THE LONG-TERM INFLOW AND STRUCTURAL TEST PROGRAM[*][†]

Herbert J. Sutherland and Perry L. Jones
Wind Energy Technology Department
Sandia National Laboratories
Albuquerque, NM 87185-0708

Byron A. Neal
USDA, Agriculture Research Service
Conservation & Production Research Laboratory
Bushland, TX 79012-0010

ABSTRACT

The Long-term Inflow and Structural Test (LIST) program is collecting long-term, continuous inflow and structural response data to characterize the extreme loads on wind turbines. A heavily instrumented Micon 65/13M turbine with SERI 8-m blades is being used as the first test turbine for this program. This turbine and its two sister turbines are located in Bushland, TX, a test site that exposes the turbines to a wind regime that is representative of a Great Plains commercial site. The turbines and their inflow are being characterized with 60 measurements: 34 to characterize the inflow, 19 to characterize structural response, and 7 to characterize the time-varying state of the turbine. The primary characterization of the inflow into the LIST turbine relies upon an array of five sonic anemometers. Primary characterization of the structural response of the turbine uses several sets of strain gauges to measure bending loads on the blades and the tower and two accelerometers to measure the motion of the nacelle. Data from the various instruments are sampled at a rate of 30 Hz using a newly developed data acquisition system that features a time-synchronized continuous data stream that is telemetered from the turbine rotor. The data, taken continuously, are automatically divided into 10-minute segments and archived for analysis. Preliminary data are presented to illustrate the operation of the turbine and the data acquisition and analysis system.

INTRODUCTION

The design of modern wind turbines is currently being driven by the “extreme loads” imposed upon the turbine. These loads come in two forms, both of equal importance to the design of a reliable turbine. The first is extreme wind loads associated with storms (as with hurricane force winds). The second is the cyclic loads that continually damage the turbine in fatigue by turbulence in the inflow. As noted by Madsen, Pierce and Buhl,[1] the extreme loads during normal operation in turbulent conditions may cause the maximum turbine response, even higher than the loads while parked in hurricane force winds. The fatigue damage to critical components, such as the blades, is dominated disproportionately by the highest operating loads even though their rate-of-occurrence is relatively small. Sutherland and Butterfield[2] have discussed the views of a panel of experts convened to discuss these “extreme events.” They conclude that the nature of the turbulence responsible for, and the dynamic structural response to, these high load events is not understood at this time. They further conclude that characterizing these extreme conditions will drive down the cost of wind turbine systems.

To characterize the spectrum of these low-occurrence events requires a long-term, time-synchronized database that characterizes both the structural responses of the wind turbine and the inflow for at least a wind season. Numerous previous studies have examined the influence of various inflow parameters on structural response. However, most of these studies are typically too short to find the extremes, or they have limited inflow data. One notable exception is the study reported by Glinou and Fragoulis.[3] In this detailed study, multiple turbines in complex mountain terrain are characterized with large arrays of inflow and structural measurements. Their work is serving as a guide for the LIST program.

The first phase of the LIST program is the development, testing and demonstration of the instrumentation and data systems required to characterize these events. The second phase is the deployment of the system on commercial size turbines at commercially interesting U.S. sites. In phase one, a relatively small turbine is being used for the first measurement campaign. The turbine, a Micon 65/13M, is being tested at the USDA Agriculture Research Service (ARS) center in Bushland, Texas, near Amarillo. This site is representative of a Great Plains commercial site.

The instrumentation and data system used for the Bushland measurement campaign are the type needed

---

[*] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the U.S. Department of Energy under contract DE-AC04-94AL85000.

[†]

Fig. 1. The Micon 65/13M Turbine at the Bushland Test Site.

to take the LIST program to the next phase. Namely, the inflow to the turbine and its structural response are monitored continuously with time-synchronized data streams. Both hard-wired and telemetered data streams are used here. Inflow and turbine responses are monitored continuously with a large array of sensors. Of particular importance in this demonstration is the use of five 3-axis ultrasonic anemometers to characterize the inflow. Once the system has demonstrated its capabilities and long-term operation, LIST will move into phase two.

In addition to the demonstration aspect of phase one, the data obtained in Phase 1 of LIST will provide the first long-term U.S. database that details both the inflow and structural response of a wind turbine. These data will provide important information that will influence turbulence modeling, that can be used to validate structural dynamic analysis tools, and that can help refine fatigue life estimates. In the long term, LIST will provide data that will influence controls design, loads estimation, and international standards for turbine design. Most importantly, it will make it possible to design around the most damaging conditions under which wind turbines must operate, reducing the design margins and turbine cost.

This paper describes the Phase 1 LIST measurement campaign at Bushland. A companion paper by Sutherland[4] presents a preliminary analysis of the data measured in this experimental investigation.

THE LIST TURBINE

The turbine used in this experimental investigation is a modified version of the Micon 65/13 turbine (65/13M), see Fig.1. This turbine is a fixed-pitch, 3-bladed up-wind turbine with an asynchronous generator. At hub height, the turbine stands 23 m (75 ft) tall on a tubular, 3-piece steel tower that weighs approximately 64.5 kN (14,500 lbs). The nacelle weight is approximately 42.7 kN (9,600 lbs).

The turbine is a used machine that ran in the Palm Springs (CA) area for approximately 15 years. During that period, several turbine subsystems were modified to increase performance and reliability. These subsystems include the breaks, gearbox, generator and blades. The new drive train is built around an asynchronous, three-phase 480v generator rated at 115 kW. The generator operates at 1200 rpm while the blades turn at a fixed 55 rpm (the standard Micon 65/13 turbine rotates at a fixed 45 rpm).

