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Sandia Vertical-Axis Wind Turbine Program Technical Quarterly Report

July - September 1976

Robert D. Grover, Anthony F. Veneruso

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SANDIA VERTICAL-AXIS WIND TURBINE PROGRAM
TECHNICAL QUARTERLY REPORT

July - September 1976

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ABSTRACT

This quarterly report describes the activities of the Sandia Laboratories' Vertical-Axis Wind Turbine (VAWT) project during the period July-September 1976, transitional Quarter of fiscal year 1976. Included are the highlights of the quarter; review of the status of general design efforts in the areas of aerodynamics, structures, and testing.

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FOREWORD AND ACKNOWLEDGMENTS

The work covered herein was performed by Sandia Laboratories under a contract administered by the Wind Energy Conversion Branch (Division of Solar Energy) of the Energy Research and Development Administration. The time period covered is from July 1, 1976 to September 30, 1976. Previous work has been reported in reports 1, 2, and 3 for each quarter since October-December 1975.

This report was edited from the contributions of the following Sandia staff members:

- J. F. Banas (System Studies)
- B. F. Blackwell (Aerodynamics)
- L. V. Feltz (Mechanical Design)
- R. D. Grover (Mechanical Design)
- E. G. Kadlec (Project Engineer)
- D. W. Lobitz (Structural Analysis)
- R. C. Reuter (17-M Blades)
- R. E. Sheddahl (Aerodynamic Tests)
- B. Stiefeld (Automatic Control, Data Acquisition)
- W. N. Sullivan (Structural Analysis, System Tests)
- A. F. Veneruso (Electrical Design)
- L. I. Weingarten (Blade Analysis)

In addition, Dr. Curtis Dodd, an Associate Professor of Electrical Engineering, on sabbatical from Southern Illinois University, joined Sandia's Advanced Energy Projects Division for one year beginning August 15, 1976. Since joining the division, Dr. Dodd has been engaged primarily in the electrical aspects of the 17-meter VAWT design such as lightning and static electrical discharge, and he has also initiated efforts for cost effective speed increase and power conversion system design.

The following personnel contributed significantly to hardware development for the project:

- K. G. Grant
- C. E. Longfellow
- J. Lackey
- R. S. Rusk
- J. E. Martinez, Jr.

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SUMMARY

Sandia has collected data from the 5-meter VAWT by the employment of an Intellec-80 micro-computer based data acquisition system. This system will be replaced by a larger, more flexible acquisition and control system. This unit can acquire data and control the operation of the 5, 17, and 2-meter turbines.

Two parallel analysis (one analytical and one numerical) have been undertaken to investigate loading configurations which may lead to buckling in the 17-meter VAWT blade assembly.

A final iteration in the design of the blades to strengthen the trailing edge root end fittings of the straight segments was made.

An anemometer tower was designed for the top of the 17-meter VAWT. Purchase orders have been placed for all of the VAWT parts and delivery is scheduled for the next three months. A lightning protection system for the 17-meter VAWT has been designed to protect the blades, bearings, and electrical equipment from the brief currents associated with lightning.

SANDIA VERTICAL-AXIS WIND TURBINE PROGRAM

I. Aerodynamics

The 5-Meter Turbine - Field Testing

During the previous quarter an automated data collection system became operational and was utilized to measure the aerodynamic performance of the 5-meter turbine configured with three blades. This section briefly describes the data collection system and the test results.

Figure 1 presents a block diagram of the data collection system. This system is basically a hardware implementation of the aerodynamic performance measurement technique BINS.¹ The components consist of the wind speed and turbine shaft torque transducers, the analog/digital converter, the microprocessor, and output devices (keyboard and paper tape punch). Samples of wind speed and turbine shaft torque can be taken at a programmable rate up to a maximum of 1 per second. Accumulators representing number of samples and sum of sampled torques, are provided which correspond to wind speed intervals of 0.5 mph between 0 mph and 60 mph. For example, if the wind speed sample is 10.2 mph, the 20th sample accumulator is incremented by 1 and the torque measurement is added to the 20th torque accumulator.

