Wind Turbine Rotor Design

Final Design Report

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ME480
Senior Design Project

BOISE STATE UNIVERSITY
College of Engineering

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1. INTRODUCTION AND BACKGROUND

In 2006, Boise State University was awarded $500,000 by the U.S. Department of Energy to fund wind energy research in Idaho. As part of the wind energy grant, Boise State University has entered into a cooperative agreement with the owners of the Lewandowski Wind Farm to use their facility as a test bed for wind energy research. The Lewandowski Wind Farm is located southeast of Boise Idaho and currently operates three Micon 108 kW turbines.

The current owners of the wind farm expressed the need for a design of replacement blades for the three turbines. In addition, the rise in popularity of wind energy throughout the Snake River valley has exposed a market for turbine blades of this size. 100 kW turbines are more desirable since the codes and laws for their operation are not as strict as those for larger turbines.

2. OBJECTIVES

The 10 meter blades on the Lewandowski turbines are beginning to deteriorate and need to be replaced. Because replacement blades are not commercially available, the objective of this project was to design marketable replacement blades that decrease the start-up wind speed of the rotor by fulfilling the following specifications:

- **Increase low speed torque**
- **Meet current power output**
- **Minimum service life of 20 years**

2.1 Design Specifications

In order to fulfill the needs of the client, a list of design specifications was created to help quantify customer satisfaction. The team determined that the customer would be 100% satisfied if:

a) There is 1-2 mph decrease in start-up wind speed
b) A peak power output of 108 kW and
c) The blades are strong enough to operate under normal conditions for the 20 year service life.

The chart shown on the following page (*Figure 1*) gives a graphical representation of the project objectives. The Torque curve is increased for associated wind speeds, while the power curve remains constant.

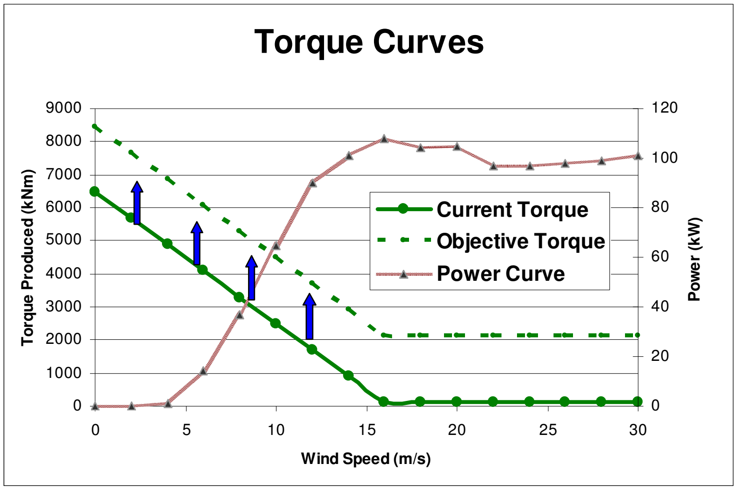


Figure 1
Objective Torque Curve

2.2 Analysis Methods

After developing a variety of design alternatives the team selected the one that would be most satisfactory to the customer. The choice was made to design a blade with new material, airfoils, and span-wise geometry. A variety of airfoil families were selected from the NREL database and evaluated based upon their ability to produce high torque and low drag near the hub in 100 kW turbine applications. The team split into two groups for efficiency purposes. One group (Fouts, Haley) proceeded with aerodynamic design and calculations while the other group (Cowgill, Whitham) worked on the structural analysis of the blade.

- ***Aerodynamic Evaluation*** – Airfoil input data files were formatted and executed in the program WT_Perf (wind turbine performance). This program uses blade element theory to perform an aerodynamic performance analysis. Two output files show overall turbine performance (power, torque, pressure, etc. vs. wind speed) as well as performance data for individual blade elements.

- ***Material/Structural Evaluation*** – Power and rotational speed requirements were used to calculate an approximate force distribution along the blade. A structural analysis was then carried out using a cantilever beam analysis, with the help of COSMOS Finite Element software.

3. THE BLADE DESIGN

3.1 Design Alternatives

Alternative airfoil families were evaluated based upon published information from the NREL database that described the lift and drag characteristics for given turbine applications. Of these alternatives, the following families were selected for further evaluation:

- NREL S816, S818
- NREL S819, S820, S821
- NREL S805A, S806A, S807A

3.2 Methods of Aerodynamic Analysis

WT_Perf is performance evaluation software for Horizontal Axis Wind Turbines. It was designed to have the environmental and geometric properties of a wind rotor as input information, and it outputs performance information, such as total power and torque produced. The software uses a blade element momentum theory to iterate the performance characteristics on both a blade element level (section of constant airfoil) and on an overall turbine performance level. This software has been certified accurate by the National Renewable Energy Laboratories (Buhl, 2004). A complete user's guide was compiled and can be found in Appendix A.

In order to use the program with the specific airfoils chosen, it was necessary to create Airfoil Input Files that related the lift, drag, and moment coefficient with variations in angle of attack of each of the airfoils. Since the data was published on the NREL website, the Airfoil Input Files were created by interpolating values from the published charts. The files were then executed for the desired geometry and site characteristics using the software mentioned above.

After running the program with various airfoils, the S818 airfoil shown in *Figure 2* (below) was selected to increase torque at lower wind speeds.

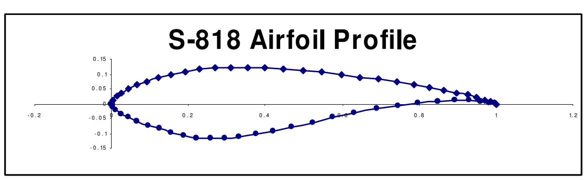


Figure 2
Selected Airfoil

3.3 Methods of structural Analysis

Preliminary loading calculations were made based on the maximum power that the turbine produces and the angular velocity at which the rotor rotates. Based on these values we were able to calculate how much torque each blade needed to produce and therefore how much load the flange of the blade had to withstand (see eq. 1).

$$P = T\omega \Rightarrow T = \frac{P}{\omega} \qquad \text{(eq. 1)}$$

All of the stress equations are based on the loads applied to the blades by the wind, and the loads are based upon the blade geometry itself. The following Excel spreadsheet (*Table 1*) was created as a preliminary force calculator to determine approximate forces acting on the blade. The output from the aerodynamic program (WT_Perf) allowed the verification of these forces. The solid model of the blade with the selected airfoil was analyzed using COSMOS finite element analysis with the force determined below.

Constants	Power (kW)			
	108			
Input	RPM			
	44			
			Torque/ Blade	
Outputs	Angular Velocity	Torque (N*m)	N*m	Pound Feet
	4.61	23439.2	7813.1	5762.6

Table 1
Preliminary Force Calculator

3.4 Final Design

As stated in section 3.3, the S818 airfoil was selected for the design. The blade was solid modeled with a constant airfoil but with various angles of attack and various chord lengths. The parameters were based upon the variable inputs in the WT_Perf program. Carbon Fiber was selected for the construction material due to its high strength and rigidity. The basic dimensioning is shown in *Figure 3* below.

