UPDATE OF THE LONG-TERM INFLOW AND

STRUCTURAL TEST PROGRAM[*†]

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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. The initial data set, collected from a heavily instrumented Micon 65/13M turbine with SERI 8-m blades, has been reported previously. The test turbine is located in Bushland, TX, a site that exposes it to a wind regime representative of a Great Plains commercial site. The turbine and its inflow are being characterized with 59 measurements: 34 to characterize the inflow, 18 to characterize structural response, and 7 to characterize the time-varying state of the turbine. While the initial measurement campaign obtained over 330 hours of data, the test was terminated early because of premature failure of the blade strain gauges. During the measurement campaign the Accurate Time Linked data Acquisition System (ATLAS) experienced numerous failures of individual components preventing truly continuous data acquisition for extended time periods. The ATLAS has been upgraded, the strain gauges have been reworked, and a second measurement campaign has begun. The system was operated from early February 2003 until early May with an availability of 95.6 percent. The new data set contains over 1630 hours of data. This manuscript describes the upgrades to the ATLAS, and then updates the data presented previously to illustrate the long-term, continuous operation of the ATLAS. Load and fatigue spectra are updated to illustrate their similarities and differences.

INTRODUCTION

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 [1]. To characterize 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 in duration to find the extremes, or they have limited inflow data. One notable exception is the study reported by Glinou and Fragoulis [2]. 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 acquire the long-term database needed to characterize extreme loads. Additional phases of the LIST program will

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

gather long-term data from larger turbines at different sites.

Sutherland, Jones and Neal [3] reported on the acquisition of the initial data set for the LIST program. They obtained data on a heavily instrumented Micon 65/13M turbine with SERI[**] 8-m blades. This test turbine is located in Bushland, TX, a site that exposes it to a wind regime representative of a Great Plains commercial site. The turbine and its inflow were characterized with 59 measurements: 34 to characterize the inflow, 18 to characterize structural response, and 7 to characterize the time-varying state of the turbine. The initial measurement campaign obtained over 330 hours of data. Sutherland, et al have conducted extensive evaluations of the relationship between inflow parameters and structural response [1, 4—6],

and Pandey and Sutherland [7] have examined extreme structural loads.

Although a large database was obtained in this test series, the test was terminated early because of premature failure of the blade strain gauges. In addition, the <u>A</u>ccurate <u>T</u>ime <u>L</u>inked data <u>A</u>cquisition <u>S</u>ystem (ATLAS) experienced several component failure, preventing continuous data acquisition. To correct these problems and to complete the demonstration of a reliable data system that is capable of taking data 24 hours a day, 7 days a week, the ATLAS has been upgraded, and the strain gauges have been reworked. The second measurement campaign began in early February 2003 and was concluded in early May. During this period, the data system had an availability of 95.6 percent. The new data set contains over 1630 hours of data.

This manuscript describes the upgrades to the ATLAS, and then updates the data presented previously to illustrate the long-term, continuous operation of the ATLAS.   The original load and fatigue spectra are updated with the additional data obtained in this test campaign. These data extended the spectra deeper into their tails. A comparison of the initial spectra to the updated spectra illustrates the similarities and differences between the tails extrapolated from the initial data and the tails measured in the significantly longer updated data set

THE LIST TURBINE

As discussed previously [3, 5], 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 including the brakes, gearbox, generator and blades were modified to increase performance and reliability. 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).

The test site is surrounded by farmland, and it slopes down approximately 1 m (3 ft) to the SSE across the

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** SERI is now the National Renewable Energy Laboratory (NREL).