Figure 1. Aerodynamic Performance Data Collection System for the 5-Meter Turbine

The microprocessor program allows intermediate termination of sampling and output of the current contents of the accumulators; upon completion of output, sampling is automatically resumed. Final output consists of a punched paper tape indicating test conditions (date, rotational speed, and number of blades), and the final contents of the accumulators. Such tapes are input to a PDP-10 computer for further data reduction to obtain; (1) wind speed frequency distribution f versus wind speed V , (2) power coefficient $C_p = P/1/2 AV^3$ versus tip speed ratio RW/V , (3) power coefficient $K_p = P/1/2 A(RW)^3$ versus advance ratio V/RW , and (4) torque T versus wind speed V . The PDP-10 computer code allows simultaneous data reduction of all test results for a given rotational speed in order to account for a wide variety of wind conditions.

The 5-meter turbine was tested at rotational speeds of 137.5 rpm and 150 rpm in a 3-bladed configuration representing a solidity of approximately 0.25. Figures 2 and 3 show the resulting power coefficients C_p and K_p . For comparative purposes, these figures also show previous test results for the 2-bladed configuration¹ representing a solidity of approximately 0.17. Qualitative trends in aerodynamic performance with respect to solidity are as expected when compared to results of wind tunnel tests of the 2-meter turbine.² For example, with increasing solidity, maximum power coefficients $C_{p,max}$ and $K_{p,max}$ are increasing while the tip speed ratio at zero power coefficient is decreasing.

Figure 2. Power Coefficient C_p for 2- and 3-Bladed Configurations of the 5-Meter Turbine

Figure 3. Power Coefficient K_p for 2- and 3-Bladed Configurations of the 5-Meter Turbine

II. Automatic Control and Data Acquisition

During this quarter Sandia has employed an Intellec-80 microcomputer based data acquisition system to acquire data from the 5-meter VAWT. In another section of this report some of the results of data acquired on the 5-meter VAWT are discussed. Due to problems associated with programing speed, number and speed of data channels to be acquired and data display, Sandia will replace the minicomputer system with a larger, more flexible acquisition and control system. This new system will be located in Building 899 at the installation site for the VAWT units. This unit will then be able to acquire data and control the operation of the 5-meter, 17-meter and 2-meter machines which will be sited around Building 899.

Hardware Description

The new system is based on a Hewlett Packard (HP) 21 Mx minicomputer with 32k of core memory and has been equipped with a significant array of peripheral equipment to perform the functions of control, data acquisition and data reduction and display. Table I itemizes the peripheral device and briefly describes the principal functions.

TABLE I
System Devices

Peripheral Device	Function Description
Tektronix 4014 Console with Hard Copy Unit	This CRT based console device will serve as the input console as well as the fast graphic display unit. Hard copy produced on this system is of report quality.
Paper Tape and Punched Card Readers	These two reading devices provide fast program input from paper tape or punched card.
Magnetic Tape Drive	The magnetic tape system is a 9-track industry-compatible tape system and will be used primarily as a data transport from the acquisition system to Sandia's main computer facility.
Disc System	System mass storage of programs and data will be done on this disc system. The system (HP 7905) features 7.5 million words (16-bit word length), 5 mega words of this is on a removable platter. The removable platter feature allows great flexibility in use of the system from a program and data storage point of view.
HP 2313 Analog/Subsystem	The analog subsystem provides 32 channels of ± 10 V and 16 channels of low level ± 20 MV analog/digital conversion. These data channels will be used to read most of the data points whose sources are not mounted on the rotating shaft. These readings will include wind speed, power, current, voltage, temperatures, etc. Various programs within the computer can treat the data as required.
HP 6940B Digital Subsystem	The digital subsystem provides 32 channels of programmable relay contacts, 6 channels of programmable analog outputs and 24 interrupt sensing lines. The principal use of the relay contacts will be to control on/off sequences. The analog outputs will provide variable servotype outputs or supplemental data displays. The 24 interrupt sensing lines with auxiliary circuits will monitor safety aspects of the system, providing interrupts to the computer if preset limits are exceeded.
PCM Encoder/Decoder System	This device will provide the interface between the computer system and transducers mounted on the rotating shaft/blade members. This will include the 25 or more strain gages that will supply most of the information on the VAWT's structural performance. The PCM Encoder provides up to 65 channels of data acquisition and will be mounted on a plate on the rotating main vertical shaft. The decoder portion is located adjacent to the computer in Building 899. During operation the PCM Encoder will digitize 65 channels of information