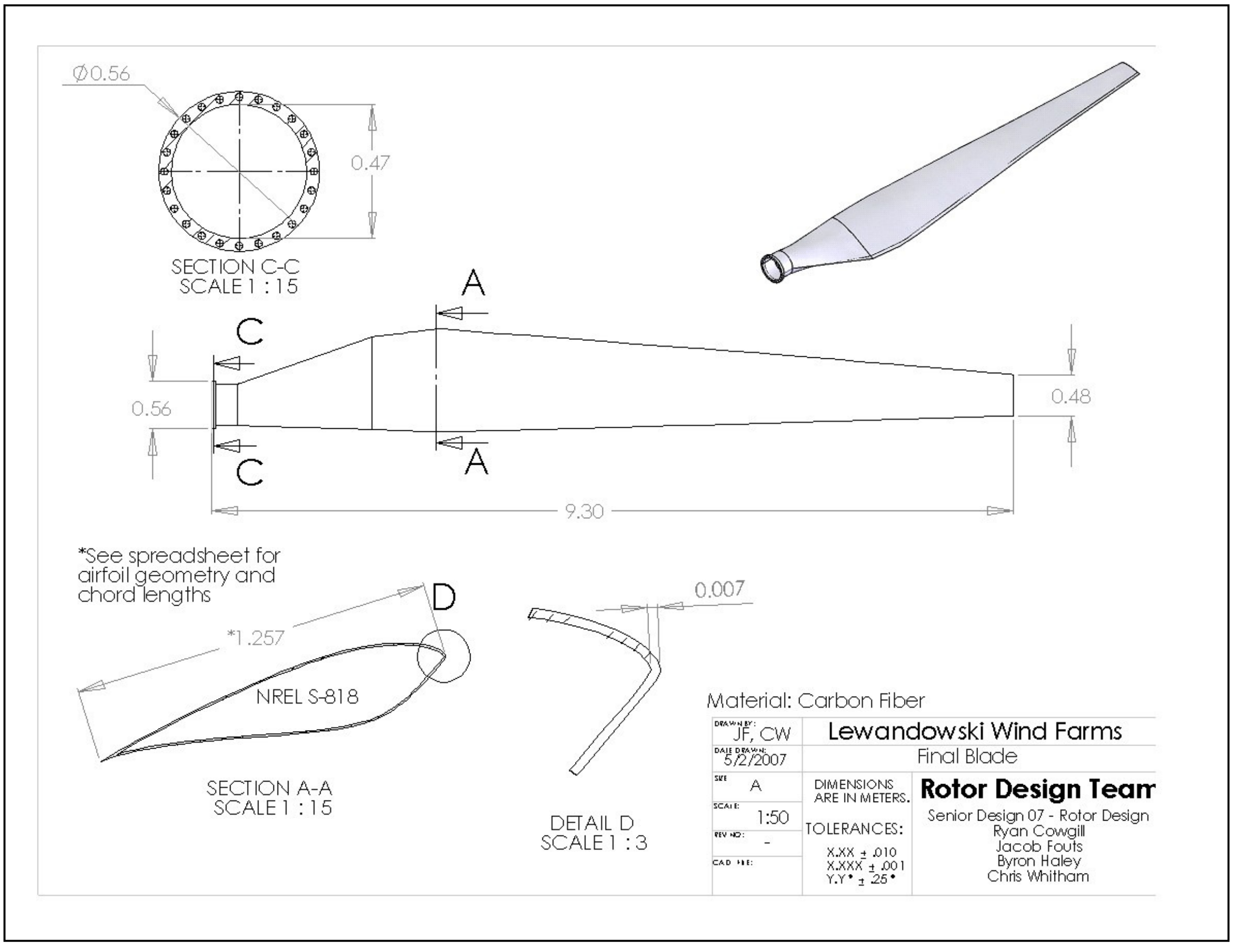


Figure 3
Final Design Parameters

4. *ANALYSIS AND DISCUSSION*

4.1 Aerodynamic Performance

The first step in designing a blade for this location was to set up initial conditions for the site. This meant gathering elevation, temperature and wind speed data for the site. This data was used to find average wind speed and air density to be used in the calculations. The axial induction factor was assumed to be 1/3. The angle of attack desired was chosen base on finding the minimum C_D/C_L value. It was known that these were conflicting assumptions; however, it was assumed it would be a good starting point. This angle of attack was used to find the twist angle that would stall the blade above the desired rated wind speed. Approximate current blade dimensions were used as an initial starting point because actual current blade dimensions are unavailable. This information was fed into WT_Perf and the output files were analyzed. Adjustments were made to the root chord twist values to attempt to lower the start up speed. This was successful. Reynolds numbers were calculated to verify that we were using an acceptable airfoil data file. The initial design, while fitting within the design criteria, is not the most efficient design. More power at a lower speed is theoretically possible.

The next step in this design process is to set up the Excel analysis for the proper iteration process to find the most efficient design possible. There are probably many designs that will work. The current design should also be verified by other means if possible.

Current blade dimensions were approximated because no actual information was available.

- Hub chord length=4.5ft
- Tip chord length=1.5ft
- Rotor diameter=62ft

The following parameters (*Table 2,* next page) were used to create the rotor test file for WT_Perf. A more detailed explanation of these parameters can be found in Appendix A.

Rotor dimensions		
# of elements	20	
Hub Radius	0.819	m
Rotor Radius	9.39	m
Hub Chord Length	1.3716	m
Tip Chord Lenth	0.4572	m
RPM	44	
Ω	4.61	
Tip Angluar speed	43.27	mps
Rotor Area	277.00	m^2
Cp(rated wind spd)	0.22	
Cp(start up spd)	0.14	
# of Blades (B)	3	

S818 airfoil specifications		
predicted alpha for minimum cd/cl	8.50	deg
Stall angle	11.00	deg
Cl=	1.4450	
Cd=	0.0014	

Site Conditions					
Avg Wind	8.5	mph	Air density	1.110	kg/m^3
	3.78	m/s	kt	1.02	temp c.f.
Avg temp	50	F	ka	0.888	alt c.f.
	10	C	Viscosity	1.7E-05	N-s/m^2
Altitude	3000	ft			
	909.1	m			

Tower Conditions		
Tower ht	153 ft	46 m
alpha(suf)	0.2	Cons.
Tower wind spd	5.137	m/s

Table 2
Aerodynamic Input Parameters

The result from the WT_Perf program showed an estimated start-up wind speed of 7 mph which is an improvement from the current 8 mph start-up speed. As for customer satisfaction, 100% satisfaction was initially determined with a decrease of between 1 and 2 mph. For this objective, the project was successful.

On the other hand, the power curve (shown in *Figure 4*) increases beyond the 108 kW range at relatively low wind speeds. This would cause a lack of torque production at the medium and high wind speeds, and the power output could decrease drastically. In this respect, the objective was met with less than 100% satisfaction.

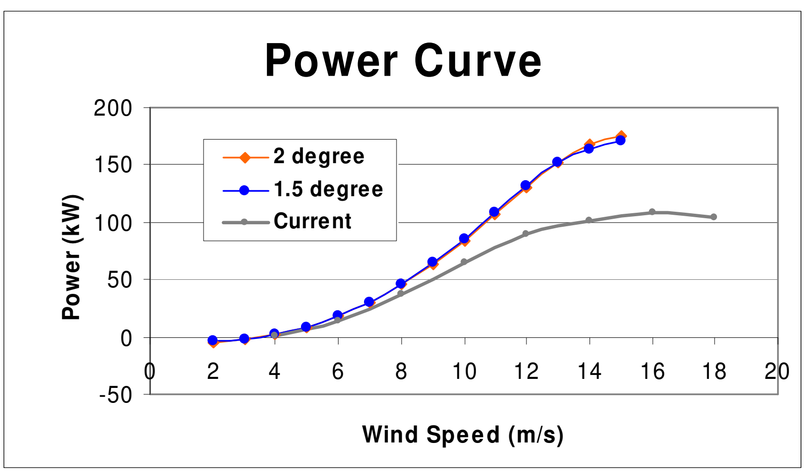


Figure 4
Final Design Power Curve

4.2 Structural Performance

Selecting the material for the blade construction was a quasi-interpolative process, as the type of material used would affect the overall weight of the blade itself, and thus relate directly with the centrifugal force that it would experience during its service.

Based on preliminary stress and deflection analyses performed using a simulated test material that had a similar density to modern composite materials (60% glass filled nylon), we were able to get numerical data on the max stresses in the blade as well as estimate in blade deflection.

Upon viewing this data, an intermediate modulus carbon fiber composite material was selected. This material was able to allow us to achieve a blade weight of approximately 400lbs, eliminate a great deal of deflection, and grant us a safety factor of 16 at its rated wind speed.

We felt that a safety factor this high was acceptable, as these blades would have to remain in safe service for a target life of at least 20 years. In addition, any failure of these components could possibly result in damaged property or death.

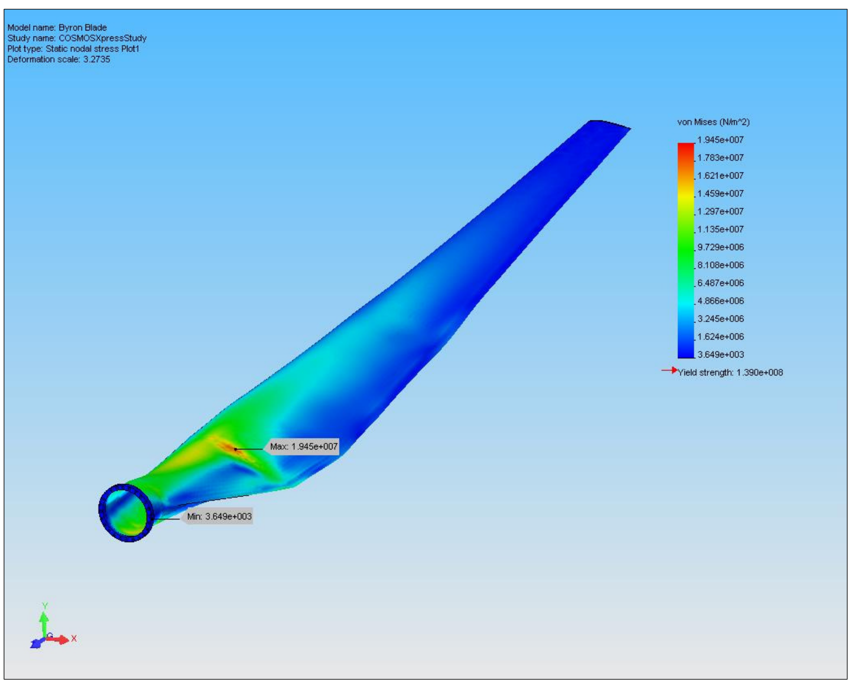


Figure 5
COSMOS Analysis

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The blade design was estimated to decrease the start-up wind speed by at least 1 mph which meets the primary objective of the project. A variation of airfoils and chord line progression would ultimately increase efficiency to help maintain current power output. If the current blade were produced, it is predicted to increase the torque at lower wind speeds but would not maintain power at higher wind speeds.