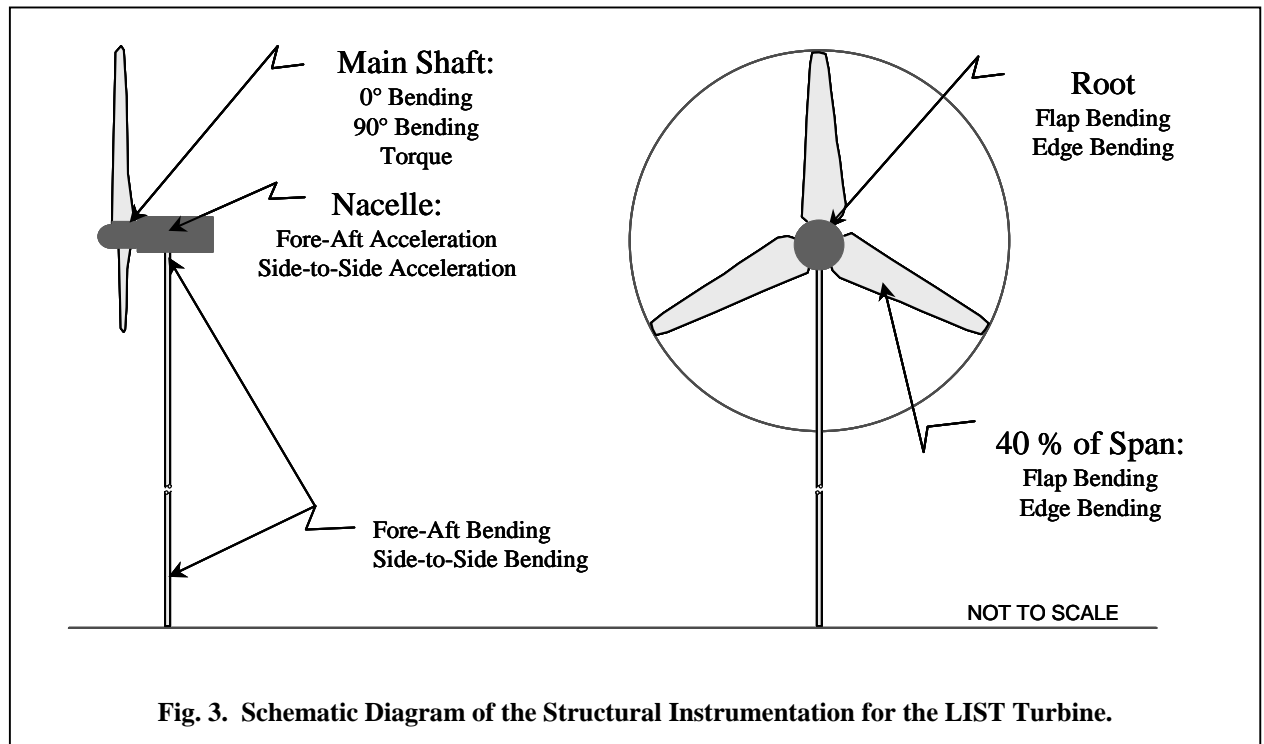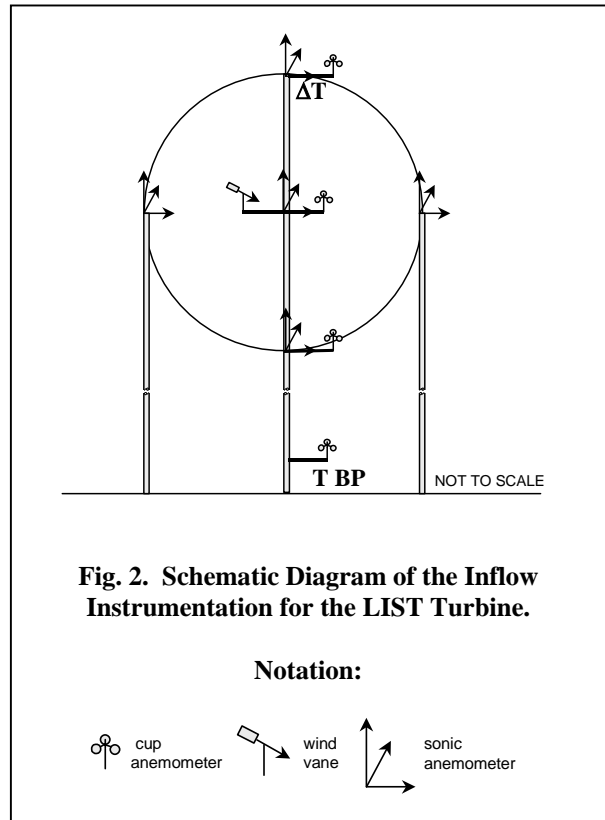span of the turbine bases. To the NNW of the turbines is a stock tank with an approximately 1.2 m (4 ft) berm.

INSTRUMENTATION

The turbines and the inflow at the Bushland site are being monitored with a total of 59 instruments [3, 5]. Figs. 2 and 3 show schematic diagrams of the placement of the various instruments on and about the turbine. The instrumentation is described in detail in Ref. 8; a brief description is given here.