TABLE I(Contd)

<u>Peripheral Device</u>	<u>Function Description</u>
PCM Encoder/Decoder System (Contd)	at a 50 hertz rate (a data frame is then 20 milli-seconds long). This multichannel data with appropriate frame sequencing bits added is converted to a serial bit stream, passed through a slip ring pair and 600-ft cable to the decoder box in Building 899. The decoder reconverts the serial bit stream to the appropriate parallel data word form compatible with inputs to the computer. The encoder sampling rate is fast enough to meet the Nyquist criteria for the expected frequency response of the blade/shaft system.

Status of A/D System

All major parts of the system with the exception of the PCM encoder will be delivered by December 20, 1976. The PCM encoder is scheduled for delivery by January 18, 1977. The computer system will be assembled and checked out for basic operations prior to movement to Building 899. This move should occur about January 15, 1977.

Software Development

Creation of operating programs for computer systems is generally recognized as a major task, and one that is frequently underestimated in terms of both cost and time. This is particularly true of a system such as this being used in a laboratory environment which will require high-level analytic routines (for example fourier transforms for frequency response analysis) and control algorithms.

To reduce this potential software effort the system will operate under HP's standard Disc Operating System (DOS) and the bulk of the programing will be done in the Fortran language. Special subroutines to handle peripheral devices and emergency conditions will be placed in the system for use by the Fortran programers. This approach has the following advantages for laboratory type applications:

1. Most, if not all the principal users of the system are familiar with Fortran and therefore do not have to learn a detailed low-level language. This will spread the programing load and allow a great deal of flexibility for individual staff members.
2. It is anticipated that the principal users will desire to perform analytic operations on their data. Fortran is usually the language of choice for complex analytic programs.

III. Structures

17-Meter Blade Buckling Studies

During this quarter two parallel analyses (one analytical and one numerical) have been undertaken to investigate loading configurations which may lead to buckling in the 17-meter VAWT blade assembly. A mathematical model of a strutted blade on a parked turbine has been devised and subjected to a 150 mph wind. The blade is oriented to the wind to maximize the possibility of buckling.

The numerical analysis is being carried out using an in-house general-purpose finite element code. The blade material (6061-T6 aluminum) is modeled as a linear elastic material. Loads imposed by the wind are determined using the single stream tube aerodynamic model.¹ As gravitational effects are ignored in this analysis, only the upper half of the blade is modeled with appropriate symmetry conditions applied at the midline. As specified in the blade design, hinges are placed at the intersection of the blade straight section, the blade curved section and the strut, and at the points of attachment of the blade and strut to the tower. Nonlinear geometrical effects which accompany large deformations are included in the analysis.

The initial analysis required 30 elements to model the upper half of the blade assembly. Results indicated that buckling would definitely not occur in a 150 mph wind. However, unexplainable variations in the midplane stress along the straight section of the blade rendered the results suspect. Upon refining the mesh to 90 elements, these stress variations were significantly reduced. Although buckling was not indicated with the refined mesh, the onset of buckling appear to be imminent. This is shown in Figure 4 where, for each model, the axial displacement of the midpoint of the straight section is plotted versus the percentage of applied load. Recalling that buckling occurs when curves such as these become flat, it is evident that the 90 element model is much closer to buckling at 100% of the applied load than is the 30 element model.

The two curves of Figure 4 are in good agreement out to approximately 30% of the load (this roughly corresponds to a wind velocity of 80 mph) but deviates significantly beyond that. Maximal stresses, while remaining below yield (35 ksi), also deviate appreciably (33 ksi for the 90 element model and 22 ksi for the 30 element model) as the full load is approached. These deviations result from the fact that as the displacements become large, more elements are required to capture the true deformations in the structure. Thus to obtain an accurate solution, the mesh must be refined until results become relatively independent of further refinement. This course of action will be followed in the ensuing quarter.