Blades

The turbine is fitted with Phoenix 8-m blades that are based on Solar Energy Research Institute (SERI)[‡] airfoils. These "SERI" blades are 7.9 m (312 in) long, yielding a rotor diameter of 17.1 m (55.9 ft). The blades are equipped with tip brakes. The split line for these brakes is located at 6.5 m (256 in) from the blade flange. The hub flange for mounting the blades is located 599 mm (23.6 in) from the centerline of the low-speed shaft. The blades are a fixed-pitch design. They were set to approximately 2.2° at the 75 percent span line, per the instructions of J. Tangler.[5]

O'Gorman and Simmermacher,[6] and Simmermacher, O'Gorman, Martin and Lopez[7] characterized the static and dynamic properties of the blades. The weight of the 3 blades varies between 3.31 and 3.34 kN (745 and 750 lbs). Their center of gravity is located approximately 2.36 m (93 in) from the blade flange. The chordwise moment-of-inertia I_{zz} was measured to be 1533 kg-m^2 (5.25 x 10^6 lb-in^2) ± 20 percent.[6]

[‡] SERI is now the National Renewable Energy Laboratory (NREL).

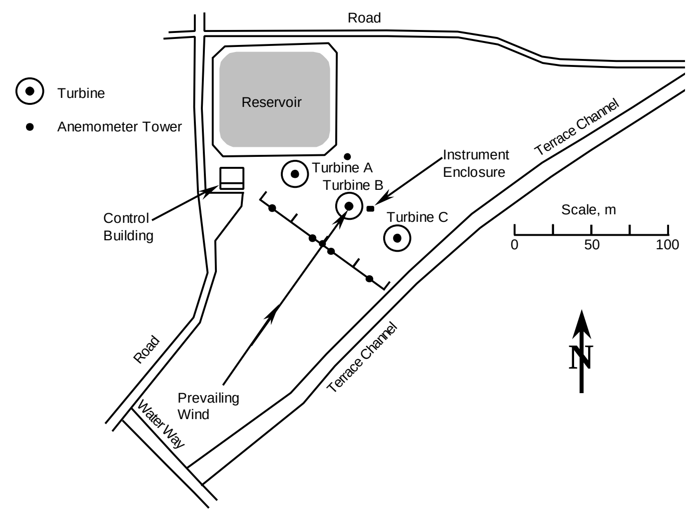


Fig. 2. Site Diagram.

Modal Survey

The modal survey of the blades was conducted using a ‘free-free’ configuration (the blades were suspended using nylon straps).[7] The survey yielded 31 modes. All of the modes were very complicated combined modes. The first mode was primarily flap motion (probably the first bending mode of the blade). Its frequency was measured to be 8.21 Hz with a damping of 1.16 percent. The next mode, at 14.75 Hz with a damping of 1.70 percent, primarily consisted of tip motion in the edgewise direction. The third mode, best described as the second flap-bending mode, occurred at 16.8 Hz with a damping of 1.06 percent. The mode best described as the first edgewise-bending mode occurred at 64.49 Hz with a damping of 1.02 percent.

Simmermacher and Carne[8] conducted a modal survey of the tower. The modal survey of the tower without the nacelle attached yielded a first bending mode of 3.29 Hz with 2.4 percent damping in the fore-aft direction (along the prevailing wind direction) and 3.31 Hz with 2.6 percent damping in the side-to-side direction (across the prevailing wind direction). The second bending modes were 15.27 and 15.76 Hz with 4.6 and 3.5 percent damping, respectively.

Sister Turbines

Two additional Micon 65/13M turbines have been erected at this test site. These turbines are equipped with Aerostar 7.5 m (292 in) blades, yielding a rotor diameter of 16 m (52.6 ft). The three turbines are sited in a straight line across the prevailing wind direction of 215° with-respect-to True North.[§] The turbine centerlines are spaced at a distance of approximately 2.25 diameters,[**] 38.2 m (125.3 ft) apart. These turbines are being used to provide reference data for a “standard” configuration of the turbine, and will be used in the future to test advanced blades.

The positions of the turbines are described in the site diagram shown in Fig. 2. In this diagram, the turbines are labeled A, B and C. A and C turbines are the Aerostar fitted turbines and Turbine B is the LIST turbine with the SERI blades.

Previous Testing of the Micon 65/13 Turbine

Tangler, et al.,[9, 10] tested a similar turbine in San Gorgonio Pass, California. The data from that turbine is not directly comparable to the data cited here because the turbines were very different. In particular, the turbine tested here has a larger generator, 115 kW rather than 65 kW, and a faster rotation rate, 55 rpm rather than 45 rpm.

Although built by the same manufacturer with the same external shape, the blades tested here are also different. The difference, essentially the difference between a prototype blade and a production blade, is manifested as an increase in blade weight. Namely, the LIST blades are approximately 15 percent [0.45 kN (100 lb)] heavier than the blades tested by Tangler, et al.[9,10] The effect of the additional weight on modal response is not readily comparable in the two data sets. In particular, the modal tests reported by Tangler, et al.[9,10] were conducted with the blade mounted to the hub assembly. Their results for the first flap and edgewise-bending modes were 3.16 Hz and 7.2 Hz, respectively. The difference between these results and the ones reported above can be attributed to the differences in the test conditions (‘fixed-free’ vs. ‘free-free’) and to the differences in the weight of the blades.

THE SITE

The turbines are located on the USDA-ARS site in Bushland, TX. This site is characteristic of a Great Plains site with essentially flat terrain. The test site is surrounded by farmland, and it slopes down approximately 1 m (3 ft) to the SSE across the span of the turbine bases. To the NNW of the turbines is a stock tank with an approximately 1.2 m (4 ft) berm, see Fig. 2.

[§] All compass headings are given with-respect- to True North.