From a structural standpoint, the material selection and general blade geometry should be able to withstand the loads seen in daily operational conditions at all necessary wind speeds.

5.2 Recommendations

Due to time constraints, the team was not able to evaluate a significant number of alternative airfoil families. It is recommended that the primary and tip sections of the blade be re-evaluated with various airfoil selections.

5.3 Successes in Blade Analysis

Throughout the course of this project, the team was successful in developing a structured method for using the WT_Perf program to predict wind turbine performance. The following user's help guides were developed and are included in the appendices:

- **WT_Perf** – Details the input variables of the program
- **Airfoil Input Files** – Details methods for creating the data file to run in WT_Perf
- **Airfoil Solid Modeling** – Details methods for importing airfoils to SolidWorks

6. REFERENCES

1. Buhl, Marshall L. "WT_Perf User's Guide." National Wind Technology Center, 2004

2. Eggert, Rudolph J. *Engineering Design.* New Jersey: Pearson Education, 2005.

3. Manwell, J.F., J.G. McGowan and A.L. Rogers. *Wind Energy Explained.* England: John Wiley & Sons, 2002.

4. Somers, D.M. "The S819, S820, and S821 Airfoils." NREL, 1993.

5. Tangler, J.L. and D.M. Somers. "NREL Airfoil Families for HAWTs." AWEA, 1995.

APPENDIX A
WT_PERF USER MANUAL

WT_Perf

Wind Turbine Performance Evaluation Software

Supplemental Users Manual

By

Byron Haley

May 1, 2007

Introduction

WT_Perf is a wind turbine performance evaluation software. It is written in Fortran 95 by Marshall L. Buhl, Jr. from National Renewable Energies Laboratory. This software is designed to produce a performance prediction of a wind turbine rotor based on the geometric dimensions of the blade/rotor. This software is designed to be run in a DOS environment. This software has been certified by NREL to be accurate through experimental testing (www.NREL.org). This manual is intended to provide additional information about WT_Perf, and not the primary source of information. The instruction manual provided by NREL with WT_Perf is intended for those who have a clear understanding of wind turbine nomenclature, equations, calculation procedures; DOS operating system, and DOS based programming techniques and restrictions before reading the instruction manual. This manual is intended to help those that aren't very familiar with the above information. Not all sections are completely understood at this time.

This software uses the Blade Element Momentum Theory (BEM) to calculate predicted rotor performance. This theory breaks the blade into small elements along the radius of the rotor plane; calculates the performance information for each element; then sums individual components such as power, torque, thrust, drag, etc. for total performance information of the entire rotor. BEM uses several equations in an iteration process to calculate performance. BEM requires lift and drag information for the airfoil shape used in the blade design. Airfoils are the cross-sectional shapes associated with blade design on wind turbines, propellers, and wings. Lift and drag information for each airfoil shape is produced by experimental examination and measurement taking measurements at every angle of attack from 0 degrees to +/-180 degrees in a controlled environment. Some of this data can be extrapolated, but it is unknown to the accuracy of this method. The process of acquiring complete and accurate airfoil data is beyond the scope of typical undergraduate research projects.

The problem with BEM is, to calculate performance information; some of the equations require performance information to calculate environmental conditions. The equations for environmental conditions require performance information. This becomes a circular process requiring initial guesses to start the process. There are equations to get good initial guess, however, those equations are iterative in nature as well. The end result is a VERY long iteration process with lots of potential for mistakes.

To use WT_Perf to create a new rotor design requires a lot of guess work to start with. It will give end performance information, but it will not give any information regarding what changes to make to improve performance.

DOS Environment

WT_Perf is designed to be run in a DOS environment. This can be accomplished in a Windows environment using either the MS-DOS window or the command prompt window. All files can be viewed and edited in the DOS environment. DOS is a text or command oriented operating system that is no longer in common use. It requires that commands be typed in the exact proper form to execute any command. Misspelling will result in various error statements being produced.

This data is output in two different files—the *.oup file, and the *.bed file. The input file is and *.wtp file. All three files can be read in Notepad. The input file can also we read in Word. Regardless of what the file is viewed/edited with, it must be saved with *.wtp file extension to work properly with the WT_Perf.exe file. Another file that is explained very that is needed is the airfoil data files. These have .dat file extensions and include data for the different airfoils that can be used on the blade. Each blade element can have a different airfoil applied to it. These airfoil files must be in the same directory (folder) as WT_Perf.exe.

The following commands are needed to use this software.

DIR-----directory list. This lists all the files in the current folder.
Cd -----change directory. This changes folders starting with the root folder.
Example: c:\cd\my documents changes to "my documents" folder
Cd -----change directory. This changes folders starting within the current folder.
Example: c:\my documents\cd pictures changes to "pictures" folder within the "my documents" folder
Edit-----edit command. This is used to view and edit a file's content.
F3 key---This key will repeat the last command typed in the exact form it was written.

To execute WT_Perf, the following command must me entered:

C:\"*file folder*"\WT_Perf *.wtp
*--name of input file.

