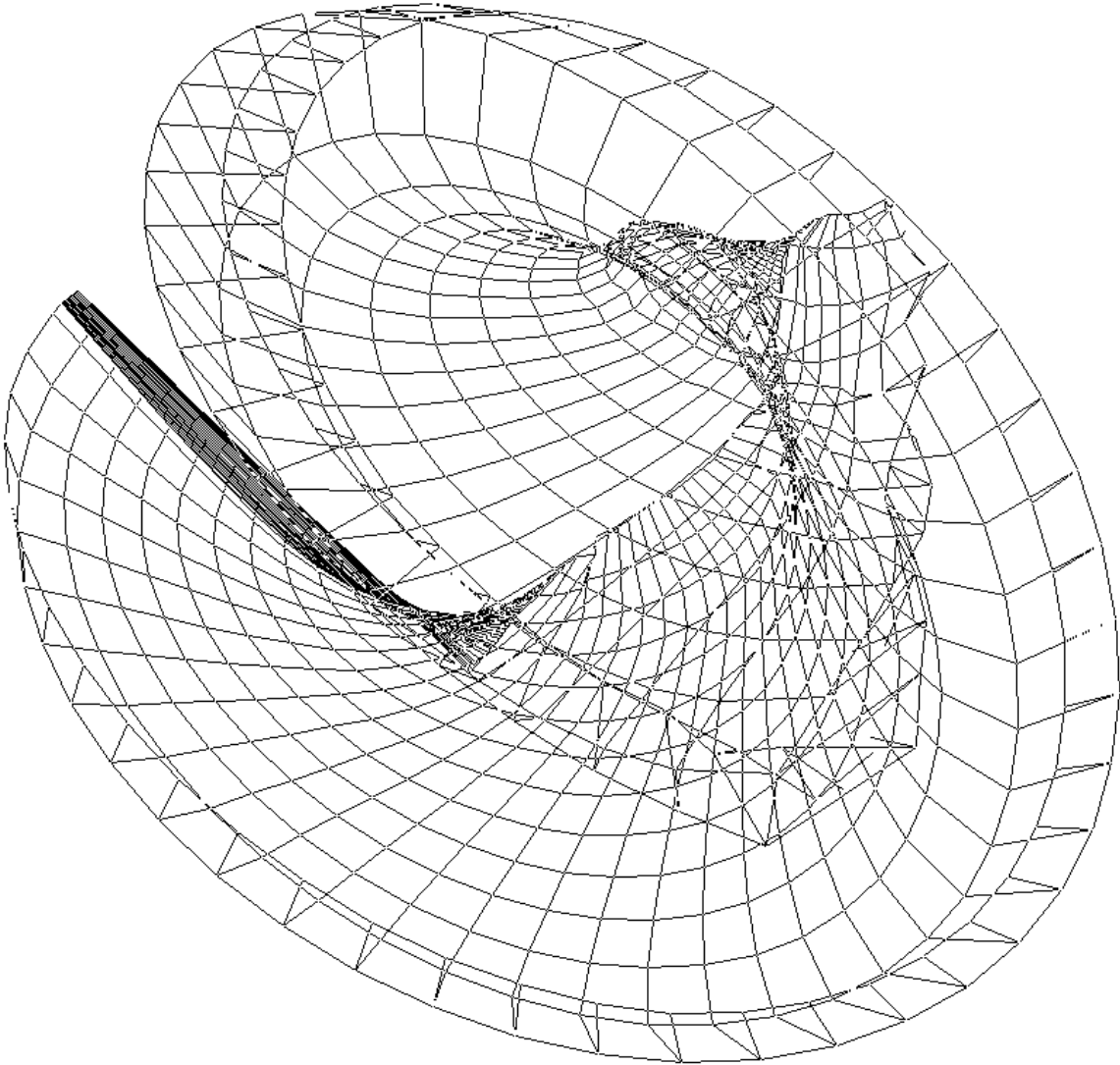
Figure 3 is a contour plot the c_p distribution of the wind turbine blade near the root. The 3D effects of leakage near the root are evident. The picture also suggests a possible overprediction of c_p along the upper surface of the rotor.

Figure 3: Cp Distribution for Final Wind Turbine Blade Design



The results of the animated wake are shown below in Figure 4. Evident is the helix shape as well as the rollup of the vortices near the tip.

