A HORIZONTAL AXIS WIND TURBINE PERFORMANCE PREDICTION CODE FOR PERSONAL COMPUTERS

(User's Guide)

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Under contract to the Wind Energy Research Center (WERC), four contractors exercised their performance prediction methods to predict the performance of two horizontal axis machines (Reference 1). Based on the results of that study, one of the methods (AeroVironment blade-element/momentum PROP code) was adopted for routine performance calculations at the WERC. Desirable features of the Aerovironment PROP code are that it is an efficiently written short code which can sweep tip speed ratio and blade pitch in one computer run. The code includes the Glauert approximation for low wind speed analysis and can accommodate a different airfoil data table for each blade element. In its original form this code had a few limitations. All calculations were done in a nondimensional format with performance expressed in terms of power coefficient versus tip speed ratio. The program was originally written with the blade segment number fixed at ten and no provisions were included to account for yawed flow effects. To enhance its capability, the WERC has added the following improvements:

o The code was reprogrammed for dimensional output

o variable input blade segment number (up to 20) was added

o crossflow effects were included to analyze rotors operating off the wind axis or with shaft tilt.

o a 3-D post-stall airfoil data synthesization routine was added (Reference 2) for better performance prediction at high wind speeds.

Some of the key features of the WERC modified-AeroVironment PROP code designated PROPSH are discussed in the following sections.

The Glauert Approximation

The use of the Glauert empirical approximation resulted from the inability of inviscid momentum theory to model the viscous flow conditions of the wake at low wind speeds during the presence of strong rotor/wake interaction. In this so-called windmill brake region, calculated thrust coefficients derived from a blade-element/momentum

balance are abnormally low relative to measured values. The Glauert empirical relationship, which is based on measured values (Reference 3), is used in lieu of momentum theory at low wind speeds when the axial induction at the blade exceeds 38 percent of the free stream value. This typically occurs at low wind speeds for blade pitch angles away from optimum performance toward stall.

3-Dimensional Post-Stall Synthesization

Development of the 3-D post-stall airfoil data synthesization subroutine was motivated by the inadequacy of 2-D airfoil data tables in predicting maximum power. Typically, post-stall 2-D airfoil data tables substantially under-predict peak power. For a horizontal axis wind turbine, stall originates at the blade root. With an increase in wind speed, stall propagates outboard along the blade. When peak power is reached, most of the blade is stalled. The stall region experiences angles of attack in the range of 15 to 40 degrees with the angular distribution decreasing toward the tip. In the stall region, the airfoil data characteristics become less dependent on airfoil geometry and Reynolds number and more governed by 3-D effects. The 3-D effects are, in large part, influenced by the blades' aspect ratio. This is the scenario upon which the 3-D post-stall synthesization (Reference 2) is based. A convenient feature of this routine is that it automatically provides a smooth curve fit from where the 2-D data leaves off up through the highest stalled angle of attack experienced by each blade section. The resulting synthesization is dependent only on the blades' characteristic aspect ratio. Although this method provides a better estimate of peak power it still underpredicts peak power by 3 to 15 percent (Reference 4). The remaining underprediction is thought to be due to additional, unaccounted for stall relief resulting from radial flow effects induced by the spanwise pressure gradient associated with blade rotation. Work is in progress to refine the synthesization theory so that this shortcoming of the program can be eliminated.

Cross-Flow/Shaft-Tilt Effects

Yawed flow effects are neglected by most performance prediction codes. A designer typically assumes his machine will operate on the wind axis. However, experience shows that, particularly for downwind machines, it is the exception rather than the rule for a machine to accurately track the wind throughout its operating range.

The causes of off-axis operation are numerous. Two common causes are rotor shaft tilt for tower clearance purposes and tower shadow-induced asymmetrical loading for downwind machines. If off-axis operation is not corrected, a machine can have a wind tracking error up to 10 to 30 degrees depending on the wind speed. Substantial losses in aerodynamic efficiency will result by allowing a machine to operate off-axis by more than 10 degrees. Aerodynamic performance codes need to accommodate this parameter so that predicted performance can be compared to measured performance. This capability is important not only for predicting net power but for calculating cyclic blade loads.

REFERENCES

1. Horizontal Axis Wind System Rotor Performance Model Comparison, Rockwell International, February 1983, (RFP-3508).

2. Viterna, L. A. and Janetzke, D. C., "Theoretical and Experimental Power from Horizontal Axis Wind Turbines," Fifth Biennial Wind Energy Conference and Workshop, October 1981, Washington, D.C.

