SERI/TR-35-225

May 1979

Summary of Currently Used Wind Turbine Performance Prediction Computer Codes

Fred Perkins

Solar Energy Research Institute
A Division of Midwest Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

Operated for the
U.S. Department of Energy
under Contract No. EG-77-C-01-4042

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Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $4.50

SERI/TR-35-225
UC CATEGORY: UC-60

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FOREWORD

This work was done as part of the SAT (Systems Analysis and Testing) program, SERI Task 3525. This is a preliminary report; revised editions will be issued periodically. The author thanks Charles J. Bishop for his support and direction.

Neil H. Woodley
Branch Chief
Systems Analysis

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

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ABSTRACT

Information on currently used wind turbine aerodynamic/economic performance prediction codes is compiled and presented. Areas of interest to wind energy researchers that are not included in the reported codes are identified. Areas which are weak in experimental support are also identified.

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SECTION 1.0

INTRODUCTION

A variety of system simulation models and design tools have been developed in recent years for wind systems. No single document, however, describes what is available for use by those interested in wind systems. Therefore, a study was undertaken to characterize and document those simulation models and design tools which are currently available in either the public domain or the private sector. The purpose of this study was to establish a compendium of existing models and tools which could be (1) made available to the general public, (2) periodically updated, (3) used as a basis of determining additional needs when user requirements/needs are defined, and (4) used to minimize duplication of efforts in future work.

All models and tools may not have been identified in this limited study, so a periodic update is anticipated that will include items previously missed or recently developed. Persons aware of items which should be added to this database should contact the Solar Energy Research Institute (SERI).

SECTION 2.0

SCOPE

SERI solicited information relating only to wind turbine aerodynamic and/or economic performance. While it is recognized that structural dynamics are of vital interest to the wind industry, the applicable codes are not included in this report. Future editions of the report will contain such information.

All of the contractors identified in the Program Summary of the Federal Wind Energy Program (1/78, DOE/ET-0023/1) having contracts with Rocky Flats, SERI, or NASA-Lewis Research Center were contacted for the information presented in this report. Sandia Laboratories, JBF Scientific, and NASA-LeRC were also contacted. In all, a total of 25 organizations were polled. Seventeen organizations responded, but seven of the respondents chose not to include information about their own codes and some organizations reported more than one code. As a result, 17 individual codes were identified. We did not attempt to contact any independent manufacturers or other investigators, but future data collection hopefully will encompass all identifiable interested parties. We also did not try to validate any of the information received. The individual respondents should be contacted for details or elaboration.

SECTION 3.0

THE CODES

Six of the codes (Version 16, SERIES/Winds, Wind Optimization, VAWTOP, Wind Off Design, SIMWEST) address wind system economics. Two of the codes (CROFTAN, Giromill Performance) address the aerodynamic properties of giromills. One of the codes (PAREP) addresses Darrieus VAWT (Vertical Axis Wind Turbine) aerodynamic performance. All of the other codes [F762, G400, Goldstein P.A., PROP (NASA-LeRC), PROP (Aerovironment), ROTOR, WRFP, UTRC PWPA, SIMWEST] address the aerodynamic performance of HAWT (Horizontal Axis Wind Turbines).

All of the codes assume the existence of an infinite bus, that is, the machine is always producing power with an output impedance matching the load input impedance. Thus, all of the available power is assumed to be used. Most of the codes use a single wind speed as input. Such codes are primarily tools for the designer. Loads, torque, and power are part of the output. All but one of the codes (WRFP) are written in FORTRAN or FORTRAN IV. WRFP is written in BASIC and may be run on a programmable desk calculator. ROTOR may be run on a minicomputer. All of the other codes are written for mainframe computers.

The SERIES/Winds program allows the inclusion of up to five years of weather data in the analysis and is a tool for economic planners. The Wind Optimization Code, VAWTOP, and Wind Off Design programs automatically optimize a wind turbine design under certain wind speed conditions.

F762 and G400 are the only aeroelastic codes reported. Both have been adapted for the analysis of HAWT machines.

Table 3-1 presents a summary of the codes and their characteristics. More complete descriptions of each code follow the table.