Input File

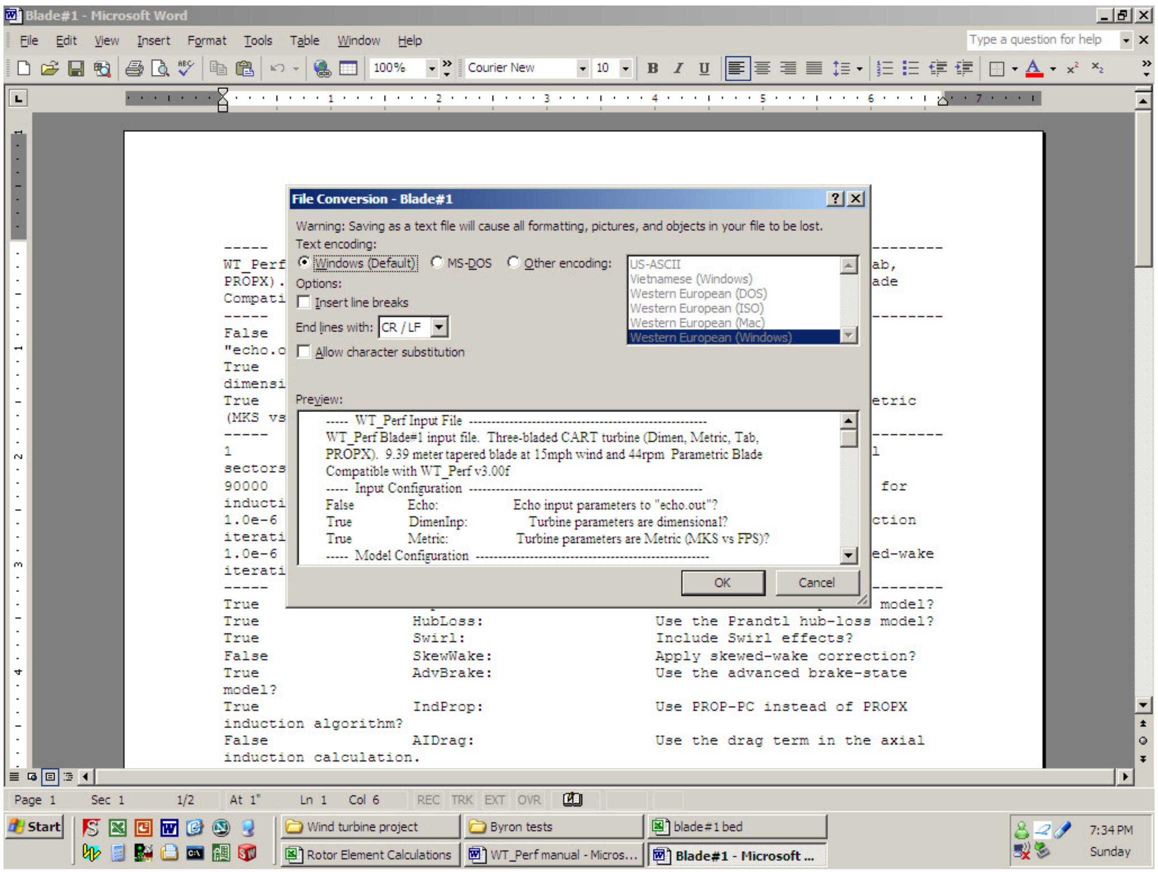
The following is an example of a *.wtp input file.

```
-----  WT_Perf Input File  -----------------------------------------------
------
WT_Perf Blade#1 input file.  Three-bladed CART turbine (Dimen, Metric,
Tab, PROPX).  9.39 meter tapered blade at 15mph wind and 44rpm  Parametric
Blade
Compatible with WT_Perf v3.00f
-----  Input Configuration  ----------------------------------------------
------
False                Echo:                     Echo input parameters to
"echo.out"?
True                 DimenInp:                 Turbine parameters are
dimensional?
True                 Metric:                   Turbine parameters are
Metric (MKS vs FPS)?
-----  Model Configuration  ----------------------------------------------
------
1                    NumSect:                  Number of circumferential
sectors.
90000                MaxIter:                  Max number of iterations
for induction factor.
1.0e-6               ATol:                     Error tolerance for
induction iteration.
1.0e-6               SWTol:                    Error tolerance for
skewed-wake iteration.
-----  Algorithm Configuration  ------------------------------------------
------
True                 TipLoss:                  Use the Prandtl tip-loss
model?
True                 HubLoss:                  Use the Prandtl hub-loss
model?
True                 Swirl:                    Include Swirl effects?
False                SkewWake:                 Apply skewed-wake
correction?
True                 AdvBrake:                 Use the advanced brake-
state model?

True                 IndProp:                  Use PROP-PC instead of
PROPX induction algorithm?
False                AIDrag:                   Use the drag term in the
axial induction calculation.
False                TIDrag:                   Use the drag term in the
tangential induction calculation.
-----  Turbine Data  -----------------------------------------------------
------
3                    NumBlade:                 Number of blades.
9.39                 RotorRad:                 Rotor radius [length].
0.819                HubRad:                   Hub radius [length or div
by radius].
0.0                  PreCone:                  Precone angle, positive
downwind [deg].
0.00                 Tilt:                     Shaft tilt [deg].
0.00                 Yaw:                      Yaw error [deg].
46.36                HubHt:                    Hub height [length or div
by radius].
20                   NumSeg:                   Number of blade segments
(entire rotor radius).

   RElm    Twist   Chord  AFfile  PrntElem
   1.033      19.74  1.1487     1   True
   1.462      18.40  1.2030     1   True
   1.890      17.07  1.2573     1   True
   2.319      16.32  1.2116     1   True
   2.747      15.79  1.1659     1   True
   3.176      14.16  1.1201     1   True
   3.605      13.50  1.0744     1   True
```

```
   4.033       13.29  1.0287     1   True
   4.462       12.76  0.9830     1   True
   4.890       11.05  0.9373     1   True
   5.319       7.58   0.8915     1   True
   5.747       6.31   0.8458     1   True
   6.176       5.20   0.8001     1   True
   6.604       4.23   0.7544     1   True
   7.033       3.37   0.7087     1   True
   7.462       2.90   0.6629     1   True
   7.890       2.71   0.6172     1   True
   8.319       2.59   0.5715     1   True
   8.747       1.73   0.5258     1   True
   9.176       1.21   0.4801     1   True
  -----  Aerodynamic Data  -----------------------------------------------
------
1.109556                                Rho:                Air density
[mass/volume].
1.73E-05                                KinVisc:            Kinematic
air viscosity
0.6666667                               ShearExp:           Wind shear
exponent (1/7 law = 0.143).
False                                   UseCm               Are Cm data
included in the airfoil tables?
1                                       NumAF:     Number of airfoil
files.
Airfoils\CART3\C3_05_S818.dat          AF_File:    List of NumAF airfoil
files.
-----  I/O Settings  -----------------------------------------------------
------
True                TabDel:                     Make output tab-delimited
(fixed-width otherwise).
True                KFact:                      Output dimensional
parameters in K (e.g., kN instead on N)
True                WriteBED:                   Write out blade element
data to "<rootname>.bed"?
False               InputTSR:                   Input speeds as TSRs?
"mps"               SpdUnits:                   Wind-speed units (mps,
fps, mph).
-----  Combined-Case Analysis  -------------------------------------------
------
0                   NumCases:                   Number of cases to run.
Enter zero for parametric analysis.
WS or TSR   RotSpd   Pitch                      Remove following block of
lines if NumCases is zero.
-----  Parametric Analysis (Ignored if NumCases > 0 )  ------------------
------
3                   ParRow:                     Row parameter    (1-rpm,
2-pitch, 3-tsr/speed).
2                   ParCol:                     Column parameter (1-rpm,
2-pitch, 3-tsr/speed).
1                   ParTab:                     Table parameter  (1-rpm,
2-pitch, 3-tsr/speed).
True                OutPwr:                     Request output of rotor
power?
True                OutCp:                      Request output of Cp?
True                OutTrq:                     Request output of shaft
torque?
True                OutFlp:                     Request output of flap
bending moment?
True                OutThr:                     Request output of rotor
thrust?
0, 3.0, .5        PitSt, PitEnd, PitDel:     First, last, delta blade
pitch (deg).
44, 44, 1.0         OmgSt, OmgEnd, OmgDel:      First, last, delta rotor
speed (rpm).
2, 20, 1            SpdSt, SpdEnd, SpdDel:         First, last, delta
speeds.
```

The input file includes many different sections. Each section is separated by a line across the page with a title in the line. The input file format must be maintained including spaces and arrangement for the file to work properly in the WT_Perf.exe file. This file can be viewed in any word processing program such as "Notepad", or "Word", however, it MUST be saved with the .wtp file extension. This is accomplished in Word by "save as" command, typing *"file name"*.wtp in the file name line.and following the instructions in the file conversion window.

Select the "other encoding" option, and the "US-ASCII" option and selecting "OK."



The following is a list of input file sections.

1. WT_PERF input file----This is a title section. Information about the file is included in standard grammar form.

2. Input Configuration----This section is used to set up the basic input parameters.

Echo:—unknown (true/false command only)

DimenInp:—Dimension Inputs. (true/false command only). This tells WT_Perf whether dimensional information is inputted in dimensional or non-dimensional values, such as mps or TSR(tip speed ratio).

Metric:—Metric or English units. (true/false command only). This tells WT_Perf whether the dimensional information is inputted in either metric or English units. Metric=true, English=false.

3. Model Configuration----This section sets up model parameters.

NumSect:--Number of section the rotor plane is divided into. This should generally be set to one unless

MaxIter:--Maximum number of iterations used to calculate the induction factors.

ATol:--Tolerance for the induction factor iterations.

SWTol:--Tolerance for the skewed-wake iterations.

4. Algorithm Configuration----This section sets up what equations are used in the calculation iteration process. (True/False command only)

Tip Loss, Hub Loss—Use Prandtl Tip Loss/ Hub Loss models. This includes tip vortex effects in the airflow calculations.

Swirl—Includes Tangential induction calculation in the iteration process.

SkewWake—Includes calculations for airflow not normal to the plane of rotation.

AdvBrake—unknown (I don't know what brake models are or how they relate).

IndProp—unknown, (I don't know what the difference is between Prop-PC and PropX induction algorithm).

AIdrag—includes the drag term in the Axial induction calculation.

TIDrag—includes the drag term in the tangential induction calculation.

5. Turbine Data----This section includes the dimensions of the turbine rotor. Values are either in dimensional or non-dimensional values depending on the selection in the INPUT Section.

NumBlade--# of blades in the rotor, must be integer greater than zero.

RotorRad—total rotor radius including hub length.

HubRad—Radius of the hub section. This section is NOT included in the BEM calculations.

Precone—coning angle. This is the angle of cone shape of the rotor away from a flat rotor plane. (This is unknown with regards to how it affect performance beyond changing the airflow angle.)

Tilt—Angle of tilt in the vertical plane of the entire rotor assembly beyond normal to air flow.

Yaw—angle in the horizontal plane of the entire rotor assembly beyond normal to air flow. Also known as furling.

HubHt—height of the rotor hub above ground level.

NumSeg—number of elements(segments) the blade is divided into.

The next section includes information about each blade Element(Relm, twist, chord, AFfile, PrntElem).

Relm—element centerline radius from center of rotor

Twist—angle of each element chord line with respect of rotor plane when entire blade as a zero pitch angle(pitch angle explained in different section.

Chord—chord length of the element.

AFfile—airfoil data file associated with that blade element. Airfoil files are listed in another section in a numbered list.

PrntElem—Print element performance information(true/false command only). One can choose whether or not to include this elements data in the output files.

Element lengths must total to total to rotor radius. The first element must start at the hub length. There is an approximation of about 1% allowed between all element dimensions.

Example:
Hub rad=.819
Rotor Rad=9.39
Element width=.43 (20 elements)
Relm #1 centerline=1.033 1.033-.5(.43)=.818
(all units apply)

6. Aerodynamic Data---This section covers the operating environment of the turbine

Rho—density of the fluid in question, usually air. This density is dependant on temperature and ground elevation of the turbine.

KinVisc—Kinematic Viscosity of the fluid in question.

ShearExp—wind shear exponent. This is the exponent value for the height difference calculation of windspeed. $(h/h_o)^{ShearExp}$.

UseCm—use the moment coefficient in the calculations. (True/false command only) This is only "true" if the C_m is included in the airfoil data being used for each element. (I don't know what will happen if some airfoil file include the C_m and some do not.)