[**] Unless noted, dimensions given in diameters are referenced to the diameter of the SERI blade set.

The primary wind direction at the site is from 215°. The wind rosette for this site shows a secondary peak for winds from approximately due North.

Two buildings are on the site. The first is the main control building that is upwind and to the west of the turbines. The second is a small instrumentation enclosure that is downwind of the turbines. Neither the tank nor the buildings obstruct the inflow to the turbines from the prevailing wind direction. For inflow from the secondary wind direction (North), the LIST turbine will also have an essentially unobstructed inflow.

INSTRUMENTATION

The turbines and the inflow at the Bushland site are being monitored with a total of 60 instruments. Most of these instruments are concentrated on the LIST turbine, see Figs. 3 and 4.

Inflow Instrumentation

The inflow into the LIST turbine is heavily monitored with both sonic and cup anemometers and with wind vanes. A schematic diagram of this instrumentation is shown in Fig. 3.

The anemometers are located at approximately 30.7 m (101 ft), upwind (with respect to the prevailing wind) of the turbines. This dimension is equivalent to 1.9 diameters for the standard Aerostar blade set and 1.8 diameters for the SERI blade set.

As shown in Fig. 3, a cup anemometer and a wind vane are used to monitor the horizontal inflow velocity and direction at hub height. Additional cup anemometers are used to measure horizontal inflow

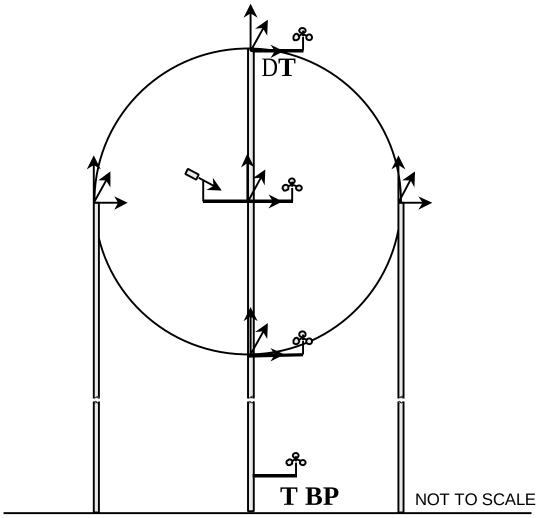
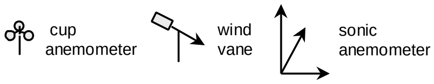


Fig. 3. Schematic Diagram of the Inflow Instrumentation for the LIST Turbine.

Notation:



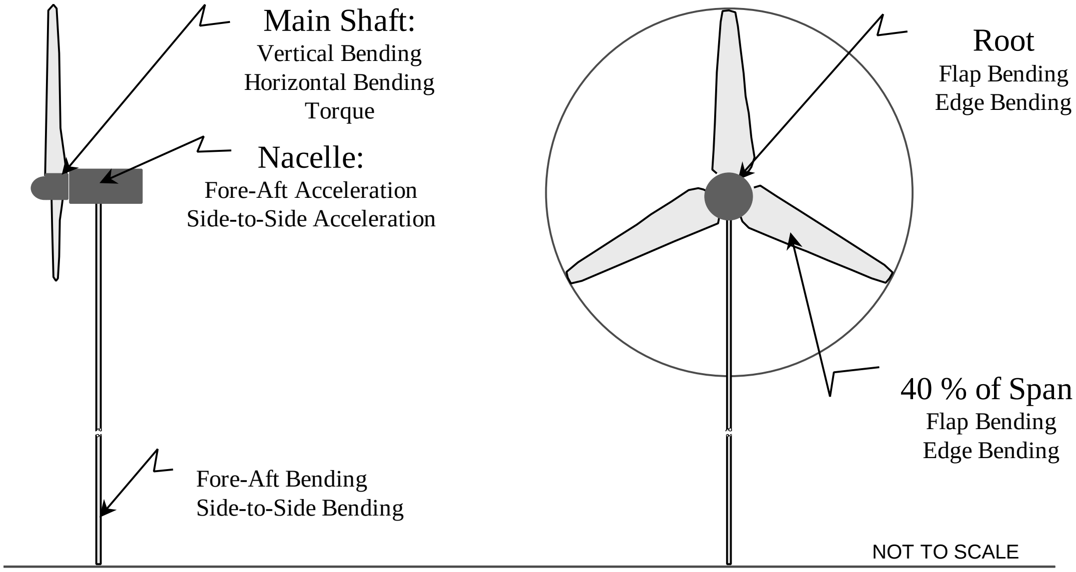


Fig. 4. Schematic Diagram of the Structural Instrumentation for the LIST Turbine.

velocity at the top and bottom of the rotor and at approximately 1.6 m (5.1 ft) above ground level.

A total of 5 sonic anemometers is used to obtain a more detailed description of the inflow. The 5 anemometers are placed in a circular pattern as shown in Fig. 3. The diameter of the circle is the same as the diameter of the turbine. Each sonic anemometer measures the three components of the inflow velocity (two horizontal and one vertical) and the sonic temperature. The quoted accuracy of these instruments is ± 0.02 m/sec on velocity and ± 0.01°C on temperature. The units have a 200 Hz internal sample rate and a 12-bit internal representation. A digital-to-analogue interface is used to change this internal digital representation to an analogue signal compatible with the data acquisition system.

As noted, all of these instruments are aligned with the prevailing wind direction of 215°. For this site, a secondary wind direction is approximately True North. To obtain an accurate measurement of the inflow when winds are from this secondary direction, an auxiliary anemometer tower is set at 12° with-respect-to the LIST turbine at a distance of 1.8 diameters, 31.3 m (102.6 ft). This tower is instrumented with a cup anemometer and wind vane that is aligned with the rotor hub. When inflow is from this secondary direction, the sonic anemometers will experience some blockage and do not provide an accurate description of the inflow.