3. Glauert, H., "The Analysis of Experimental Results in the Windmill Brake and Vortex Ring States of an Airscrew," Reports and Memoranda, No. 1026, AE 222, February 1926.

4. Tangler, J. L. and Ostowari, C., "Horizontal Axis Wind Turbine Post Stall Airfoil Characteristics Synthesization," DOE/NASA Wind Turbine Technology Workshop, May 1984, Cleveland, Ohio.

Nomenclature

a axial interference factor at the plane of the rotor

a' circumferential interference factor at the plane of the rotor

C_D drag coefficient

C_L lift coefficient

c/R nondimensional chord

d/R nondimensional hub height

J advance ratio

ℓ local blade element

MD blade root bending moment

NS number of blade segments (or elements)

P_C power coefficient (used in PROPSH for C_p)

Q_C torque coefficient

r/R nondimensional radius along blade

T_C thrust coefficient

X tip speed ratio

Symbols

α angle of attack

β angle measured from the plane of rotation to the blade chord line which describes blade twist

δ rotor solidity ratio

ϕ inflow angle

$\neq$ not equal to

USER'S MANUAL FOR THE PROPSH CODE

The PROPSH code calculates tabulated output of rotor performance parameters as a function of either tip speed ratio (wind turbine default option) or advance ratio (propellers) for a given set of blade pitch angles. Whether the rotor is specified as a wind turbine or propeller, the principles used for the calculation are the same. The following paragraphs provide details of the required input data file.

The PROPSH code is programmed in FORTRAN computer language and all input data lines have the format (7F10.0). The following is a line-by-line description of the input data set which is read sequentially during the execution of the program.

INPUT

Line 1

RD	- blade radius, ft.
RPM	- rotor revolutions per minute
RHO	- air density, slugs/ft.^{3}

Line 2

BN	- number of blades
CONE	- cone angle of rotor, degrees
HUB	- normalized hub radius (i.e., ratio of hub radius to rotor radius)

Line 3

LTIP	- tip loss model:	0 = none
		1 = Prandtl loss model
LHUB	- hub loss model:	0 = none
		1 = Prandtl loss model

USEAP	- swirl suppression:	0 = suppress swirl
		1 = include effects of swirl
IBR	- brake state model:	0 = classical model
		= advance model

Line 4

| MODE | - rotor type: | = turbine |
| | | -1 = propeller |

The mode parameter does not change the results of the analysis but only changes the sign of some output values. These values are P_C, T_C, Q_C, C_p, and $\underline{a}$. In addition, the definition of α, the angle of attack, is changed as shown:

propeller $\qquad \alpha = \phi - \beta$

wind turbine $\qquad \alpha = \beta - \phi$

WEXP	- wind boundary layer profile exponent. If this is zero **HH** and **NSEC** are automatically set to 1.0 and do not need to be input.
HH	- normalized hub height (i.e., ratio of hub height to rotor radius).
NS	- number of segments (or elements) comprising the blade. A typical value is 10, and the maximum value is 20.
NSEC	- number of circumferential sectors to be used in the analysis. If WEXP $\neq 0$ or rotor shaft or yaw angle $\neq 0$, NSEC will default to 4 if NSEC is less than this required value.

Lines 5 to Line (4 + NS) (Blade Geometry Data)

The code considers the blade split into NS equal segments; for each element the following data pair is required (1 set per line) (see attached example).

CH[1]   - normalized blade chord (i.e., ratio of blade chord to rotor radius).

TW   - blade twist angle, degrees (positive value toward feather).

Line (5 + NS)

The next several lines of data describe the airfoil performance characteristics at each element. The data begins with element 1.

NS   - blade segment number (from 1 to NS).

MM   - the number of points required to define the α versus C_L curve for the airfoil shape at each element.

NN   - the number of points required to define the α versus C_D curve for the airfoil shape at each blade element or segment.

Line (6 + NS) to Line (5 + NS + MM + NN)

Each of these lines contain one coordinate pair defining successive points on the airfoil characteristic curves. First, the α versus C_L curve is defined beginning with the most negative angle of attack with the coordinates in the order:

AL   - angle of attack, degrees.

CL   - lift coefficient.

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[1]Do not alter the chord distribution to represent a blade root cutout. The blade's chord distribution must be determined based on an extrapolation to the rotor's center of rotation. This procedure ensures calculation of the proper equivalent chord upon which the post stall airfoil data synthesization routine is based.

Following these data, the α versus C_D coordinates are then required in a similar form:

AD   - angle of attack, degrees.