NumAF—number of airfoil files to be used in the calculation process. Must be an integer greater that zero.

The next section is a list of the airfoil addresses within the computer. They are not numbered, but are referred to by there order. Ex: 1=first file, 2=second file and so forth. These file addresses must be in proper syntax, order, and include the file extensions.

Ex: `Airfoils\CART3\C3_05_S818.dat`

Notice that spaces aren't allowed, and backslashes are required between folders, subfolders, and file names.

7. I/O Settings------This section sets how the data will be output.

TabDel—unknown what output it is referring to. (True/False command only)

Kfact—output units in kilo units or not (True/False command only)

WriteBed—write out the blade element data (True/False command only)

InputTSR—are input speeds in TSR format or not (True/False command only)

Spdunits—what units are wind speeds to be inputted and outputted in. MPH doesn't appear to work correctly, mps or fps is recommended. This was tested by outputting the same data in all three forms, and plotting the power curves in Excel. The end result should be the same curve for all three units; however, mph produced a different curve.

8. Combined-Case Analysis----This section is not understood. Any attempt on my part to change this section resulted in a program crash.

9. Parametric Analysis---This section sets up the output files format and what ranges of each variable will be.

ParRow—sets what will be output in rows.

ParCol—Sets what will be output in Columns.
ParTab—Sets what will be output in Separate tables.
Each Table will have the above row and column layout.

The next five (OutPwr, OutCp, OutTrq, OutFlp, OutThr) tell whether or not to output this information to the output file.(True/False command only) Power is the power of the entire rotor at the given airspeed and blade pitch. Torque is the torque produced by the entire rotor at the given airspeed and blade pitch. Cp is the coefficient of power of the entire rotor. This is a measure of efficiency. Flap Bending Moment is unknown. A possible guess is that it is referring to the bending moment in the direction of the normal to the rotor plane on each blade. Thrust is the thrust produced by the rotor at the hub in the direction normal to the rotor plane.

The next three sections are what ranges of wind speed rotor rpm, and blade pitch WT_Perf will evaluate each element at. The must be in the format shown in the example file. If one wants to evaluate only at a constant value such as rpm enter the range as follows: "`44, 44, 1.0`". The increment number can't be zero. These ranges have a start value, end value, and increment value. Negative values can be used. Blade Pitch is the angle of the entire blade with respect to the plane of rotation.

Output Files

These files can be view in raw form in Notpad, but can also be transferred to Excel to more easily analyze and view the data in an ordered form. Follow the instructions for opening the file in Excel.

*.oup files

This file is the output of the total rotor performance. It includes the BED combined performance data. This file is the result of the Parametric Analysis section of the input file.

Example file:

Results generated by WT_Perf (v3.10b-mlb, 02-Jul-2004) for input file "blade#1.wtp".
Generated on 12-Apr-2007 at 15:44:48.
Input file title:
WT_Perf Blade#1 input file. Three-bladed CART turbine (Dimen, Metric, Tab, PROPX). 9.39 meter tapered blade at 15mph wind and 44rpm Parametric Blade

----
Power (kW) for Omega = 44 rpm.

WndSp	Pitch (deg)						
(mps)	0.000	0.500	1.000	1.500	2.000	2.500	3.000
2.000	-2.468	-2.391	-2.393	-2.413	-2.523	-2.715	-2.845
3.000	-1.009	-0.838	-0.791	-0.700	-0.724	-0.757	-0.815
4.000	2.140	2.281	2.381	2.441	2.461	2.439	2.376
5.000	7.134	7.275	7.380	7.449	7.479	7.465	7.395
6.000	14.462	14.606	14.711	14.771	14.780	14.690	14.498
7.000	24.488	24.601	24.654	24.598	24.437	24.179	23.821
8.000	37.275	37.217	37.059	36.807	36.455	36.007	35.463
9.000	52.174	51.941	51.596	51.135	50.574	49.933	49.220
10.000	68.689	68.300	67.796	67.197	66.516	65.726	64.870

11.000	84.259	84.172	84.068	84.014	83.663	82.891	82.010
12.000	93.884	95.961	97.570	98.706	99.257	99.147	98.767
13.000	97.969	100.900	103.556	106.019	108.423	110.587	112.351
14.000	99.622	103.171	106.662	110.085	113.233	116.072	118.673
15.000	100.912	104.469	108.098	111.792	115.526	119.242	122.856
16.000	102.284	105.980	109.744	113.463	117.126	120.867	124.714
17.000	103.888	107.651	111.435	115.266	119.131	123.072	126.940
18.000	105.814	109.640	113.474	117.357	121.281	125.234	129.240
19.000	108.213	112.009	115.861	119.795	123.790	127.788	131.848
20.000	110.939	114.880	118.806	122.722	126.726	130.771	134.895

Cp (-) for Omega = 44 rpm.

WndSp	Pitch (deg)						
(mps)	0.000	0.500	1.000	1.500	2.000	2.500	3.000
2.000	-2.0073	-1.9450	-1.9465	-1.9626	-2.0522	-2.2084	-2.3140
3.000	-0.2433	-0.2020	-0.1905	-0.1688	-0.1744	-0.1824	-0.1964
4.000	0.2176	0.2319	0.2421	0.2482	0.2502	0.2480	0.2416
5.000	0.3714	0.3787	0.3842	0.3878	0.3893	0.3886	0.3850
6.000	0.4357	0.4400	0.4432	0.4450	0.4453	0.4425	0.4368
7.000	0.4646	0.4667	0.4677	0.4667	0.4636	0.4587	0.4519
8.000	0.4738	0.4730	0.4710	0.4678	0.4633	0.4576	0.4507
9.000	0.4657	0.4636	0.4606	0.4564	0.4514	0.4457	0.4394
10.000	0.4470	0.4444	0.4412	0.4373	0.4328	0.4277	0.4221
11.000	0.4119	0.4115	0.4110	0.4107	0.4090	0.4053	0.4009
12.000	0.3535	0.3614	0.3674	0.3717	0.3738	0.3734	0.3719
13.000	0.2902	0.2989	0.3067	0.3140	0.3211	0.3275	0.3328
14.000	0.2362	0.2447	0.2529	0.2611	0.2685	0.2753	0.2814
15.000	0.1946	0.2014	0.2084	0.2155	0.2227	0.2299	0.2369
16.000	0.1625	0.1684	0.1743	0.1803	0.1861	0.1920	0.1981
17.000	0.1376	0.1426	0.1476	0.1527	0.1578	0.1630	0.1681
18.000	0.1181	0.1223	0.1266	0.1309	0.1353	0.1397	0.1442
19.000	0.1027	0.1063	0.1099	0.1137	0.1174	0.1212	0.1251
20.000	0.0902	0.0934	0.0966	0.0998	0.1031	0.1064	0.1097

Torque (kN-m) for Omega = 44 rpm.

WndSp	Pitch (deg)						
(mps)	0.000	0.500	1.000	1.500	2.000	2.500	3.000
2.000	-0.536	-0.519	-0.519	-0.524	-0.548	-0.589	-0.617
3.000	-0.219	-0.182	-0.172	-0.152	-0.157	-0.164	-0.177
4.000	0.464	0.495	0.517	0.530	0.534	0.529	0.516
5.000	1.548	1.579	1.602	1.617	1.623	1.620	1.605
6.000	3.139	3.170	3.193	3.206	3.208	3.188	3.146
7.000	5.315	5.339	5.351	5.338	5.303	5.248	5.170
8.000	8.090	8.077	8.043	7.988	7.912	7.815	7.697
9.000	11.323	11.273	11.198	11.098	10.976	10.837	10.682
10.000	14.908	14.823	14.714	14.584	14.436	14.264	14.079
11.000	18.287	18.268	18.245	18.234	18.157	17.990	17.799
12.000	20.376	20.826	21.175	21.422	21.542	21.518	21.435
13.000	21.262	21.898	22.475	23.009	23.531	24.001	24.383
14.000	21.621	22.391	23.149	23.892	24.575	25.191	25.755
15.000	21.901	22.673	23.460	24.262	25.072	25.879	26.663
16.000	22.199	23.001	23.818	24.625	25.420	26.232	27.066
17.000	22.547	23.364	24.185	25.016	25.855	26.710	27.550
18.000	22.965	23.795	24.627	25.470	26.321	27.179	28.049
19.000	23.485	24.309	25.145	25.999	26.866	27.734	28.615
20.000	24.077	24.932	25.784	26.634	27.503	28.381	29.276

Flap bending moment (kN-m) for Omega = 44 rpm.