The inflow into the other two turbines is monitored with hub-height cup anemometers and wind vanes. They are located 1.9 rotor diameters, 31.3 m (102.6 ft), upwind (215°) of each turbine.

In addition to these velocity measurements, the temperature, differential temperature and barometric pressure are monitored. The temperature is measured at approximately 1.6 m (5.1 ft) above ground level. The differential temperature is measured between the top of the rotor [33.6 m (110 ft)] and the ground level [1.6 m, (5.1 ft)]. The barometric pressure is measured at approximately 2.13 m (7 ft) above ground level, inside an instrument enclosure.

Structural Instrumentation

The structural response of the turbine is measured with a variety of gauges, primarily strain gauges. A schematic of their placement is shown in Fig. 4. Each blade is instrumented with root and 40 percent span gauge sets that measure flap and edgewise bending. The tower is instrumented with bending gauges located approximately 3.9 m (154 in) above the turbine base. These gauge sets measure tower fore-and-aft (along the prevailing wind direction) and side-to-side bending (across the prevailing wind direction). All strain gauges have been calibrated using static loading.

A problem was encountered with the main shaft gauges for the LIST turbine. The modifications to this turbine included increasing the diameter of the main shaft with a sleeve and a corresponding increase in the bearings. When gauges were placed on the sleeve, they did not provide consistent readings because the sleeve has some motion relative to the underlying (original) main shaft. Thus, direct measures of these quantities are not provided by the instrumentation used for this demonstration. However, these gauges are in-place and are being monitored to demonstrate capabilities and to ascertain if useful data may be obtained from them.

In addition to the strain gauges, nacelle acceleration is monitored using two semiconductor strain-gage type accelerometers. These single-axis accelerometers are attached to the main frame of the turbine. They are positioned to measure the horizontal acceleration parallel and perpendicular to the current yaw position of the turbine.

Additional Instrumentation

In addition to the instrumentation cited above, several other turbine parameters have been measured. These include yaw position, rotor position, rotor speed, and control monitor (on-off switch). The yaw and rotor positions are measured directly with 360° angle encoders. The rotor speed is derived from the rotor position using a dedicated, differentiating analogue circuit.

The power produced by each of three turbines is also monitored. Currently, only the total power (3-phase) is being recorded. However, current instrumentation also permits measurement of the power on the individual phases, the current and the VARS. As warranted, additional measurements may or may not be added to the data record.

Lightning Protection

Because this site is subject to severe lightning storms, particular attention was paid to protecting the system from lightning damage. The first line of defense was the placement of an extensive ground grid that circled the site and each piece of equipment. All grounds for the power grid are tied to this grid. Each turbine is grounded at its base. The anemometer towers and their top guy-wires are also grounded to the grid.

As noted in Fig. 2, the electronics for the instrumentation and the data acquisition system are inside an “instrumentation enclosure,” a watertight, steel electrical cabinet. A small metal building covers this cabinet. Both the cabinet and the building are grounded to the grid. Almost all of the electrical leads in and out of the enclosure are protected with commercial high-speed gas tube/diode lightning protection circuits. The only two circuits without lightning protection are a low-power antenna lead and the leads used to connect the data system to its controlling computer (located in the Control Building, see Fig. 2). The latter connections proved to be a problem and have been replaced with a fiber optic link. All grounds and shields are connected to the ground grid.

All circuits on the rotor are protected using the commercial lightning protection circuits.

Electric power to all of the instrumentation and the data system was filtered using commercial UPS units.

DATA ACQUISITION AND ANALYSIS

Berg, Rumsey and Zayas[11] have developed the unique data acquisition and analysis system used on the LIST. The hardware system, called ATLAS for Accurate, Time-Linked Data Acquisition System, is designed to acquire long-term, continuous, multi-channel time series data from an operating wind turbine. The 16-bit data stream from the ATLAS hardware system is acquired and recorded using the Advanced Data Acquisition System (ADAS) II software. ADAS II segments the data into 10-minute blocks, converts the data to engineering units, and stores them for future processing. The final step in the acquisition of continuous data is handled by the Smart Data Acquisition System (SDAS) which automatically archives the data and provides the researcher with the tools needed to organize and process the data.

For this series of experiments, the data rate was chosen to be 30 Hz. This yields a Nyquist Frequency of 15 Hz which is sufficient for capturing the behavior of the inflow and the structural response of the turbine.

ATLAS

For the LIST experiment, 3 data acquisition units are used in ATLAS. The first two are ground-based units (GBU's) that are hard-wired together. They are located in the instrument enclosure, near the base of the turbine. The slave unit is setup to sample all of the analogue data and the master unit samples the strain gauge and accelerometer data. The former is filled to capacity with five 8-channel analogue cards, and the latter contains a single 8-channel bridge circuit card. These circuits use a second-order anti-aliasing active filter followed by a programmable fifth-order Butterworth filter. The cut-off frequency for the latter filter was set to 15 Hz.

The rotor strain gauges are monitored with a single rotor-based data acquisition unit (RBU). This unit, called, "WINDY," has its own clock. Timing between the RBU and the GBU's is maintained within 1 micro-second using GPS synchronized clocks. The RBU unit contains three 8-channel bridge circuit cards. Data are telemetered to the master GBU, where it is integrated with the GBU data stream to form a single data stream that is then transmitted to the system computer.

A total of 75 channels (timing, measurement and synchronizing channels) is monitored with this systems.

All of these units are programmed using ATLAS software package developed by Berg and Zayas.[11] The ATLAS program is run on an auxiliary PC that downloads the data acquisition program to the ATLAS units over a hard-wire connection.[††] The RBU has an additional capability that permits it to be programmed via a telemeter link.