CD   - drag coefficient.

For angles of attack greater than those covered by the user's input data, the program synthesizes airfoil data based on a stalled flat plate with an effective aspect ratio corresponding to that of the blade. Two options are available. The post stall synthesization method (default option) is preferred and requires no user interaction. This method provides a smooth curve fit to where the 2-D data ends. The second method is the AeroVironment flat plate model which requires some work on the user's part to interface with the 2-D data. To properly interface with the AeroVironment flat plate characteristics, it is good practice to include the point α = 26.5,, C_L = 1.047 and C_D = 0.522 as the last points in input data. If negative angles of attack are important, then the point α = -26.5,, C_L = -1.047 and C_D = 0.522 can be used as the first data points.

Data of the same form as for Line (5 + NS) onwards is then required for elements 2 through 10 in order. However, provision has been made so that the quantity of input data can be reduced when two or more blade segments have the same airfoil characteristics. If, for example, segment 7 has the same airfoil shape as segment 3, then the total data needed for segment 7 becomes:

NS   = 7 (segment number).

MM   = 0 (no new data required).

NN   = 3 (airfoil characteristics are the same as for segment 3).

No further data for segment 7 is necessary and data for segment 8 must follow, which may or may not also be of this form. The variable NS is used by the program only to check that the input data is in correct order. An error will result if this is not the case. Up to 14 coordinate points for each C_L or C_D curve can be input.

Data to this point will occupy a different number of lines depending on the rotor. Assume that the last line used is N so that the following input lines begin with N + 1.

Line N + 1

ISI   - the number of the first segment to be used in the analysis. This will normally be 1. The computer will automatically ignore elements completely inside the radius specified by HUB.

IS2   - the last segment to be used in the analysis. This will generally by NS, but if IS2 = ISI, the performance of a particular segment can be examined and optimized individually.

Line N + 2

FS   - the most negative pitch angle to be examined, degrees.

FF   - the most positive pitch angle to be examined, degrees.

FD   - the increment in pitch angle, degrees.

Line N + 3

IS	- blade elements data	0 = none
		1 = blade element data printed
INCV	- tip speed ratio or advance ratio	0 = tip speed ratio (wind turbine)
		1 = advance ratio (propeller)
ISTL	- post stall airfoil data synthesization	0 = flat plate model
		1 = Viterna stall routine

Line N + 4

SH   - (Y or N), this variable determines whether asymmetrical loading due to shaft tilt or yaw angle is calculated. A "yes" reply includes crossflow effects in calculating performance. A "no" reply assumes the rotor is properly oriented with the wind direction. (Note: yaw angle can be

treated as a shaft tilt only if wind shear is neglected), degrees

Line N + 5

XJS
    - the lowest value of tip speed ratio (X) or advance ratio (J) to be considered. Dimensional values of mph, m/sec, or ft/sec can be used in place of tip speed ratio.

XJE
    - the largest value of tip speed ratio (X) or advance ratio (J) to be considered.

DXJ
    - the increment in tip speed ratio (X) or advance ratio (J).

IXDIM
    - 3 = tip speed ratio
       2 = mph
       1 = m/sec
       0 = ft/sec

OUTPUT

All data read by the program are output exactly as read. This allows easy checking of the input given to the program.

The program first outputs the rotor geometry. This includes the number of blades, rpm, radius, hub cutout, air density, cone angle, shaft tilt, and the tip and hub loss models. Following this the brake state model to be used is listed; the post stall airfoil data synthesization method used is listed; and the analysis mode (wind turbine or propeller) is listed. The wind shear, ratio of hub height to rotor radius, and the number of blade and circumferential stations used are then listed.

The blade element data for each of the NS segments are now output. For each segment, the blade chord and twist are given.

The airfoil section data (the data points making up the α versus C_L and α versus C_D curves) are now listed for each segment. The segments which are included in the analysis are then output followed by the results of the analysis.

The program sets the pitch angle to the initial value prescribed by the input and analyzes the rotor at all the desired tip speed ratios or wind speeds. The pitch angle is then incremented and the analysis is repeated. In this manner, the performance at all of the desired pitch angles is analyzed. At each value of X or J, the values of X, T_C, Q_C, P_C and the efficiency are given along with dimensional output.

If blade element data are to be output then the values of $\underline{a}$, a', section C_L and C_D, the airflow angle, ϕ the angle of attack, α, T_{C_P}, Q_{C_P}, and P_{C_P} are given for each blade segment along with dimensional output. If more than one circumferential station is specified, then the results for each station are given. The circumferential angle for the current station is output along with the freestream flow velocity at that point.