Figure 4. Axial Displacement at Midpoint of Straight Section

The analytical buckling analysis of the blades of the parked turbine is being performed using energy methods. Loads at the intersection of the blade straight section, curved section and strut are determined through the use of Castiglione's theorem. These loads are then applied to the blade and strut sections along with the wind loading on these blade components. It was determined that the blade straight section would experience elastic buckling in a 166 mph wind. However, when this blade section is treated as a beam-column (some of the large deflection effects which are in the finite element code are included), onset of yielding is predicted in a 134 mph wind. Though there are more assumptions made in this model than in the finite element model, both methods tend to show failures at about 150 mph.

IV. Mechanical Design

Kaman 17-Meter Blade Contract

Blades for the 17-meter turbine are being designed and fabricated by Kaman Aerospace Corporation, Bloomfield, Connecticut. The quarter of July-September 1976, saw one final iteration in design which resulted in a strengthening of the trailing edge root end fittings of the straight segments. This change yielded a fatigue life for the fittings which was at the same level as that for the flatwise bending component

in the strut. After a brief delay, the design phase final report was submitted to Sandia. Several revisions were recommended to Kaman. The report was delayed pending resolution of the discrepancy in airloads as predicted by Kaman and Sandia. The expression for wind inflow in the Kaman aerodynamics code was found to be in error. After correction, Kaman predictions were brought into good agreement with Sandia predictions, with no reported changes in original values of strength margins and fatigue life. Engineering drawings were completed and copies were sent to Kaman manufacturing and to Sandia.

Leading and trailing edge extrusions were shipped to Kaman for machining during this quarter. Leading edge extrusions were machined by Kaman and returned to Alcoa for forming and aging.

Tool fabrication was begun and continued throughout the quarter. An estimate was made for completion of all tooling by the end of September.

17-Meter Turbine Blade Ground Tests

Upon receipt of the 17-meter turbine blades from Kaman, one circular arc segment and one straight segment will be subjected to nondestructive, static and dynamic ground tests prior to mounting on the tower. Initial planning of these tests has been made. Static tests of the straight segment will consist of lateral, flatwise, point load deflection of the blade segment with simply supported ends, and simple torsion. The circular arc segment will be simply supported and loaded for flatwise bending along a line containing its end points. These static ground tests will be performed to confirm blade mechanical properties and strain gage calibration.

Nonrotating frequencies and modeshapes of predominant vibration modes of the circular arc and straight segments will be made during the dynamic ground tests. Test procedures will be repeated on these blade segments after they have been mounted on the tower, without rotation. Finally, an attempt will be made to repeat the tests during turbine rotation. Dynamic characterization of the blade segments and blade assemblies is sought and correlations with analytical predictions will be made.

Mechanical Design

An anemometer tower has been designed for the top of the 17-meter VAWT. The anemometer tower is 30 ft high with an anemometer mount at the top and another anemometer mount at the middle of the tower. The anemometer tower was designed to withstand

a 90 mph wind without yielding the material and deflect no more than three inches in a 60 mph wind. Five foot long pipes were added to the tower center to support cables attached to the tower ends to increase the tower resonant frequency.

The VAWT blade centerline is 43 feet above the ground and the anemometers are 94 and 109 ft above the ground.

Purchase orders have been placed for all of the VAWT parts and delivery is expected within the next three months.

V. Lightning Protection

Introduction

A lightning protection system for the 17-meter VAWT is required to protect the blades, bearings, and electrical equipment from the high currents associated with lightning. Evidence of lightning damage has been reported by numerous governmental and private agencies. Summaries of this data can be found in The Lightning Book by Viemeister⁵ or Understanding Lightning by Vman.⁶ Without adequate lightning protection; blade, bearing and electrical damage could occur.

Chances of a Strike

The probability of having lightning strike the turbine can be calculated a number of ways. A calculation using a Stanford Research Institute Report on Lightning⁷ predicts there will be 0.7 strikes per year at the 17-meter VAWT. This means lightning will probably strike the turbine once every 1.3 years. Details of the procedure and data used for the calculation can be found in Table II.⁸ The effective area of attraction expression for objects less than a few hundred feet high and of height h is⁹

$$\pi(4h)^2.$$

For the 33.5 meter (110 ft) height of the 17-meter VAWT the effective area of attraction is $.0565 \text{ km}^2$.