Table 3-1. SUMMARY OF CODES

	Name of Code																
	WRFP	WIND OPT.	VERSION 16	VAWTOP	UTRC PWPA	SIMWEST	SERIES/WINDS	ROTOR	PROP[b]	PROP[a]	PAREP	OFF DESIGN	GOLDSTEIN P.A.	GIROMILL PERF.	G400	F762	CROFTAN
Date Available																	
(if not presently available)					h								h			h	
Documentation																	
User's manual[c]	●	●	●		●		●	●	●	●	●	●			●	●	●
Program manual[d]			●			●		●	●								
References	●		●			●			●	●	●			●	●		●
Rotor Types																	
High speed horizontal[e]	●	●			●	●	●	●	●	●		●	●		●	●	
Darrieus			●	●							●						
Giromill														●			●
Control Strategy																	
Constant speed	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●
Constant tip speed rate					●	●		●	●				●	●			
Inputs																	
Single wind speed	●					●		●	●	●	h		●	●	●	●	●
Wind speed distribution		●	●	●	●	●		●				●				●	●
Weather tapes						●	●										
Type of Code																	
Design tool[f]	●				●			●	●	●	●		●	●			●
Economic Analysis[g]		●	●	●		●	●					●					
Aeroelastic Analysis															●	●	
Experimental Verification																	
Wind tunnel					●			●	●		●		●	●	●	●	
Field data	●							●	●	●	●				●	●	●

[a]NASA Lewis Research Center version.
[b]Aerovironment version.
[c]Users manual is the minimum description of the program necessary for its operation.
[d]Program manual is a detailed operations manual including instructions for program modifications.
[e]A high speed wind turbine is one in which the linear speed of some portion of the rotating parts is five times or more the oncoming wind speed during normal operations.
[f]The output of these codes includes the loads and power output of a particular wind turbine. This information is necessary for design.
[g]The output of these codes includes some information on the economic qualitites of the considered system.
[h]See code description in text.

NAME	CROFTAN
ORIGINATOR	West Virginia University
REFERENCE	Walters, R. E.; et al. Vertical Axis Wind Turbine Experiments and Analysis. Morgantown, WV: Dept. of Aerospace Engineering, West Virigina University; May 1978; ORO/5135-78/1.
INPUT REQUIREMENTS	Wind speed, rotor geometry
OUTPUT DATA	Loads, power
DESCRIPTION	This program is useful for the analysis of the aerodynamic performance of a giromill. Manuals have been written for the program. The program is primarily a design tool and has been verified with field data.
AVAILABILITY	In the public domain
CONTACT	Richard E. Walters Dept. of Aerospace Engineering West Virginia University Morgantown, WV 26506 (304) 293-2570

NAME	F762 - Wind Turbine Aeroelastic/Aerodynamics Analysis
ORIGINATOR	Richard L. Bielawa (United Technologies Research Center)
REFERENCE	None
INPUT REQUIREMENTS	Rotor and support geometry
OUTPUT DATA	Natural modes, natural frequencies
DESCRIPTION	This program can accommodate only a small amount of linear blade twist. The equations of motion couple the blade deflections with the support flexibility. An equivalent spring and damper is one of the load options. This program is useful for the analysis of high speed horizontal axis wind turbines. It has been verified with field and wind tunnel data.
AVAILABILITY	Currently proprietary but may be made public within one or two years
CONTACT	Richard L. Bielawa United Technologies Research Center Silver Lane MS-16 East Hartford, CT 06108 (203) 727-7154

NAME	G400 - Rotor Aeroelastics/Aerodynamics Analysis.
ORIGINATOR	Richard L. Bielawa (United Technologies Research Center)
REFERENCE	NASA. Aeroelastic Analysis for Helicopter Rotor Blades with Time Variable, Non-Linear Structural Twist and Multiple Structural Redundancy; Mathematical Derivation and Program Users Manual; 1977; CR-2638.
INPUT REQUIREMENTS	Rotor and support geometry
OUTPUT DATA	Natural modes, natural frequencies
DESCRIPTION	G400 is the successor to F762. Both codes employ elastic coupling between the blades and support. G400 allows nonlinear blade twist and the resolution of a larger number of natural frequencies than F762 allows. This program is useful for the analysis of high speed horizontal axis wind turbines. This program has been verified with both field and wind tunnel data.
AVAILABILITY	A basic rotor version is available from NASA-Langley for a fee.
CONTACT	For information: Richard L. Bielawa United Technologies Research Center Silver Lane MS-16 East Hartford, CT 06108 (203) 727-7154 For code acquisition: John Shipley or Gene Hammond Air Mobility Res. & Dev. Lab. Langley Directorate NASA Langley Research Center Hampton, VA