EXAMPLE INPUT FILE FOR PROPSH (ENERTECH 1500)

Radius, ft.	RPM	Air Density, slugs/ft.^{3}
6.56	162.0	0.002378

Blade Number	Coning Angle	Hub Cut-out, r/R
3.0	0.0	0.25

Tip Loss	Hub Loss	Swirl Suppression	Brake State Model
1.0	1.0	1.0	1.0

Mode	Wind Exp.	Hub Height, d/R	Number of Blade Segments	Number of Circular Sectors
1.0	0.00	6.0	10.0	1.0

Blade* Stations	Nondimensional Chord, c/R	Blade Twist, deg.
5%	0.089	0.000
15%	0.089	4.870
25%	0.089	4.300
35%	0.089	3.730
45%	0.089	3.150
55%	0.089	2.580
65%	0.089	2.010
75%	0.089	1.430
85%	0.086	0.860
95%	0.084	0.287

hub center

*Location of blade segment centers from ~~root~~ to tip when 10 stations are used. (just a reference, not an input)

Blade Segment Number	Number of Lift Coefficients	Number of Drag Coefficients
1.0	5.0	6.0

Left column:

1.0

-7.0
6.0
10.0 } angles for C_L
14.0
18.0

-6.0
0.0
2.0 } angles for C_D
5.0
8.0
14.0

2.0
3.0
4.0
5.0
6.0 } blade segments 2-10
7.0
8.0
8.0
10.0

First Blade Segment

1.0

First Blade Pitch

-1.0

Blade Element Data

0.0

Shaft Angle

0.0

Middle column:

5.0

-0.400
1.000
1.200 } values of C_L
1.260
0.990

0.038
0.024
0.023 } values of C_D
0.026
0.035
0.085

0.0
0.0
0.0
0.0
0.0 } zero indicates segments C_L, C_D are a repeat
0.0
0.0
0.0
0.0

Last Blade Segment

10.0

Last Blade Pitch

4.0

Wind Turbine Propeller

0.0

Right column:

6.0

1.0
1.0
1.0
1.0
1.0 } indicates repeat segment 1 C_L, C_D data
1.0
1.0
1.0
1.0

Increment Size

1.0

Viterna Stall Routine

1.0

Bottom row:

First X or Wind Speed	Last X or Wind Speed	Increment Size	3 = X, 2 = mph 1 = m/sec, 0 = ft/sec
2.0	12.0	2.0	3.0

Input File WTS4.IPT

radius	rpm	density
128.0	48.6	0.00191

2.0 blade no. 6.0000 coning 0.15 root cutout

1.0 tip loss 1.0 hub loss 1.0 swirl app 1.0 brake state

1.0 mode 0.00000 wind exp. 2.05 tower height 10.0 blade segments 1.0 circular sectors

chord, c/R	twist, deg.
0.050	16.8
0.120	15.4
0.114	9.4
0.106	5.3
0.094	3.0
0.082	1.6
0.068	0.6
0.054	0.0
0.041	-.2
0.031	-.4

1.0 station. 7.0 no. of C_ℓ 9.0 no. of C_d

	C_ℓ
-4.0000	-.3000
.0000	.1000
4.0000	.4400
8.0000 γ	.8200
12.0000	1.1300
14.0000	1.2000
15.0000	1.1200

	C_d
-4.0000	.0083
.0000	.0084
4.0000	.0095
6.0000	.0106
8.0000 γ	.0122
10.0000	.0152
12.0000	.0194
14.0000	.0230
15.0000	.0320

station no. for airfoil data	repeats	station 1 repeated
2.0	0.0	1.0
3.0	0.0	1.0
4.0	0.0	1.0
5.0	0.0	1.0
6.0	0.0	1.0
7.0	0.0	1.0
8.0	0.0	1.0
9.0	0.0	1.0
10.0	0.0	1.0

1.0 — to — 10.0 blade segments

-1.00 2.0 1.0 blade pitch sweep

0.0 no blade ele. data 0.0 tip speed ratio 1.0 stall routine (Viterna) used

0.0 shaft angle (windturbine)

2.0 10.0 1.0000, 3.0000 tip speed ratio

tip speed ratio sweep or mph, m/sec, ft/sec

2 mph
1 m/sec
0 ft/sec

To Execute PROPPC

PROPPC — execution command

WTS4.IPT — specify input data set

WTS4.OPT — specify name for output data set