Although other analytical techniques¹⁰ exist for determining the chances of a strike the technique presented in this paragraph is easy to apply and given good results.

TABLE II

Lightning Strike Probabilities in the Albuquerque Area*

	<u>J</u>	<u>F</u>	<u>M</u>	<u>A</u>	<u>M</u>	<u>J</u>	<u>J</u>	<u>A</u>	<u>S</u>	<u>O</u>	<u>N</u>	<u>D</u>	<u>Years Total</u>
(1) Thunderstorm Days	0.5	0.7	1.0	3.0	5.0	7.0	14	14	6	2.5	0.7	0.6	55
(2) Flashes/km ²	0.1	0.15	0.2	0.5	0.8	1.0	4.5	4.5	0.8	0.3	0.15	0.1	13
(3) Flashes to Wind Turbine	0.006	0.008	0.011	0.028	0.045	0.056	0.254	0.254	0.045	0.017	0.008	0.006	.738

$$\text{Flashes to turbine} = \text{Effective Area} \times \text{Flashes/km}^2$$

$$\text{Effective Area} = 0.0565 \text{ km}^2$$

* Note. (C. Jackson and W. Wagner of Sandia Laboratories were helpful in providing data and advice for the lightning protection system).

It is possible to determine the number of strikes per year to a tower in any area of the United States by using Figures 5 and 6. To make a comparison with the results of the method of Table II the chances of a strike in the Albuquerque area will again be determined. Figure 6 shows Albuquerque lies on the 60 thunderstorm per year line. If we examine Figure 7 it can be determined that a 110 ft tower is struck .15 times per year. Since Figure 5 is for an area where the average number of thunderstorm days per year is 35, we obtain by linear interpolation

$$\text{Strikes per year} = \left(\frac{60}{35} \right) (.15) = 0.257.$$

This means that we can expect one strike every 3.9 years $\left(\frac{1}{0.257} \right)$.

It is obvious that this second technique gives different results than the first. Another technique¹⁰ will give a third result. Furthermore, none of the techniques consider these characteristics of lightning in mountainous areas. Because of the variation in results from the different techniques the only statement that can be made with certainty is, there is a chance of lightning striking the wind turbine.

Figure 5. Available Wind Power - Annual Average

Figure 6. Map Showing the Average Number of Thunderstorm Days Per Year in the United States.

Figure 7. Frequency of Lightning Strike as a Function of Object Height: (a) Calculated Effect of the Area of a Structure at Various Heights; (b) Curve Plotted from Actual Records in Areas With an Average of 34 Thunderstorm Days per Year.

If we assume the second technique is valid, calculations show a 1.5 MW turbine of height 300 ft can be expected to be struck .75 times per year in an area of 60 thunderstorm days per year. A wind turbine farm of 30 MW capacity consisting of 20 units rated at 1.5 MW will be struck 15 times per year. Hence the development of a lightning protection system for the 17-meter VAWT will serve not only to protect this experimental model but will give data which can be used for the design of lightning protection for larger turbines.

Lightning Protection Design

When designing a lightning protection system the characteristics of lightning must be known. Since lightning is a charge transfer process the current characteristics give a sufficient description of a strike. In the 1.5 MW turbine design for NASA the lightning model is as shown in Figure 8. This model is in close agreement with the characteristics of lightning found in standard texts^{5,7,10} on lightning and is satisfactory for the design of a protection system. It should be noted that less than 2% of lightning has peak current greater than these shown in the model.

Figure 8. Diagrammatic Representation of Lightning Model.
(Note that the diagram is not to scale.)
From Reference 11.

As can be seen in Figure 9 there are five possible paths for lightning current to flow should a strike occur at the top of the turbine. Currents going down each of the four guy wires should do no damage to the turbine. If current goes down the turbine shaft, the most probable damage would be to the turbine's bearings and electrical equipment. It is doubtful that blade damage would occur unless a strike directly to the blade occurs. Because of the height of the anemometer tower on top of the turbine, a strike directly to a blade is improbable.

Figure 9. The 17-Meter VAWT - An Artist's Conception. The current splits in 5 paths after leaving the anemometer tower.