WndSp	Pitch (deg)						
(mps)	0.000	0.500	1.000	1.500	2.000	2.500	3.000
2.000	2.210	1.915	1.554	1.343	1.033	0.617	0.575
3.000	3.623	3.392	3.048	2.828	2.524	2.268	2.050
4.000	5.549	5.231	4.919	4.614	4.315	4.023	3.736
5.000	7.569	7.236	6.908	6.586	6.270	5.958	5.646

6.000	9.770	9.422	9.079	8.741	8.406	8.060	7.700
7.000	12.129	11.769	11.408	11.035	10.651	10.257	9.852
8.000	14.599	14.199	13.791	13.375	12.950	12.517	12.077
9.000	17.058	16.625	16.183	15.732	15.274	14.813	14.348
10.000	19.460	19.006	18.544	18.075	17.602	17.122	16.640
11.000	21.423	21.045	20.663	20.283	19.864	19.391	18.910
12.000	22.146	22.152	22.084	21.933	21.678	21.320	20.926
13.000	22.051	22.191	22.277	22.327	22.364	22.357	22.287
14.000	21.682	21.900	22.108	22.305	22.451	22.540	22.587
15.000	21.447	21.619	21.809	22.012	22.224	22.432	22.624
16.000	21.350	21.511	21.697	21.871	22.028	22.202	22.395
17.000	21.472	21.583	21.703	21.843	21.998	22.177	22.341
18.000	21.786	21.850	21.923	22.015	22.122	22.240	22.377
19.000	22.308	22.300	22.315	22.359	22.424	22.497	22.590
20.000	22.946	22.927	22.908	22.891	22.898	22.922	22.972

Thrust (kN) for Omega = 44 rpm.

WndSp	Pitch (deg)						
(mps)	0.000	0.500	1.000	1.500	2.000	2.500	3.000
2.000	0.898	0.750	0.563	0.451	0.285	0.078	0.023
3.000	1.681	1.569	1.396	1.284	1.129	0.996	0.875
4.000	2.757	2.599	2.442	2.288	2.135	1.983	1.833
5.000	3.909	3.743	3.578	3.415	3.252	3.090	2.926
6.000	5.185	5.010	4.836	4.662	4.488	4.307	4.119
7.000	6.570	6.385	6.198	6.005	5.805	5.599	5.388
8.000	8.009	7.805	7.596	7.384	7.166	6.945	6.717
9.000	9.402	9.188	8.971	8.748	8.514	8.277	8.039
10.000	10.736	10.517	10.290	10.058	9.823	9.580	9.335
11.000	11.783	11.609	11.432	11.258	11.060	10.829	10.596
12.000	12.144	12.178	12.168	12.119	12.019	11.860	11.677
13.000	12.119	12.202	12.264	12.312	12.355	12.380	12.378
14.000	12.043	12.148	12.250	12.349	12.428	12.487	12.532
15.000	12.076	12.150	12.235	12.328	12.425	12.524	12.619
16.000	12.265	12.310	12.366	12.425	12.487	12.561	12.647
17.000	12.594	12.612	12.634	12.666	12.705	12.756	12.806
18.000	13.028	13.023	13.022	13.030	13.043	13.062	13.089
19.000	13.568	13.532	13.504	13.488	13.480	13.477	13.482
20.000	14.177	14.132	14.088	14.044	14.151	14.124	14.106

As seen in the example file, the top row is the blade pitch, the First Column is the wind speed, and the rest of the number is the various power, torque, etc. values for the entire rotor that fits the initial conditions. If one were to vary the Omega values, additional tables would be shown for each different RPM value as well.

***.bed files**

This file is the Blade Element Data file. It breaks down the performance data even further into each individual element. It also lists some of the environmental conditions, such as angle of attack, lift and drag coefficients, and induction factors. The column units appear to be somewhat mislabeled. Below is the information included in the BED file. This data is given for every element, free stream wind speed, RPM, and blade pitch angle evaluated if selected to do so in the input file.

Example File section

Element (-)	Azimuth (deg)	Loc Vel (m/s)	Re (-)	Loss (-)	Axial Ind. (deg)	Tang. Ind. (deg)	Airflow Angle (-)	AlfaD (-)
1	45	5.1	0.341	0.839	0.274	0.034	16.46	-3.28
1	135	5.1	0.341	0.839	0.273	0.034	16.45	-3.29
1	225	5.1	0.341	0.839	0.273	0.034	16.45	-3.29
1	315	5.1	0.341	0.839	0.274	0.034	16.46	-3.28

Cl (-)	Cd (-)	Thrust Coef (-)	Torque Coef (N/m)	Power Coef (N)	Thrust/Len (kW)	Torque/Len	Power
0.199	0.01	0.678	0.165	0.394	0.8	0.2	0.001
0.198	0.01	0.674	0.164	0.39	0.8	0.2	0.001
0.198	0.01	0.674	0.164	0.39	0.8	0.2	0.001
0.199	0.01	0.678	0.165	0.394	0.8	0.2	0.001

Each column contains information the element listed in column 1.

Element—Which element is being evaluated.

Azimuth—Which section of the rotor plane is being evaluated. This angle is the center angle of the section. Minimum of four sections is evaluated unless tilt, skewed wake and/or wind-shear is set to something other than zero.

Local Velocity—Velocity of the direct wind (relative wind-combination of axial wind and blade rotational velocity.)

Re—Reynolds number *10^6.

Loss—assumed to be tip and hub loss coefficient.

Axial Induction factor—This is the value of the axial induction factor. "a"
This is where I believe the units become incorrect.

Tangential Induction factor—Value of the Tangential induction factor. "a'"

Airflow angle—this is the local angle of relative wind with respect to the plane of rotation. φ

AlfaD—This is the local angle of attack. α

C_l—Lift coefficient of the airfoil selected at the airflow angle.

C_d—Drag coefficient of the airfoil selected at the airflow angle.

Thrust, Torque, and Power Coefficient—Self explanatory.

Thurst/Length, Torque/Length, Power—individual element values for each. These values are summed to equal the total values given in the *.oup files. It is assumed that if the length of each element is different, the total values will be weighted before summing them. Given that the last two columns do not have units given, and that the induction factors have units that do not fit, leads me to believe this is simply a typo error in the output instructions.

Airfoil Data Files

*.dat file

These are the airfoil files that must be used in the input file. These file must have a specific format. These file can be generated in one of two ways, experimentally, and extrapolation. The files provided with the software were generated experimentally and are considered very accurate. They are the result of many hours of measurements and can't generally be reproduced in the scope of an undergraduate project. The other method is to extrapolate the data using graphical methods and simulation software such as Fluent. This method has its limitations regarding accuracy. The most important section of the file would be the angle of attacks of +/- 20^o. This data can be acquired graphically from several different sources of data. The rest of the data is "theoretically speaking" unimportant, however, without the right format, the files will not function in WT_Perf. The -180^o and +180^o degree values must be identical. Other airfoil files indicate that the +/- 90^o through +/-180^o values may have to be identical as well. Without experimental examination, this is only a guess. The extrapolation method may not produce accurate results, however, without knowing what process is used in WT_Perf to analyze this data, this method can't be verified. Some files include Pitch moment coefficients as well. If they do, the input file will have to set up, in the "**Aerodynamic data**" section, to accept that information.

The following is an example of an airfoil data file.

```
AeroDyn airfoil file.  Compatible with AeroDyn v13.0.
S818 - Generated by M. Buhl.
Data came from Eppler data that was extended and blended by AirfoilPrep.
  5        Number of airfoil tables in this file
  1.5      Reynolds numbers in millions
 11.00     Stall angle (deg)
 -5.2087   Zero Cn angle of attack (deg)
  6.0251   Cn slope for zero lift (dimensionless)
  1.7045   Cn extrapolated to value at positive stall angle of attack
 -0.9037   Cn at stall value for negative angle of attack
 -6.00     Angle of attack for minimum CD (deg)
  0.0092   Minimum CD value
-180.00   0.000   0.0100
-170.00   1.023   0.0149
-160.00   0.858   0.1722
-150.00   0.807   0.4133
-140.00   0.778   0.7095
-130.00   0.712   1.0254
-120.00   0.594   1.3233
-110.00   0.425   1.5678
-100.00   0.220   1.7299
 -90.00   0.000   1.7908
 -80.00  -0.220   1.7299
 -70.00  -0.425   1.5678
 -60.00  -0.594   1.3233
 -50.00  -0.712   1.0254
 -40.00  -0.778   0.7095
```

-30.00	-0.807	0.4133
-20.00	-0.858	0.1722
-10.00	-0.914	0.0228
-6.00	-0.094	0.0092
-5.00	0.014	0.0093
-4.00	0.122	0.0095
-3.00	0.230	0.0096
-2.00	0.337	0.0098
-1.00	0.445	0.0099
0.00	0.552	0.0101
1.00	0.658	0.0102
2.00	0.765	0.0105
3.00	0.871	0.0107
4.00	0.977	0.0110
5.00	1.082	0.0114
6.00	1.187	0.0118
7.00	1.291	0.0124
8.00	1.394	0.0130
9.00	1.496	0.0136
10.00	1.539	0.0235
11.00	1.608	0.0262
12.00	1.566	0.0424
13.00	1.523	0.0586
20.00	1.226	0.1722
30.00	1.153	0.4133
40.00	1.112	0.7095
50.00	1.018	1.0254
60.00	0.848	1.3233
70.00	0.607	1.5678
80.00	0.314	1.7299
90.00	0.000	1.7908
100.00	-0.220	1.7299
110.00	-0.425	1.5678
120.00	-0.594	1.3233
130.00	-0.712	1.0254
140.00	-0.778	0.7095
150.00	-0.807	0.4133
160.00	-0.858	0.1722
170.00	-1.023	0.0149
180.00	0.000	0.0100