ADAS II

The data stream from ATLAS is acquired by the ADAS II data acquisition system. This system, run on a dedicated PC, is a specialized version of the original code developed for NREL. The current version is designed to acquire and store continuous time-series data from the ATLAS hardware.

ADAS II acquires the data from the ATLAS system in a PCM format. It then decodes these data, converts them into engineering units via a user-defined calibration table, and records the data to hard disk. Each data file is assigned a unique name based upon the date and time the data was acquired. All data files are stored in a collimated ASCII format. A header file is included with each data file. This file contains all of the pertinent information, including the calibration table that belongs to that specific data file.

SDAS

The SDAS software, developed by Rumsey,[11] has two primary modes of operation. The first is the stand-alone mode. In this mode, the software acquires an existing data file, determines the statistical characteristics of each data channel, places those statistics in a database, and archives the data file. The second mode is the data analysis mode. This mode permits an operator to query the database for data files that meet user-defined criteria and to analyze the data contained in these files. The package is highly interactive and allows the operator to perform detailed analysis of the data. This package is particularly strong for computing statistics and for plotting data.

In the stand-alone mode, a second, networked, PC is used to archive the data using the SDAS software.

[††] The hard-wire connection has been replaced with a fiber-optic cable.

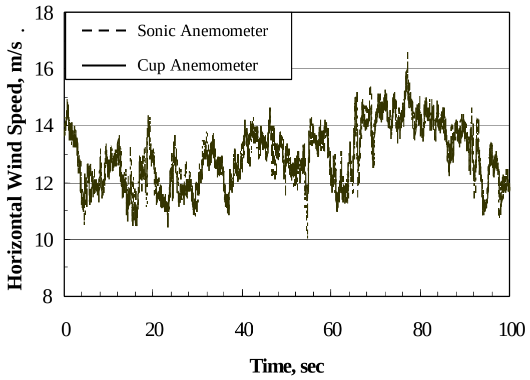


Fig. 5a. First 100 seconds of Data.

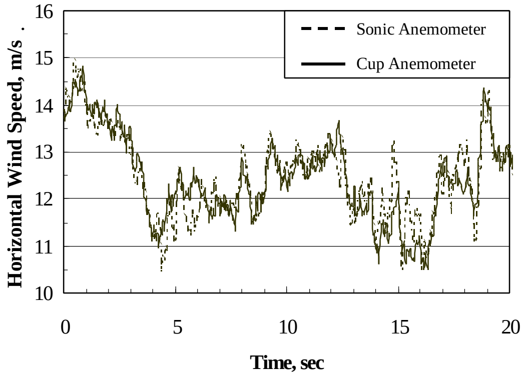


Fig. 5b. First 20 seconds of Data.

Fig. 5. Typical Horizontal Wind Speed Data.

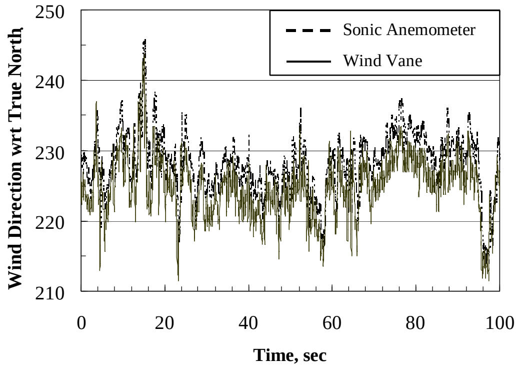


Fig. 6a. First 100 seconds of Data.

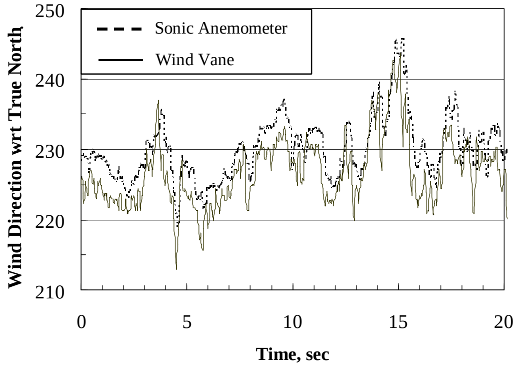


Fig. 6b. First 20 seconds of Data.

Fig. 6. Typical Horizontal Wind Speed Direction Data.

The SDAS software automatically identifies each new data file (and its associated header file) written by the ADAS II software. The statistics for the data set are computed and recorded in a database. The data and header file are then 'zipped' into a file suitable for the data archive. The resulting zip file typically has compression ratios that range from approximately 80 to 90 percent, e.g., a 14 MB data file and its 20 KB header file are zipped to 2.7 MB. The zip file is then stored to hard disk and the original data and header files are erased.

Approximately once a week the zip files are downloaded by an operator to CD for permanent storage.

Once the data are archived, an operator can use the SDAS software in the analysis mode to query the database and analyze data files. And, as the data are in a standard format, the data files can be unzipped and processed with any of the other data analysis systems that are currently available and/or any specialty codes written to perform specific data analysis tasks.

TYPICAL DATA

The power of this system to collect long-term data is illustrated by a few statistics. In the first month of operation, the system took 19.2 days of data. The data system was available for 68 percent of this period,[‡‡] recording a total of 2,760 10-minute data files. Each file contains 75 channels: 60 data channels and 15 timing and 'sync' channels. At 30 Hz, each channel is sampled 18,000 times in a 10-minute data record. Thus, each file contains over one and a quarter million data points ($1.33x10^6$). The size of the uncompressed data file is approximately 14 MB. When compressed, a total of approximately 200 data files (1.5 days) can be stored on a single CD.