NAME	GIROMILL PERFORMANCE
ORIGINATOR	H. C. Larsen
REFERENCE	Giromill Wind Tunnel Test and Analysis. October 1977; COO/2617/4. Available from NTIS.
INPUT REQUIREMENTS	Rotor geometry, wind speed, tip speed ratio, desired angle of attack (actual or effective)
OUTPUT DATA	Side forces, axial forces, torque, power
DESCRIPTION	This program, still under development, is intended to be a design tool for the analysis of giromill wind turbines. The input options allow the resolution of loads with respect to either geometrically or aerodynamically constant angle of attack. The program has been verified with wind tunnel data.
AVAILABILITY	In the public domain
CONTACT	H. C. Larsen A. F. Institute of Technology/END Area B. Bldg. 640 Wright Paterson AFB, OH 45433 (513) 255-3633

NAME	GOLDSTEIN PERFORMANCE ANALYSIS
ORIGINATOR	S. Goldstein (modified by United Technologies)
REFERENCE	None
INPUT REQUIREMENTS	Rotor geometry, wind speed, angular speed
OUTPUT DATA	Power, loads
DESCRIPTION	This program is used for routine wind turbine and rotor/propeller performance calculations at the United Technologies Corp. when relatively short computer times are desired. It is a design tool for the analysis of high speed horizontal axis wind turbines and has been verified with wind tunnel data.
AVAILABILITY	Not publicly available
CONTACT	Anton J. Landgrebe United Technologies Research Center Silver Lane East Hartford, CT 06108 (203) 727-7358

NAME	OFF DESIGN
ORIGINATOR	General Electric Co.
REFERENCE	None
INPUT REQUIREMENTS	Wind speed, design wind speed
OUTPUT DATA	Energy cost, energy collected
DESCRIPTION	This is a version of the Wind Optimization Code designed to indicate economic performance at wind speeds other than the design speed. It is intended for the prediction of the economic performance of high speed horizontal axis wind turbines.
AVAILABILITY	Currently available in the public domain
CONTACT	Frank Barr General Electric Co. P.O. Box 8555 Philadelphia, PA 19101 (215) 962-2903

NAME	PAREP - Aerodynamic Performance Model for Vertical Axis Wind Turbine Systems
ORIGINATOR	Sandia Laboratories
REFERENCE	Sandia Labs. Economic Analysis of Darrieus Vertical Axis Wind Turbine Systems for the Generation of Utility Grade Electrical Power. Albuquerque, NM; 1978; SAND/78-0962, vol. II.
INPUT REQUIREMENTS	Rotor geometry, rpm
OUTPUT DATA	Power coefficient vs. tip speed ratio.
DESCRIPTION	The program models the performance of a Darrieus VAWT constrained to operate at constant rpm in conjunction with a utility grid. It is intended for use in an interactive time sharing mode. A graphics package is included for output formatting. This model has been verified with wind tunnel and field data.
AVAILABILITY	In the public domain
CONTACT	W. N. Sullivan Div. 4715 Sandia Laboratories Albuquerque, NM 87112 (505) 264-6434

NAME	PROP (Aerovironment)
ORIGINATOR	Stel N. Walker and Robert E. Wilson
REFERENCE	Walker, Stel N. "Performance and Optimum Design Analysis/Computation for Propellor Type Wind Turbines". Ph.D. Thesis, Oregon State University; 1976.
INPUT REQUIREMENTS	Rotor geometry, wind speed, rotational speed
OUTPUT DATA	Loads, torque, power
DESCRIPTION	This is an updated version of PROP (NASA-LeRC). Manuals have been written. The program is useful for the analysis of high speed horizontal axis wind turbines, and it has been verified with both field and wind tunnel data.
AVAILABILITY	Not publicly available
CONTACT	Stel N. Walker Aerovironment, Inc. 145 Vista Ave. Pasadena, CA (213) 449-4392