EOT

APPENDIX B
(Sample WT_Perf files)

Sample Input File

```
-----  WT_Perf Input File  --------------------------------------------
---------
WT_Perf Test03 input file.  Three-bladed CART turbine (Dimen, Metric,
Tab, PROPX).  10 meter rect blade at 15mph wind and 30 rpm  Parametric
Blade
Compatible with WT_Perf v3.00f
-----  Input Configuration  -------------------------------------------
---------
False                 Echo:                      Echo input parameters
to "echo.out"?
True                  DimenInp:                  Turbine parameters are
dimensional?
True                  Metric:                    Turbine parameters are
Metric (MKS vs FPS)?
-----  Model Configuration  -------------------------------------------
---------
1                     NumSect:                   Number of
circumferential sectors.
90000                 MaxIter:                   Max number of
iterations for induction factor.
1.0e-6                ATol:                      Error tolerance for
induction iteration.
1.0e-6                SWTol:                     Error tolerance for
skewed-wake iteration.
-----  Algorithm Configuration  ---------------------------------------
---------
True                  TipLoss:                   Use the Prandtl tip-
loss model?
True                  HubLoss:                   Use the Prandtl hub-
loss model?
True                  Swirl:                     Include Swirl effects?
False                 SkewWake:                  Apply skewed-wake
correction?
True                  AdvBrake:                  Use the advanced brake-
state model?
False                 IndProp:                   Use PROP-PC instead of
PROPX induction algorithm?
False                 AIDrag:                    Use the drag term in
the axial induction calculation.
False                 TIDrag:                    Use the drag term in
the tangential induction calculation.
-----  Turbine Data  --------------------------------------------------
---------
3                     NumBlade:                  Number of blades.
10.819                RotorRad:                  Rotor radius [length].
0.819                 HubRad:                    Hub radius [length or
div by radius].
0.0                   PreCone:                   Precone angle, positive
downwind [deg].
```

```
   0.00              Tilt:                    Shaft tilt [deg].
   0.00              Yaw:                     Yaw error [deg].
  40.00             HubHt:                   Hub height [length or
                       div by radius].
4                  NumSeg:                  Number of blade segments
                     (entire rotor radius).
                 RElm    Twist   Chord  AFfile  PrntElem
                 1.320   10.000   1.5000     1      True
                 3.320    8.000   1.1250     1      True
                 6.320    6.000   0.8750     1      True
                 9.320    4.000   0.5000     1      True
  -----  Aerodynamic Data  --------------------------------------------
                          ---------
   1.225                                Rho:                 Air
                     density [mass/volume].
1.7E-05                               KinVisc:            Kinematic
                        air viscosity
  0.0                                  ShearExp:            Wind
                  shear exponent (1/7 law = 0.143).
 False                                UseCm                 Are Cm
                 data included in the airfoil tables?
1                                     NumAF:              Number of
                        airfoil files.
   airfoils\cart3\c3_16-20_s817.dat        AF_File:  List of NumAF
                        airfoil files.
-----  I/O Settings  --------------------------------------------------
                          ---------
   True              TabDel:                  Make output tab-
                  delimited (fixed-width otherwise).
  True              KFact:                   Output dimensional
                parameters in K (e.g., kN instead on N)
True                WriteBED:               Write out blade element
                     data to "<rootname>.bed"?
 False               InputTSR:                Input speeds as TSRs?
"mps"               SpdUnits:                Wind-speed units (mps,
                          fps, mph).
-----  Combined-Case Analysis  ----------------------------------------
                          ---------
0                   NumCases:               Number of cases to run.
                 Enter zero for parametric analysis.
 WS or TSR   RotSpd   Pitch                   Remove following block
                    of lines if NumCases is zero.
-----  Parametric Analysis (Ignored if NumCases > 0 )  ----------------
                          ---------
  3                  ParRow:                  Row parameter    (1-
                     rpm, 2-pitch, 3-tsr/speed).
  2                  ParCol:                  Column parameter (1-
                     rpm, 2-pitch, 3-tsr/speed).
  1                  ParTab:                  Table parameter  (1-
                     rpm, 2-pitch, 3-tsr/speed).
True                OutPwr:                 Request output of rotor
                           power?
 True                OutCp:                   Request output of Cp?
True                OutTrq:                 Request output of shaft
                           torque?
 True                OutFlp:                  Request output of flap
                       bending moment?
```

```
True                OutThr:                   Request output of rotor
                         thrust?
  0,0, 1               PitSt, PitEnd, PitDel:     First, last, delta
                          blade pitch (deg).
 30, 30, 1.0            OmgSt, OmgEnd, OmgDel:     First, last, delta
                          rotor speed (rpm).
   2, 20, 2            SpdSt, SpdEnd, SpdDel:     First, last, delta
                             speeds.
```

Sample Airfoil Data File (ADF) File

```
AeroDyn airfoil file.  Compatible with AeroDyn v13.0.
1*S818 + 6*S816 - Generated by M. Buhl.
Data came from Eppler data that was extended and blended by
AirfoilPrep.
   5        Number of airfoil tables in this file
   2.0      Table ID parameter (Reynolds number in milllions).  For
efficiency, make very large if only one table.
   7.00     Stall angle (deg)
  -3.3859   Zero Cn angle of attack (deg)
   6.0875   Cn slope for zero lift (dimensionless)
   1.1035   Cn extrapolated to value at positive stall angle of attack
  -0.6098   Cn at stall value for negative angle of attack
  -1.00     Angle of attack for minimum CD (deg)
   0.0051   Minimum CD value
-180.00    0.000   0.0100
-170.00    0.611   0.0445
-160.00    0.611   0.2133
-150.00    0.689   0.4719
-140.00    0.729   0.7893
-130.00    0.704   1.1273
-120.00    0.607   1.4453
-110.00    0.444   1.7051
-100.00    0.234   1.8756
 -90.00    0.000   1.9364
 -80.00   -0.234   1.8756
 -70.00   -0.444   1.7051
 -60.00   -0.607   1.4453
 -50.00   -0.704   1.1273
 -40.00   -0.729   0.7893
 -30.00   -0.689   0.4719
 -20.00   -0.611   0.2133
 -10.00   -0.611   0.0445
  -4.00   -0.066   0.0087
  -3.00    0.037   0.0082
  -2.00    0.145   0.0077
  -1.00    0.255   0.0051
   0.00    0.363   0.0052
   1.00    0.470   0.0053
   2.00    0.576   0.0053
   3.00    0.681   0.0055
   4.00    0.785   0.0057
```

```
   5.00    0.888   0.0059
   6.00    0.990   0.0062
   7.00    1.019   0.0148
   8.00    0.970   0.0247
   9.00    0.922   0.0346
  10.00    0.873   0.0445
  20.00    0.873   0.2133
  30.00    0.984   0.4719
  40.00    1.042   0.7893
  50.00    1.006   1.1273
  60.00    0.867   1.4453
  70.00    0.634   1.7051
  80.00    0.334   1.8756
  90.00    0.000   1.9364
 100.00   -0.234   1.8756
 110.00   -0.444   1.7051
```