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. 2. 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 used. This tower is set at 12° to the turbine, and it is instrumented at hub-height with a cup anemometer and wind vane.

In addition to these velocity measurements, the temperature, differential temperature and barometric pressure are monitored.

Fig. 2. Schematic Diagram of the Inflow Instrumentation for the LIST Turbine.

Notation:

cup anemometer   wind vane   sonic anemometer

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

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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. 3. Each blade is instrumented with root and 40 percent span gauge sets that measure flap and edgewise bending. The root gauges are located on the hub and are aligned parallel to and perpendicular to the rotor disk. The 40 percent span blade gauges are aligned with respect to the local chord. The tower is instrumented with bending gauges located near the top and the bottom of the tower. 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.

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 to and perpendicular to the current yaw position of the turbine.

Additional Instrumentation

In addition to the instrumentation cited above, several other turbine parameters are measured. These include power production, 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.

DATA ACQUISITION SYSTEM

The Accurate Time-Linked data Acquisition System (ATLAS) has been developed by Sandia National Laboratories to acquire continuous, long-term, time-synchronized data from multiple data acquisition units for a period of weeks or months. The ATLAS utilizes an acquisition computer and multiple data acquisition subsystems (DAS). For the typical installation shown in Fig. 4, the ATLAS is set up with one rotor-based DAS unit (RBU) and three ground-based DAS units (GBU). The RBU is mounted on the rotor. One GBU is mounted in the nacelle, another is located at the base of turbine tower and the final one is located at the base of the meteorology tower.

The acquisition computer, equipped with the ATLAS data acquisition software, is used to program the individual units, to monitor/acquire the data and to store the data.