Wind Data

A typical set of inflow data is shown in Figs. 5 through 10. The data shown in these illustrations are taken from a 10-minute record. For this 10-minute record, the average wind speed was 12.2 m/s, the

---

[‡‡] See discussion on availability under Concluding Remarks.

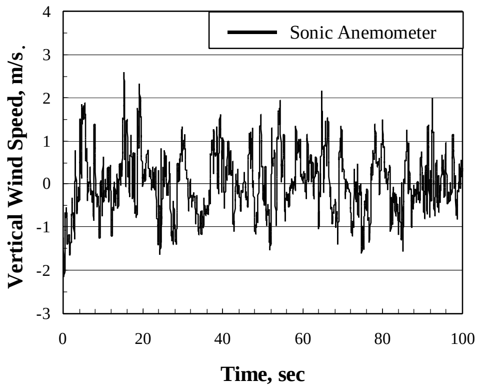


Fig. 7. Typical Vertical Wind Speed.

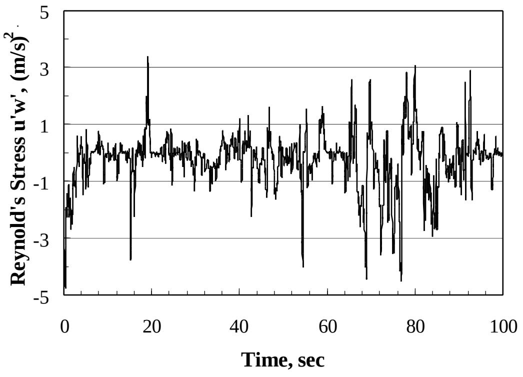


Fig. 8. Instantaneous Reynolds Stress for the Horizontal and Vertical Velocity Components.

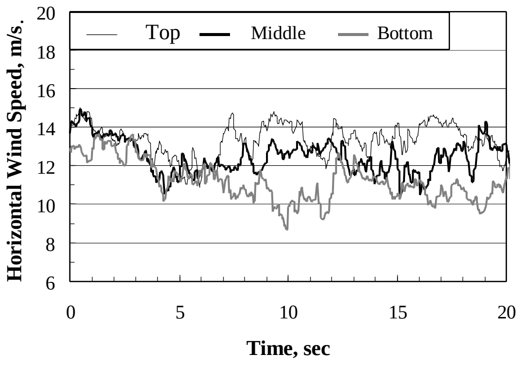


Fig. 9. Horizontal Wind Speed from the Bottom to the Top of the Rotor.

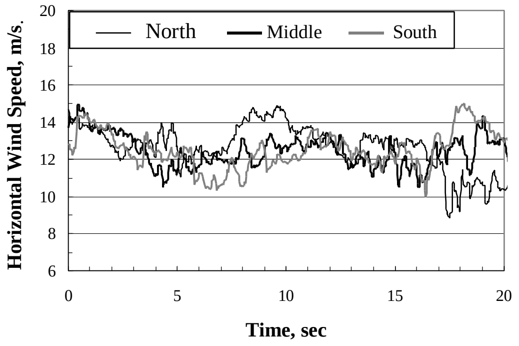


Fig. 10. Horizontal Wind Speed Across the Rotor Disk at Hub Height.

turbulence intensity was 11.9 percent, and the average inflow direction was 225° with-respect-to True North.

Fig. 5 compares the horizontal wind speed at the hub height as measured by a sonic and a cup anemometer that are co-located at hub height on the center anemometer tower, see Fig. 3. The direction of the horizontal component of the wind speed for a sonic and a wind vane are compared in Fig. 6. The measurements are in close agreement, with the data from the sonic anemometer illustrating its faster response time.

Fig. 7 illustrates the vertical velocity (positive up) as measured by the sonic anemometer at hub height. During this rather turbulent period, the vertical wind speed ranged typically ±1 m/s with one spike going over 2.5 m/s.

From the sonic wind speed data, the instantaneous Reynolds stress components can be determined.[12, 13] The horizontal/vertical Reynolds stress, u'w', is shown in Fig. 8. These instantaneous values yield an average local friction velocity u* of 0.63 m/s for this 10-minute record.

In addition to hub-height data, cross-rotor spectra are also obtained. The horizontal wind speed from the bottom to the top of the rotor is shown in Fig. 9 and across the rotor is shown in Fig. 10.

Turbine Performance

Typical power data are shown in Fig. 11. These data correspond to the wind speed data shown in Fig. 5. When the power data are processed using standard techniques, a power curve may be developed for each of the three turbines on site. The respective power curves are shown in Fig. 12.

In these power curves, the wind speed increment is 0.5 m/s. The data have not been corrected for the altitude of the site. The solid symbols present data from bins that contain a minimum of 5 hours of data. Open symbols present data from bins that have a minimum of 1 hour of data but less than 5 hours of data.

As shown in this figure, the SERI blades produce significantly more power than the Aerostar blades, with the former producing a maximum of approximately 100 kW and the latter producing approximately 60 kW. Both reach rated capacity at approximately 15 m/s. The SERI blades start producing power at approximately 4.0 m/s and the Aerostar blades at approximately 5.5 m/s.

In the initial study of the power produced by similar turbines in San Gorgonio Pass, CA,[10] the maximum power production was approximately 65 and 70 kW respectively (as noted in Ref. 10, the SERI blades had not been optimized for maximum power production). Thus, the increase in rotor speed in the modified turbines used here has significantly increased the power production from the SERI 8-m blades.

At the Bushland site, these power curves translate to an estimated annual energy production of 130 MWh from the LIST turbine and an average of 77.5 MWh from the other two turbines. Thus, the SERI blades nearly double the annual energy production of the Aerostar blades.