Insulator Design

One method to keep lightning currents from going down the turbine shaft would be to place insulators between the guy wires and the turbine shaft and the anemometer tower and shaft as shown in Figure 10. The amount of insulation required can be determined by finding the $L(du/dt)$ drop on the guy wires. The guy wires have a one-inch diameter and are 130-ft long. If the path is shortened by taking path ABC, which will reduce the inductance,

$$L = .2\ell \left(\ln \frac{4\ell}{d} - 1 + \frac{\mu}{4} \right)$$

$$L = .2(31) \ln \frac{4(31)}{.0254} - 1.0 + .25 = 48 \mu\text{H}$$

Where ℓ is the length in meters by path ABC and d the diameter in meters. The constant, μ , is one for air. The four parallel guy cables have a combined inductance of 12 μH . The rate of change of current taken from the model is 100,000 KA/ μs which means the insulator material must have a standoff protection of

$$L \frac{di}{dt} = 12 \mu\text{H} \cdot 100,000 \text{ KA}/\mu\text{s} = 1200 \text{ KV}.$$

One candidate for insulator would be the porcelain insulators used in transmission lines and power substations. It was found that standard size porcelain suspension insulators do not have the tensile strength necessary to support the load variations at the safety factor required in the guy cables. Preliminary calculations indicated that off the shelf post type insulators have sufficient mechanical and electrical strength to support a lightning rod on field models, but not the 30 ft anemometer tower or the 17-meter experimental model. Typical porcelain insulators are shown in Figure 11.

The use of material other than porcelain in insulators was considered. One product that appeared suitable for use were some insulators made with a fiberglass core and coated with cycloaliphetic¹³ epoxy weather rings. Cycloaliphatics are an epoxy specifically developed for outdoor use and can withstand weathering and ultra violet radiation from the sun. A picture of one of these insulators is shown in Figure 12. It is possible to build these insulators suitable for use as shown in the design of Figure 10. A technical evaluation of this insulator is presently being performed.

Figure 10. Lightning Protection Using Insulators.
The Current Path is Shown by the Arrows.

98390

(a)

(b)

Figure 11. Porcelain Insulators; (a) Suspension Type, (b) Post Type

Figure 12. Fiberglass Cove Insulators with Cycloaliphatic Epoxy Weather Rings. This Tension Insulator has an Electrical Standoff Rating of 400 kV With 50,000 lb M & E.

Brush System

A second method to protect the bearings from lightning damage is to provide a low resistive parallel path to ground. The means chosen for providing a parallel path was carbon brushes. These brushes will be in contact with a rotating brass ring. The design used can be seen in Figure 13. This type of design has been successfully used for bearing protection on large dish antennas, although the rotational speed of these antennas has been slower than the wind turbines. The validity of this design can be verified by field tests on the turbines or by testing on a lightning simulator. Because of the time lag involved with setting up a test, the brush design was incorporated in the wind turbine with expectations that it will work. Besides providing a path for lightning current the brush system also provides a path for static charge developed on the blades.

Figure 13. Lightning Protection Using a Brush Design

Conclusions

The bearing by-pass system using brushes is the lightning protection system that will be installed in the 17-meter VAWT. There is some question as to how well it will function. Until experience is obtained with the installed brush system, or laboratory verification shows different; it will not, at this time, be considered the design to be used on other experimental turbines.

The insulator protection system will be the best way to go if suitable insulators can be obtained. Tests are now being performed on some porcelain insulators to see if they have mechanical strength suitable for the variations in load on the turbines guy cables. Porcelain insulators have established an excellent record in the power industry, but are not normally made to withstand tension above 50,000 lb. There have also been questions raised concerning their ability to perform under the type of cyclic loading which can occur on the guy cables.

A series of tests on some porcelain insulators is now underway to determine their suitability for use in lightning protection for VAWT's. The fiberglass insulators with cycloaliphatic epoxy rings also will be evaluated. Some of these insulators have been ordered and will be evaluated at a later date.

In order to find a suitable lightning protection system for VAWT's both the brush protection system and the insulator system need further investigation. Because the insulator system is the most desirable of the two methods for protection, present efforts are directed toward finding and testing materials suitable for this design.

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