Figure 4: Wake of Final Wind Turbine Blade Design



V. Conclusion

The aerodynamic design of this large horizontal-axis wind turbine was comprised of several steps, ultimately resulting in a highly optimized final design. The design process began by using technical data from a real-world wind turbine, the Boeing Mod-2, to model a baseline design. From this design, different aerodynamic parameters were varied in order to achieve a more optimal design. Not only did this method allow performance improvements, but it provided an understanding of many of the fundamentals of wind turbine design and qualitative effects of different aerodynamic changes.

After each design iteration, the power output was computed and compared to both the baseline model, as well as other previous design iterations. Design changes and modifications continued in hopes of improving the performance even further. Ultimately, a model with the highest power output was chosen as the final design.

VI. References

¹ Eggleston, David M. and Forrest S. Stoddard. Wind Turbine Engineering Design. New York: Van Nostrand Reinhold Company, 1987.

² Piggot, Hugh. *Small Wind Turbine Design Notes*. Retrived Dec 3, 2003, from <http://users.aber.ac.uk/iri/WIND/TECH/WPcourse>.

³ US Department of Energy. *Wind and Hydropower Technologies Program: How Wind Turbines Work*. US Department of Energy. Retrived December 18, 2003.
<http://www.eere.energy.gov/windandhydro/wind_how.html>

0.50000	0	-0.02606
0.45032	0	-0.02773
0.40064	0	-0.02854
0.35097	0	-0.02863
0.30128	0	-0.02814
0.25157	0	-0.02710
0.20183	0	-0.02547
0.15202	0	-0.02314
0.10212	0	-0.01999
0.07711	0	-0.01791
0.05203	0	-0.01536
0.02682	0	-0.01191
0.01411	0	-0.00944
0.00893	0	-0.00781
0.00628	0	-0.00661
0.00000	0	0.00000
0.00372	0	0.00861
0.00607	0	0.01061
0.01089	0	0.01372
0.02318	0	0.01935
0.04797	0	0.02800
0.07289	0	0.03487
0.09788	0	0.04067
0.14798	0	0.05006
0.19817	0	0.05731
0.24843	0	0.06290
0.29872	0	0.06702
0.34903	0	0.06983
0.39936	0	0.07138
0.44968	0	0.07153
0.50000	0	0.07018
0.55029	0	0.06720
0.60053	0	0.06288
0.65073	0	0.05741
0.70085	0	0.05099
0.75090	0	0.04372
0.80088	0	0.03577
0.85076	0	0.02729
0.90057	0	0.01842
0.95029	0	0.00937
1.00000	0	0.00000

```

&BPNODE TNODE=3, TNPC=0, TINTC=0, &END
&SECT1 STX=0, STY=11.4, STZ=-1.0, SCALE=8.0,
ALF=66.7, THETA=0.0, INMODE=0, TNODS=0,
TNPS=14, TINTS=3, &END
&SECT1 STX=0, STY=22.9, STZ=-2.0, SCALE=6.0,
ALF=83.4, THETA=0.0,
INMODE=0, TNODS=0, TNPS=14, TINTS=3, &END
&SECT1 STX=0, STY=34.3, STZ=-3.0, SCALE=4.0,
ALF=93.8, THETA=0.0,
INMODE=0, TNODS=0, TNPS=14, TINTS=3, &END
&SECT1 STX=0, STY=45.7, STZ=-4.0, SCALE=2.0,
ALF=111.6, THETA=0.0,
INMODE=0, TNODS=3, TNPS=14, TINTS=3, &END
&PATCH1 IREV=0, IDPAT=1, MAKE=1, KCOMP=1, KASS=1, &END

```

```
      - - - RIGHT TIP - - -
&PATCH2  ITYP=1, TNODS=5,    TNPS=3,    TINTS=3,    NPTTIP=0,    &END

&WAKE1    IDWAK=1,          IFLXW=0,          &END
      - - - RIGHT WAKE - - -
&WAKE2    KWPACH=1,    KWSIDE=2,    KWLIN=0,    KWPAN1=0,    KWPAN2=0,    NODEW=5,
INITIAL=0,          &END

&ONSTRM   NONSL=0          KPSL=0          &END
&BLPARAM  RN =1640000, VISC =0.00016,    NSLBL = 1,    &END
&VS1      NVOLR=0,    NVOLC=0,    &END
&SLIN1    NSTLIN=0,    &END
```