Structural Response

During the time cited in the above wind speed records, the average rotor speed was measured to be 55.3 rpm, with a variation of ±1.5 percent.

A typical plot of blade position is shown Fig. 13. At the zero degree position, blade 1 is vertically up. The rotational sequence of the blades is 1, followed by 3, followed by 2.

Edge Bending

The corresponding edge-bending moments are shown in Figs. 14 and 15. The data illustrated in the former are from the root-bending gauge on blade 1, and the latter are from the blade bending gauge on blade 2 at the 40 percent span position.

Flap Bending

The corresponding flap-bending moments are shown in Fig. 16 and 17 for root and blade bending, respectively. Both of the plots are data from blade 2.

CONCLUDING REMARKS

In an experimental program that is unprecedented in the United States, the LIST program is collecting long-term continuous inflow and structural response data. In the first full month of operation, over 460 hours of data were taken. The automated data acquisition and archival system has been working as advertised. During one period (from initial start-up of the full system to the first lightning strike), the system acquired over 10 days of continuous data!

Availability of the data system for the first full month of operation was approximately 68 percent, with lightning strikes the primary cause of down time. Shortcomings in the initial grounding and lightning protection system have been identified and corrected. The system has survived several thunderstorms without damage since the lightning protection system has been upgraded.

The instrumentation used in this experiment has

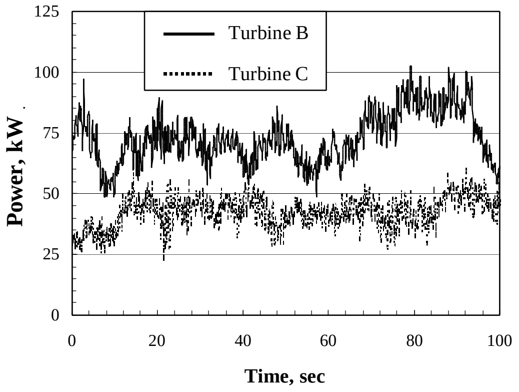


Fig. 11. Typical Power Data for Turbine A and Turbine C.

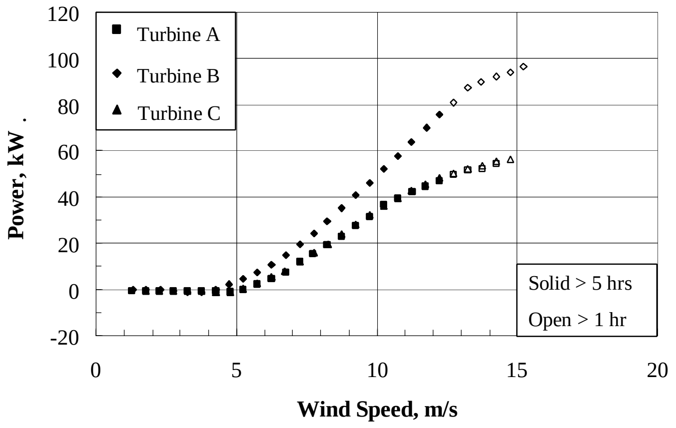


Fig. 12. Power Curve for the Three Micon 65/13M Turbines at the Bushland Site.

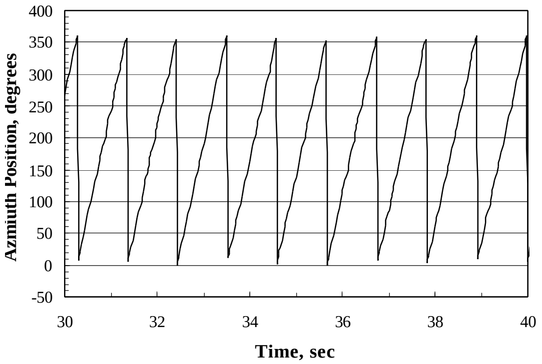


Fig. 13. Azimuth Position of Blade 1.

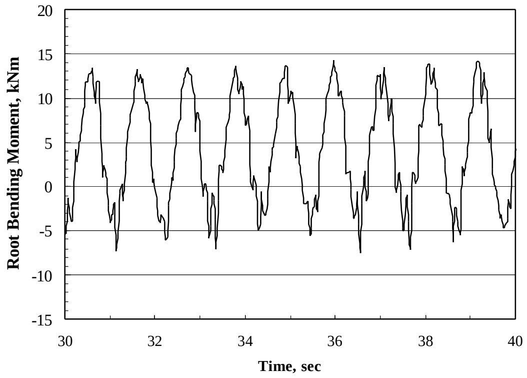


Fig. 14. Edge-Bending in the Root of Blade 1.

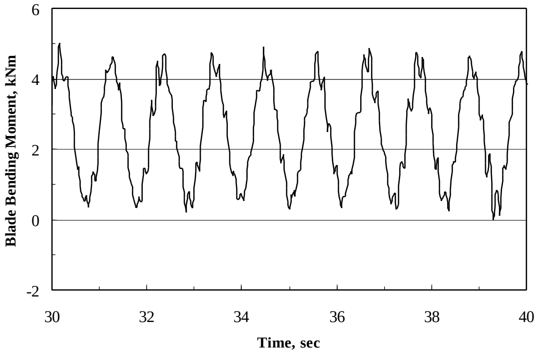


Fig. 15. Edge-Bending at the 40 percent Span Location of Blade 2.