All DAS units are located as close to the sensors as possible to minimize electrical noise. They may be
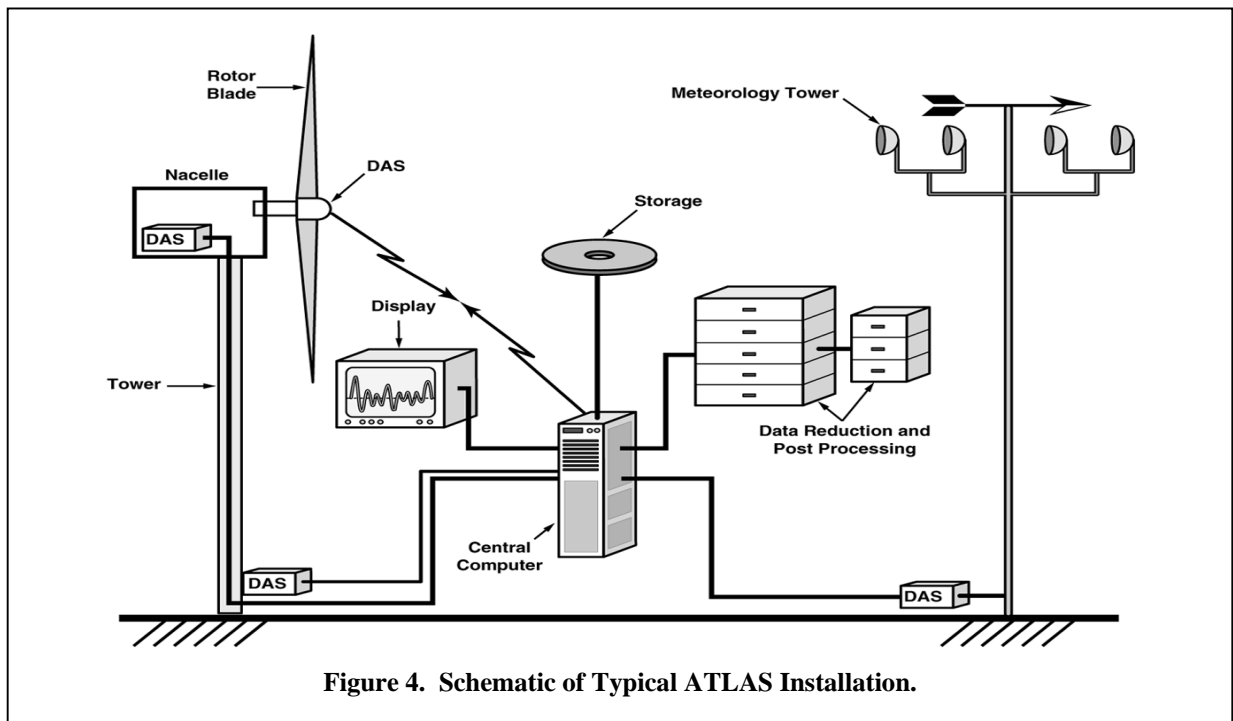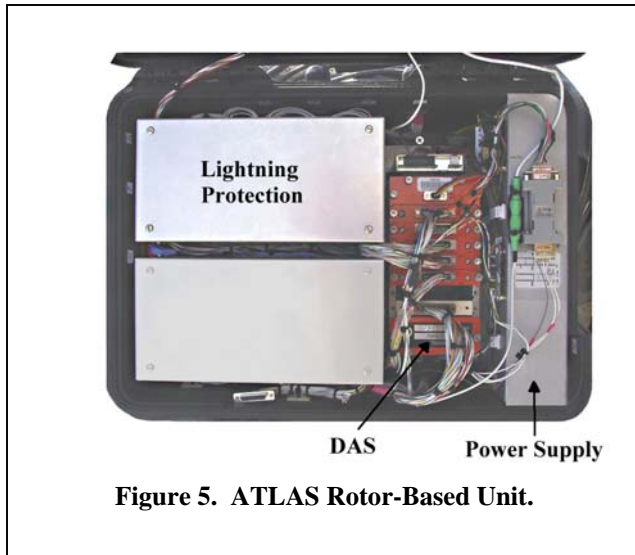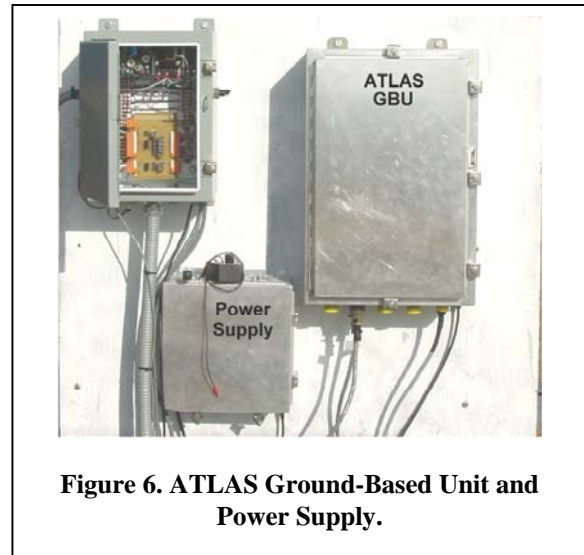

Figure 4. Schematic of Typical ATLAS Installation.

Figure 5. ATLAS Rotor-Based Unit.

Figure 6. ATLAS Ground-Based Unit and Power Supply.

configured to collect data from strain gauges and from other sensors that have either an analogue or a digital output. The number of DAS units used in an ATLAS installation is variable; the number of units chosen for a particular measurement campaign depends on test requirements.

The DAS with the toughest operating requirements is the RBU. This unit must be small in size, light in weight and still be sufficiently robust to withstand the vibration, rotation, g-loads, etc. associated with its position on the rotor. Since most wind turbine rotors are not equipped with slip rings to transmit the data, the RBU is equipped with 2.4 Ghz frequency-hopping, spread-spectrum radio modems. The RBU, shown in Figure 5, can be viewed as a compact version of a GBU. It contains a subset of all the components and capabilities of a GBU with the addition of telemetry communication.

Additional information on the system components, including system requirements and hardware, is provided in Refs. 9-11.

New Features

After the initial LIST project in 2000, the hardware for the ATLAS was completely revised. The revisions include the second generation of the data acquisition unit, the KAM-500, built by ACRA Control of Dublin, Ireland. The new units incorporate new features and hardware that improve the reliability of the system and make it more robust; also, all components are now "Mil Spec'ed."

To reduce electronic noise within each DAS unit and to improve their high ambient temperature operation, the AC power has been removed from all of the GBU units. A power pack now provides each GBU with DC power. Each power pack is a separate unit that is mounted in its own weather tight box. The power pack contains lightening protection, noise suppression circuitry and an uninterruptible power supply. The latter provides power to the GBU for approximately 30 minutes if AC power is lost.