NAME	PROP (NASA-LeRC)
ORIGINATOR	Robert E. Wilson, Oregon State University
REFERENCE	Wilson, Robert E.; Lissaman, Peter B. S. Applied Aerodynamics of Wind Power Machines. Corvallis, OR: Oregon State University; May 1974.
INPUT REQUIREMENTS	Rotor geometry, wind speed, tip speed ratio
OUTPUT DATA	Loads, torque, power
DESCRIPTION	This program is a design tool for the analysis of high speed horizontal axis wind turbines. It computes the effects of wake interference and tip losses, and the output is in a tabular form. A program manual has been written. The program has been verified with field data.
AVAILABILITY	In the public domain
CONTACT	For questions of use by NASA: David C. Janetzke NASA-LeRC MS 49-6 21000 Brookpark Rd. Cleveland, OH 44135 (216) 433-4000 x5102 For acquiring program and manual: Robert E. Wilson Dept. of Mechanical Engineering Corvallis, OR 97331 (503) 754-2218

NAME	ROTOR
ORIGINATOR	P. M. Sforza
REFERENCE	None
INPUT REQUIREMENTS	Rotor geometry, operation mode, wind speed
OUTPUT DATA	Power, loads
DESCRIPTION	This currently available program is designed for the analysis of high speed horizontal axis wind turbines. It is a design tool and has been verified with both wind tunnel and field data.
AVAILABILITY	Private, but publicly available
CONTACT	P. M. Sforza Polytechnic Institute of New York Farmingdale, NY 11735 (516) 694-5500

NAME	SERIES/WINDS
ORIGINATOR	JBF Scientific
REFERENCE	JBF Scientific. Wind Energy Systems Application to Regional Utilities. Draft Report. Sept. 1978.
INPUT REQUIREMENTS	5 years of wind data, wind turbine power characteristics
OUTPUT DATA	Performance of an average wind turbine in an array
DESCRIPTION	This program uses up to 5 years of weather data from the National Climatic Center to establish the performance characteristics of an average wind turbine in an array, taking into account spatial and time variations between individual turbines. It considers only high speed horizontal axis wind turbines. The program has not been experimentally verified.
AVAILABILITY	In public domain
CONTACT	Martin Goldenblatt c/o JBF Scientific Corp. 2 Jewel Drive Wilmington, MA 01887 (617) 657-4170

NAME	SIMWEST
ORIGINATOR	Boeing Computer Systems
REFERENCE	NASA. A Simulation Model for Wind Energy Storage Systems. August, 1977; CR-135284.
INPUT REQUIREMENTS	System configuration wind speed, component costs
OUTPUT DATA	Energy cost, energy collected, system status
DESCRIPTION	This code is designed for the Simulation of Wind Energy Storage systems. It is a modular program arranged in subroutines representing components (e.g., wind turbines, generator, battery storage) which may be assembled at the user's discretion. Statistical treatment of the output data is available. Plots of any variables vs. any other variables are available. The program requires a large computer facility and the output requires the use of a line printer for reasonable connect times.
AVAILABILITY	In the public domain
CONTACT	Michael Connolly Solar Energy Research Institute 1536 Cole Blvd. Golden, CO 80401 (303) 231-1007

NAME	UTRC PWPA (Prescribed Wake Performance Analysis)
ORIGINATOR	A. J. Landgrebe
REFERENCE	None
INPUT REQUIREMENTS	Rotor geometry, wake geometry, wind speed
OUTPUT DATA	Rotor loads, power, torque
DESCRIPTION	This program is a design tool. Once the wake geometry and rotor geometry are specified, the loads are also specified. This program is useful for the analysis of high speed horizontal axis wind turbines and has been verified with wind tunnel data.
AVAILABILITY	This program could be made available following additional documentation, demonstration, and refinement. The cost to acquire would involve only these activities.
CONTACT	Anton J. Landgrebe United Technologies Research Center Silver Lane East Hartford, CT 06108 (203) 727-7358

NAME	VAWTOP
ORIGINATOR	General Electric Co.
REFERENCE	None
INPUT REQUIREMENTS	Rated power, design wind speed
OUTPUT DATA	Component costs optimized for minimum electricity cost; tower cost, rotor cost, gearbox cost, generator cost, blade cost; energy collected
DESCRIPTION	Using prescribed scaling factors, the program optimizes VAWT component sizes with respect to minimum energy cost. The program is dated, so the absolute numbers presented are wrong; it is useful, however, for parametric studies.
AVAILABILITY	Currently available in the public domain
CONTACT	Frank Barr General Electric Co. P.O. Box 8555 Philadelphia, PA 19101 (215) 962-2903