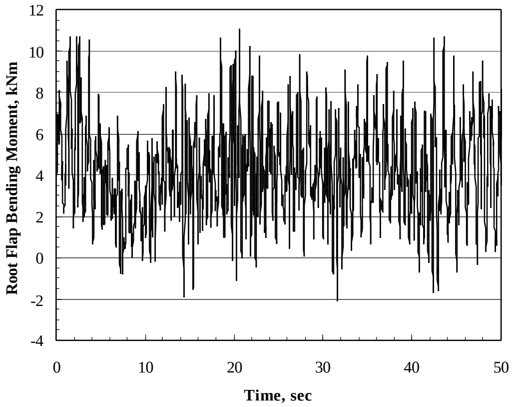


Fig. 16. Flap-Bending Moment in the Root of Blade 2.

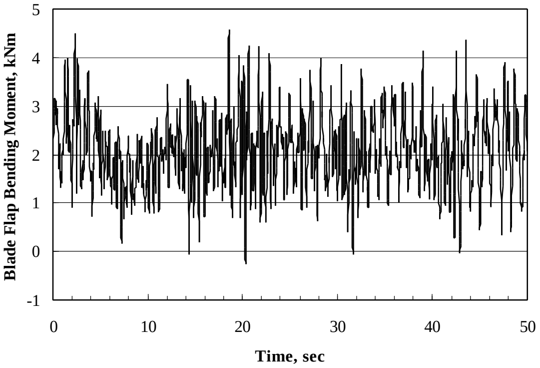


Fig. 17. Flap-Bending Moment at the 40 percent Span Location of Blade 2.

been performing reasonably well, with a few exceptions. The sonic anemometers have functioned without any faults. Several cup anemometers and wind vanes were destroyed by hail and have been replaced. In addition to the installation problems noted above, the strain gauges have been failing at an unexpectedly high rate, with only approximately half still in working order. Currently, the working gauges are supplying sufficient information for characterizing the structural response of the turbine; however, if additional gauges fail, the entire suite of strain gauges will have to be replaced.

Thus, the LIST program has demonstrated the capability of the ATLAS hardware and the ADASII and SDAS software to monitor long-term continuous data from an operating wind turbine. Current plans call for the turbine at the Bushland site to be monitored for approximately one calendar year. In addition to gaining more experience in the operation of our data system, the data will provide a unique description of the inflow and structural response of a wind turbine operating in a typical U.S. Great Plains site. Sutherland[14] presents a preliminary analysis of these data with special emphasis on fatigue spectrum.

Future plans call for the LIST system to monitor the inflow and structural response of a large, commercial grade turbine.

ACKNOWLEDGEMENTS

The construction and testing of the turbines described in this report are the result of a team effort. The personnel (including the authors) and their primary duties in this project are: Henry Dodd: Program Manager, SNL; Nolan Clark: Program Director, USDA-ARS; Herb Sutherland: Project Leader; Byron Neal: Site Engineer, USDA-ARS; Perry Jones: Site Engineer, SNL; Dale Berg and Jose Zayas: Data Acquisition System; Mark Rumsey: Data Analysis System; Tom Ashwill: Construction and Foundation Design; Clint Sanders: Student Assistant.

REFERENCES

1. Madsen, P.H., K. Pierce and M. Buhl, "Predicting Ultimate Loads for Wind Turbine Design," *1999 ASME Wind Energy Symposium*, 1999, p. 355.

2. Sutherland, H.J., and C.P. Butterfield, "A Summary of the Workshop on Fatigue Life Methodologies for Wind Turbines," *Proceedings of WindPower '94*, AWEA, Washington, DC, May, 1994.

3. *Mounturb Final Report*, G. Glinou and A. Fragoulis, eds., 3 vols., JOU2-CT93-0378, November, 1996.

4. Sutherland, H.J., "Preliminary Analysis of the Structural And Inflow Data From the LIST Turbine," *2001 ASME Wind Energy Symposium*, 2001, in publication.

5. Tangler, J., National Renewable Energy Laboratory, National Wind Technology Center, private communication.

6. O'Gorman, C.C., and T.W. Simmermacher, *SERI Wind Turbine Blade (B3) Mass Properties Testing, Bushland, TX*, Internal SNL Memo, Sandia National Laboratories, Albuquerque, July 16, 1999.

7. Simmermacher, T., C. O'Gorman, W. Martin and F. Lopez, *Modal Test of SERI-Blade B1*, Internal SNL Memo, Sandia National Laboratories, Albuquerque, July 22, 1999.

8. Simmermacher, T. and T. Carne, *Tower Modal Survey*, Internal SNL Memo, Sandia National Laboratories, Albuquerque, December 20, 1999.

9. Tangler, J., B. Smith, D. Jager, and T. Olsen, *Atmospheric Performance of the SERI Thin-Airfoil Family*, SERI/TP-257-3939, Solar Energy Research Institute, Golden, CO, 1990.

10. Tangler, J., B. Smith, D. Jager, E. McKenna,and J. Allread, "Atmospheric Performance Testing of the Special-Purpose SERI Thin Airfoil Family: Preliminary Results," *Proceedings of Windpower '89*, SERI/TP-257-3628,, Solar Energy Research Institute, Golden, CO, 1989 , p. 115.

11. Berg, D.E., M.A. Rumsey and J.R. Zayas, "Hardware and Software Developments for the Accurate Time-Linked Data Acquisition System," *2000 ASME Wind Energy Symposium*, 2000, p. 306.

12. Kelley, N.D., and H.E. McKenna, "The Evaluation of a Turbulent Loads Characterization System," *1996 ASME Wind Energy Symposium*, 1996, p. 69.

13. Kelley, N.D., R.M. Osgood, J.T. Bialasiewicz and A. Jakubowski, "Using Time-Frequency and Wavelet Analysis to Assess Turbulence/Rotor Interactions," *2000 ASME Wind Energy Symposium*, 2000, p. 130.

14. Sutherland, H. J., "Preliminary Analysis of the Structural and Inflow Data From the LIST Turbine," *2001 ASME Wind Energy Symposium*, 2001, in publication.