Each GBU, shown in Fig. 6, is enclosed in an aluminum NEMA box and includes lightning protection on all channels. Cooling fins may be added to the unit for high ambient temperature operation.

The RBU is similar to a GBU. All channels have lightning protection. The unit is capable of operating from either AC or DC power. For the former, the AC power is typically supplied through slip rings or a rotary transformer. If AC power is not available on the rotor, the RBU may be powered with a battery pack. The battery pack is a 17.6 AHr Lithium-ion dual battery pack system with an output voltage of approximately 30 volts. This battery pack provides sufficient power to operate the RBU for approximately 26 hours, depending on the number of signals being acquired. The battery pack system, shown in Figure 7, is also equipped with an in-line circuitry to prevent the batteries from discharging to an unsafe level. The current weight of the RBU and the battery pack are 15 and 7 pounds, respectively.[‡]

[‡] The battery system is currently being evaluated in a test campaign on a 100 kW turbine in a wind farm environment in California. To eliminate data loss during the time required to charge a battery pack,
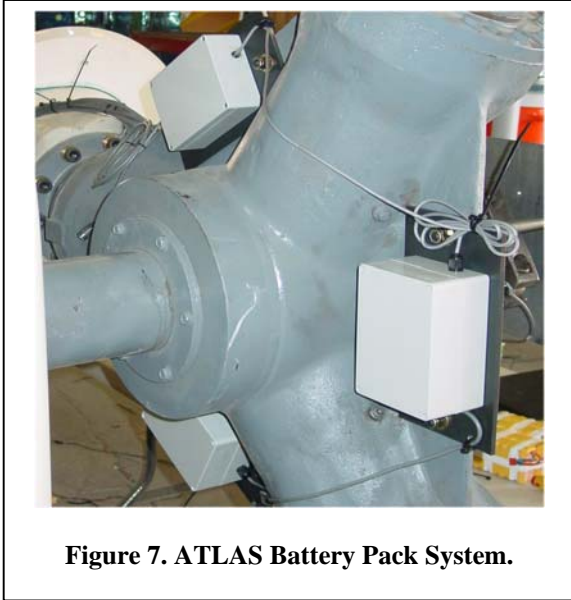
Figure 7. ATLAS Battery Pack System.

In addition to the hardware changes, the ATLAS has a new software program to acquire and archive the data. In the past, two independent codes were used. The first was used to program the hardware and to verify that the system was working properly, and the second was used to acquire and archive the data. Now both functions have been combined into a single software package, the ATLAS II software. All the basic features of the initial software package [9] are still available in the ATLAS II software, but this package increases the functionality of the older system while simplifying its use. Some of the new features include: web access, e-mail features, and event triggering.

ATLAS-LIST Project

For the LIST experiment, only two DAS units were used for the configuration; one GBU and one RBU. The GBU is located near the base of the turbine and is configured to sample all of the meteorological data, the tower strain gauges, the accelerometer data and the turbine state data. This DAS is populated with six 8-channel analog cards, as well as a single 8-channel bridge-circuit (strain gauge) card. All instrumentation channels are equipped with a second-order anti-aliasing active filter followed by a programmable fifth-order Butterworth filter.

The rotor strain gauges are monitored by a RBU, which is powered with a rotary transformer for this campaign. The RBU contains three 8-channel bridge circuit cards, and is configured to acquire data from the 15 strain gauge circuits mounted on the blades and the hub. Data is telemetered from the RBU to the acquisition computer, and the GBU data stream is transferred via fiber optics. The ATLAS II software segments the data into 10-minute blocks, converts the data to engineering units, compresses the data, and stores them for future processing.

For the LIST project a total of 75 channels (59 for instrumentation measurement and 16 for timing and synchronizing channels) at 30 Hz is monitored with the ATLAS software. Each 10-minute record is approximately 15 Mb in size (ASCII). This rate produces approximately 2.2 Gb of uncompressed data daily.

During the 3-month measurement campaign,[§] the ATLAS acquired 1633 hours of data, with an availability of 95.6 percent. No ATLAS hardware failures were reported during this period. The only downtime for the ATLAS was the result of network errors between the acquisition computer and the storage computer. These network errors "froze" the data acquisition computer and a hard re-boot by an operator was required to restart the system.