Sample .BED File

```
Blade-element data generated by WT_Perf (v3.10b-mlb, 02-Jul-2004) for
input file "parametric.wtp".
Generated on 22-Feb-2007 at 07:51:06.
Input file title:
  WT_Perf Test03 input file.  Three-bladed CART turbine (Dimen, Metric,
Tab, PROPX).  10 meter rect blade at 15mph wind and 30 rpm  Parametric
Blade


Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 2  m/s.

Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0         4.4       0.392       0.995       0.587
0.053   10.72        0.72      0.440       0.005       1.161
0.205  0.426             7.9          1.8        0.017
  2    180.0        10.6       0.701       1.000       0.391
0.009    6.60       -1.40      0.211       0.006       0.956
0.083  0.431            16.3          4.7        0.132
  3    180.0        19.9       1.027       1.000       0.323
0.002    3.89       -2.11      0.133       0.008       0.878
0.009  0.086            28.5          1.8        0.050
  4    180.0        29.3       0.863       0.999       0.415
0.001    2.28       -1.72      0.176       0.007       0.973
0.000  0.006            46.5          0.2        0.005

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 4  m/s.
```

```
Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0         5.5       0.487       0.901       0.320
0.158   29.53       19.53      0.873       0.205       0.889
0.260  0.269           24.1          9.3         0.088
  2    180.0        11.0       0.731       1.000       0.416
0.035   12.22        4.22      0.808       0.006       0.974
0.204  0.531           66.4         46.1         1.303
  3    180.0        20.2       1.040       1.000       0.333
0.009    7.58        1.58      0.532       0.005       0.890
0.109  0.543          115.5         89.7         2.539
  4    180.0        29.5       0.868       0.945       0.273
0.003    5.66        1.66      0.540       0.005       0.750
0.067  0.489          143.5        119.2         3.368

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 6  m/s.

Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0         7.0       0.617       0.832       0.203
0.229   43.17       33.17      1.002       0.573       0.827
0.197  0.136           50.4         15.9         0.150
  2    180.0        12.0       0.794       1.000       0.150
0.041   25.16       17.16      0.873       0.165       0.556
0.143  0.249           85.3         72.9         2.059
  3    180.0        20.7       1.064       0.996       0.261
0.017   12.39        6.39      1.001       0.010       0.769
0.161  0.534          224.6        297.5         8.418
  4    180.0        29.8       0.877       0.859       0.208
0.006    9.17        5.17      0.905       0.006       0.566
0.088  0.427          243.8        351.3         9.926

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 8  m/s.

Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0         8.7       0.764       0.799       0.150
0.293   51.73       41.73      1.036       0.848       0.831
0.183  0.095           90.1         26.2         0.247
  2    180.0        13.1       0.868       0.999       0.094
0.048   33.57       25.57      0.935       0.357       0.425
0.095  0.124          115.7         86.2         2.436
  3    180.0        21.4       1.100       0.974       0.112
0.016   19.40       13.40      0.873       0.102       0.405
0.092  0.227          210.0        300.1         8.490
```

```
  4    180.0        30.3       0.891       0.769       0.118
0.006   13.47        9.47      0.899       0.039       0.324
0.063  0.230           248.2        448.4       12.669
```

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 10 m/s.

```
Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0        10.5       0.922       0.781       0.116
0.347   57.70       47.70      1.014       1.050       0.847
0.176  0.073           143.5         39.3        0.371
  2    180.0        14.4       0.954       0.997       0.069
0.056   40.21       32.21      0.997       0.542       0.374
0.077  0.081           159.2        109.2        3.086
  3    180.0        22.2       1.143       0.951       0.073
0.016   24.67       18.67      0.873       0.191       0.284
0.062  0.124           230.6        318.8        9.020
  4    180.0        30.9       0.908       0.706       0.078
0.006   17.38       13.38      0.873       0.102       0.211
0.040  0.117           251.9        445.4       12.586
```

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 12 m/s.

```
Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0        12.3       1.086       0.770       0.094
0.394   62.00       52.00      0.978       1.191       0.863
0.174  0.060           210.4         56.0        0.529
  2    180.0        15.9       1.050       0.993       0.054
0.063   45.67       37.67      1.028       0.715       0.348
0.067  0.058           213.5        135.9        3.839
  3    180.0        23.2       1.192       0.928       0.056
0.018   29.29       23.29      0.909       0.298       0.231
0.046  0.075           270.1        335.7        9.499
  4    180.0        31.6       0.928       0.659       0.058
0.006   20.99       16.99      0.873       0.163       0.155
0.029  0.070           266.2        457.4       12.925
```

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 14 m/s.

```
Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0        14.2       1.254       0.763       0.078
0.434   65.28       55.28      0.933       1.295       0.877
0.171  0.051           290.9         74.9        0.707
```

```
  2    180.0        17.4       1.153       0.991       0.044
0.070   50.19       42.19      1.034       0.863       0.332
0.061  0.045           277.3       167.9        4.744
  3    180.0        24.3       1.248       0.908       0.046
0.019   33.43       27.43      0.956       0.406       0.202
0.037  0.053           321.7       374.5      10.597
  4    180.0        32.3       0.951       0.624       0.046
0.006   24.39       20.39      0.877       0.223       0.122
0.022  0.045           285.6       474.4      13.405
```

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 16 m/s.

```
Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0        16.1       1.424       0.758       0.066
0.474   67.74       57.74      0.898       1.373       0.890
0.172  0.045           385.7        98.3        0.929
  2    180.0        19.1       1.262       0.988       0.036
0.075   53.97       45.97      1.021       0.991       0.322
0.056  0.036           351.2       201.6        5.696
  3    180.0        25.4       1.310       0.891       0.039
0.021   37.19       31.19      0.991       0.510       0.184
0.032  0.040           380.9       423.2      11.973
  4    180.0        33.2       0.978       0.595       0.039
0.007   27.55       23.55      0.912       0.305       0.105
0.017  0.031           321.5       477.9      13.503
```

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 18 m/s.

```
Element     Azimuth     Loc Vel     Re    Loss  Axial Ind.  Tang. Ind.
      Airflow Angle     AlfaD Cl    Cd    Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0        18.1       1.595       0.755       0.058
0.515   69.66       59.66      0.872       1.434       0.902
0.174  0.040           494.8       126.3        1.193
  2    180.0        20.8       1.375       0.986       0.031
0.081   57.12       49.12      1.009       1.097       0.317
0.054  0.031           436.9       248.4        7.019
  3    180.0        26.7       1.376       0.876       0.033
0.022   40.61       34.61      1.011       0.618       0.171
0.028  0.030           448.3       456.7      12.922
  4    180.0        34.2       1.007       0.573       0.034
0.007   30.52       26.52      0.945       0.382       0.093
0.014  0.023           361.9       505.4      14.280
```

Blade-element data for Rotation Rate = 30 rpm, Blade Pitch = 0 deg,
Wind Speed = 20 m/s.

```
Element     Azimuth     Loc Vel     Re     Loss  Axial Ind.  Tang. Ind.
     Airflow Angle     AlfaD Cl    Cd     Thrust Coef Torque Coef Power
Coef  Thrust/Len  Torque/Len  Power
(-)   (deg) (m/s) (-)   (-)   (deg) (deg) (-)   (-)   (-)   (-)   (-)
      (N/m) (N)   (kW)
  1    180.0        20.0       1.768       0.752       0.051
0.548   71.31       61.31      0.836       1.479       0.909
0.173  0.036           615.6       154.9        1.463
  2    180.0        22.5       1.491       0.984       0.026
0.086   59.82       51.82      0.981       1.185       0.311
0.052  0.027           530.6       292.5        8.264
  3    180.0        28.1       1.447       0.863       0.029
0.024   43.69       37.69      1.029       0.716       0.162
0.025  0.025           524.6       516.2       14.606
  4    180.0        35.3       1.038       0.554       0.030
0.008   33.32       29.32      0.976       0.454       0.085
0.013  0.018           406.7       557.6       15.757
```

Sample .OUP File

```
Results generated by WT_Perf (v3.10b-mlb, 02-Jul-2004) for input file
"parametric.wtp".
Generated on 22-Feb-2007 at 07:51:06.
Input file title:
  WT_Perf Test03 input file.  Three-bladed CART turbine (Dimen, Metric,
Tab, PROPX).  10 meter rect blade at 15mph wind and 30 rpm  Parametric
Blade

-----------------------------------------------------------------------
---------
Power (kW) for Omega = 30 rpm.

WndSp Pitch (deg)
(mps)   0.000
  2.000          0.205
  4.000          7.297
  6.000         20.553
  8.000         23.843
 10.000         25.062
 12.000         26.791
 14.000         29.453
 16.000         32.100
 18.000         35.414
 20.000         40.089

-----------------------------------------------------------------------
---------
Cp (-) for Omega = 30 rpm.

WndSp Pitch (deg)
(mps)   0.000
  2.000      0.1137
  4.000      0.5062
  6.000      0.4225
  8.000      0.2068
```

```
 10.000      0.1113
 12.000      0.0688
 14.000      0.0477
 16.000      0.0348
 18.000      0.0270
 20.000      0.0222

------------------------------------------------------------------------
---------
Torque (kN-m) for Omega = 30 rpm.

WndSp Pitch (deg)
(mps)   0.000
  2.000           0.065
  4.000           2.323
  6.000           6.542
  8.000           7.589
 10.000           7.978
 12.000           8.528
 14.000           9.375
 16.000          10.218
 18.000          11.273
 20.000          12.761

------------------------------------------------------------------------
---------
Flap bending moment (kN-m) for Omega = 30 rpm.

WndSp Pitch (deg)
(mps)   0.000
  2.000           1.782
  4.000           6.074
  6.000          10.586
  8.000          10.706
 10.000          11.493
 12.000          12.951
 14.000          14.818
 16.000          17.312
 18.000          20.150
 20.000          23.317

------------------------------------------------------------------------
---------
Thrust (kN) for Omega = 30 rpm.

WndSp Pitch (deg)
(mps)   0.000
  2.000           0.845
  4.000           3.000
  6.000           5.133
  8.000           5.435
 10.000           6.205
 12.000           7.379
 14.000           8.835
 16.000          10.641
 18.000          12.709
 20.000          15.005
```

APPENDIX C-G

Please refer to official Report
(Submitted to Dr. Eggert; Boise State University)