NAME	VERSION 16
ORIGINATOR	Sandia Laboratories
REFERENCE	Sandia Labs. Economic Analysis of Darrieus Vertical Axis Wind Turbine Systems for the Generation of Utility Grade Power. Albuquerque, NM; 1978; SAND 78-0962, vol. II.
INPUT REQUIREMENTS	System component specifications, rotor geometry, wind speed distribution .
OUTPUT DATA	Annual energy, energy cost, peak power, rated power, component cost
DESCRIPTION	This program analyzes the economic performance of a Darrieus VAWT operated at constant rpm in conjunction with a grid. It is intended for use in an interactive time sharing mode. A graphics package is included for output formatting.
AVAILABILITY	In the public domain
CONTACT	W. N. Sullivan Div. 4715 Sandia Laboratories Albuquerque, NM 87112 (505) 264-6434

NAME	WIND OPTIMIZATION CODE
ORIGINATOR	General Electric Co.
REFERENCE	None
INPUT REQUIREMENTS	Rated power, design wind speed
OUTPUT DATA	Component costs optimized for minimum electricity cost; rotor cost, tower cost, gearbox cost, generator cost, blade cost, and energy collected
DESCRIPTION	Using prescribed scaling factors, the program optimizes HAWT components with respect to energy cost. The program is dated, so the absolute numbers presented are wrong, but it is useful for parametric studies. It is written for the analysis of high speed horizontal axis wind turbines. Only cursory manuals have been written.
AVAILABILITY	In the public domain
CONTACT	Frank Barr General Electric Co. P.O. Box 8555 Philadelphia, PA 19101 (215) 962-2930

NAME	WRFP
ORIGINATOR	Enertech Corp.
REFERENCE	None
INPUT REQUIREMENTS	Rotor geometry, rotational speed, wind speed
OUTPUT DATA	Loads, torque, power
DESCRIPTION	WRFP is a BASIC version of PROP (NASA-LeRC). This program is useful for the analysis of high speed horizontal axis wind turbines. It is not public property. The program has been verified with field data.
AVAILABILITY	Contact Enertech
CONTACT	William Drake Enertech Corp. P.O. Box 420 Norwich, VT 05055 (802) 649-1145

SECTION 4.0

CONCLUSIONS AND RECOMMENDATIONS

Many codes have been written to describe the performance of HAWT. Most of these are based on the method of Wilson, Lissman, and Walker [1]. There has been little verification of these codes with wind tunnel data by the respondents. Some verification with field data has been undertaken and reported [2]. VAWT theoretical development has lagged behind HAWT development. Only one code useful for the determination of Darrieus aerodynamic performance was reported. It has been verified with both field and wind tunnel data [3]. One giromill program has been verified with wind tunnel data [4] and the other with field data [5]. It is obvious that additional validation is needed of both HAWT and VAWT models.

Noticeably lacking is appreciation for the effect of load feedback on the predicted performance. All of the listed programs operate under the assumption that all of the energy produced will be consumed. This assumption is true only if the supplied power perfectly matches the load requirements at all times. Also lacking is an appreciation for the effects of the control system and transient parameters on the power produced at some instant. These objections are more serious for the economic codes than for the design codes. The design codes resolve the aerodynamic quantities at a single operating point.

The use of the maximum possible power coefficient for all operating conditions will overstate the energy capture because of mismatches between available and required power. A code should be developed which is capable of resolving the aerodynamic input to a wind system, modeling the load, and implementing the control system which optimizes the energy productions. This would serve not only the validation of existing data but also the innovation of design and control strategies specifically optimized for wind turbine use.

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1. Wilson, Robert E.; Lissaman, Peter B. S. Applied Aerodynamics of Wind Power Machines. Corvallis, OR: Oregon State University; May 1974.
2. Cromack, Duane E. Design and Operational Aspects of the UMASS Wind Furnace. Amherst, MA: Dept. of Mechanical Engineering, University of Massachusetts; May 1977; WF/TR/77/3.
3. Sandia Labs. Economic Analysis of Darrieus VAWT Systems for the Generation of Utility Grid Electrical Power. Albuquerque, NM: 1978; SAND 78-0962, vol. II.
4. Giromill Wind Tunnel Test and Analysis. Oct. 1977; CO/2617/4. Available from NTIS.
5. Walters, R. E.; et al. Vertical Axis Wind Turbine Experiments and Analysis. Morgantown, WV: Dept. of Aerospace Engineering, West Virginia University; May 1978; ORO/5135-78. Available from NTIS.

*U.S. GOVERNMENT PRINTING OFFICE: 1979--O-677-083/39