THE DATA SET

The new data set contains a total of 9801 10-minute records. When these records are reduced to those where the turbine is operating for the entire record, the mean wind speed is greater than 7 m/s, and the inflow measurements are not blocked, a total of 3763 10-minute records remain. This compares with a total of 491 10-minute records in the initial data set that meet this same criteria. Thus, a total of 4254 10-minute records are available for analyzing the operational behavior of the turbine under closely monitored inflow conditions.

The distribution of the 4254 ten-minute records contained in the current and former data sets is summarized in Fig. 8. As illustrated by this figure, the records have been divided into wind speed bins for this analysis. The wind speed bins encompass speed ranges of 7-9, 9-11, 11-13, 13-15, 15-17and >17 m/s.

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two battery packs are used. A "hot swap" capability allows a recharged battery pack to be switched into the system before the discharged pack is removed, keeping the system running continuously.

[§] During this period, the test turbine was down for approximately 4 weeks due to a mechanical failure of the yaw drive.

LONG-TERM FATIGUE LOAD SPECTRUM

One of the long-term objectives of the LIST program is to obtain long-term fatigue spectra for the turbine blade loads. The long-term fatigue spectra for 669 10-minute records in the 11-13 m/s wind speed bin offer an important database for studying long-term fatigue spectrum. These data are summarized in Figs. 9 and 10.

In these two figures, the fatigue spectra are typical spectra for this class of turbines; namely, the edge-bending spectra in Figs. 9a and 10a, display a bi-modal distribution that is directly attributed to the large 1P gravity component of the bending moment, see Sutherland [5]. As illustrated in Figs. 9b and 10b, the fatigue spectrum for flap-bending moment has a very different character, with a single-mode distribution.

In Figs. 9 and 10, the approximately 19-hours of data in the 11-13 m/s wind speed bin from the initial data set
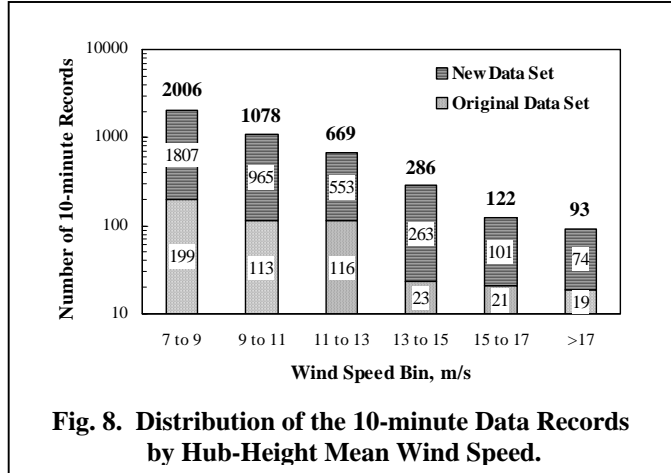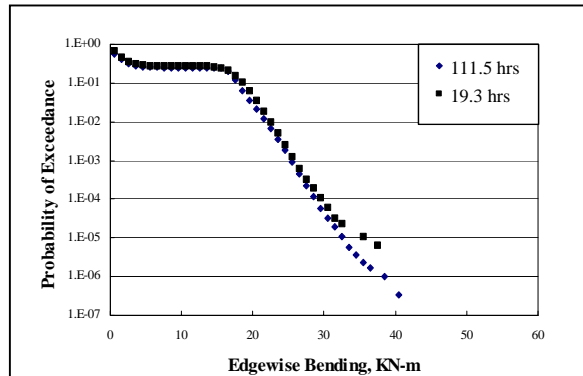

Fig. 8. Distribution of the 10-minute Data Records by Hub-Height Mean Wind Speed.

are contrasted to the approximately 111-hours of data from the combined data set from the two measurement campaigns. These comparisons illustrate the importance of long-term data sets. In particular, the 19-hour data spectra have a so-called "floor" occuring at approximately 1 cycle count per 19 hours, or 0.05 cycles in one hour. This floor is easily observed in the
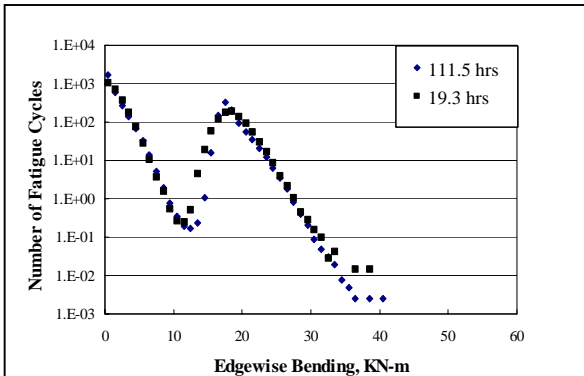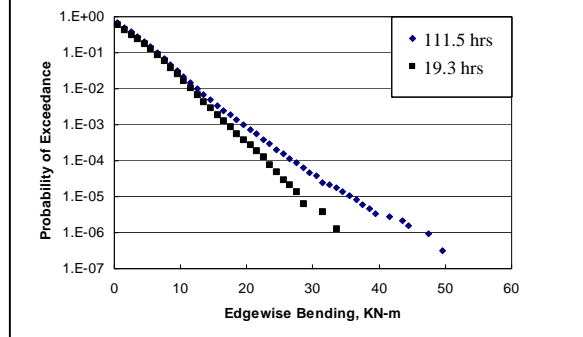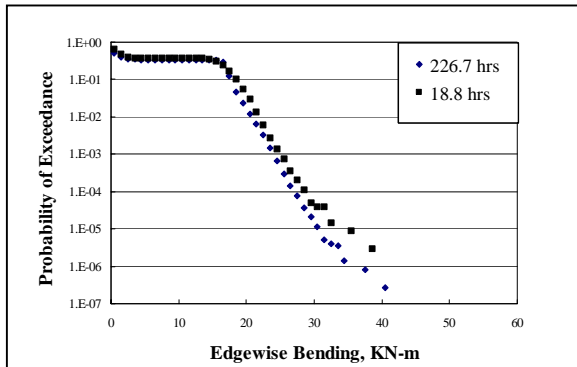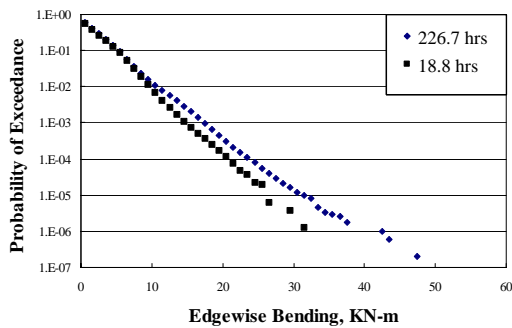

Fig. 9a. Edgewise Bending in the Root of Blade 1.
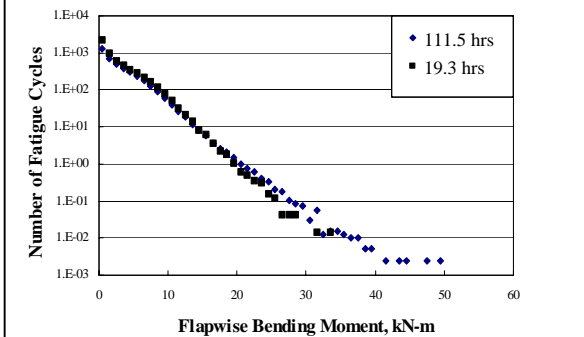
Fig. 9b. Flapwise Bending in the Root of Blade 2.

Fig. 9. Fatigue Load Spectrum for the 11-13 m/s Wind Speed Bin.

Fig. 10a. Edgewise Bending in the Root of Blade 1.

Fig. 10b. Flapwise Bending in the Root of Blade 2.

Fig. 10. Exceedence Plots of the Fatigue Load Spectrum for the 11-13 Wind Speed Bin.

Fig. 11a. Edgewise Bending in the Root of Blade 1.

Fig. 11b. Flapwise Bending in the Root of Blade 2.

Fig. 11. Exceedence Plots of the Fatigue Load Spectrum for the 9-11 Wind Speed Bin.

data presented in Fig. 9a and b in bins above approximately 37 kNm and 32 kNm, respectively. As the bins that constitute the floor of the data contain only a single cycle count, using them as an estimate of the long-term behavior would not be accurate because the number of observations is not statistically significant.

When more data are added, in this case approximately 90 hours of data are added, the floor is lowered to approximately 0.009 cycles per hour, i.e., one cycle in approximately 111 hours. For edgewise bending, the 111-hour exceedence curve lies virtually on top of the 19-hour curve until the floor in the 19-hour data set is reached. For flapwise bending, the initial slope of the 19-hour data is maintained by the 111-hour data, but the two curves diverge at the higher bending moments, starting at approximately 25 kN-m, see Fig. 9b. This divergence is a result of a proportionally larger number of high bending moment cycles that were measured during the second measurement campaign. Thus, based

on the relatively long-term data from the combined data sets, the cycle counts in the initial 19-hour data set were not statistically representative for bins above approximately 25 kN-m.

The significant difference between the various data sets is that the expansion of the data set to 111 hours extends the exceedence curve to a new floor. In particular, the additional data indicate that the primary slope of the exceedence curve in the high bending moment region of the spectrum continues unabated past the floor of the 1-hour data set for this turbine.

The data shown in Fig. 9 indicate that the extrapolation of relatively short-term spectra to long-term spectra is consistent with measured data. And, based on the data analyzed here, the high-stress tail of the fatigue load distribution for this turbine continues to at least a floor of 1 count in 111 hours, with no end in sight.

Similar trends are observed in the 9-11 wind speed bin shown in Fig. 11, although these data do show some divergence of the 227-hr data from the 19-hr data.
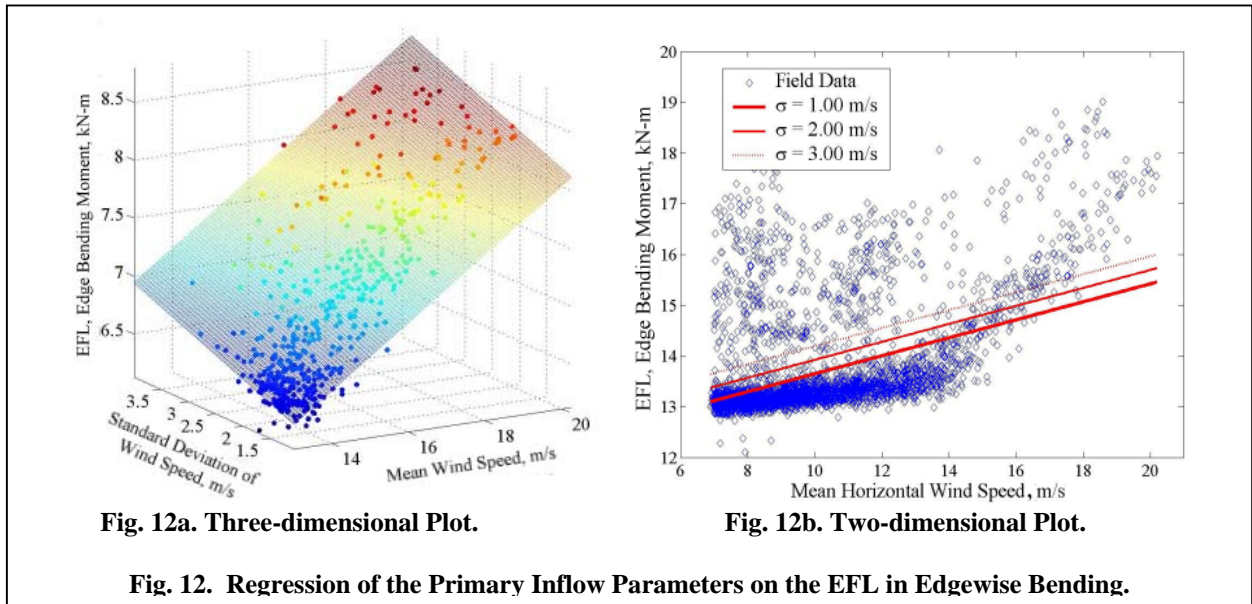
INFLOW ANALYSIS

Several authors have examined the influence of inflow parameters on fatigue loads. Fragoulis [2], Glinou and Fragoulis [12], and Sutherland [1] have examined the influence of various inflow parameters on equivalent fatigue loads. Kelley [13] has examined the influence of several parameters on the shape of the fatigue spectrum.

Nelson, et al [14] has recently demonstrated a sequential regression analysis that differs significantly from previous analysis. The procedure does not bin the data sets by wind speed, and, in sharp contrast to these previous studies, examines the inflow parameters in a sequential analysis, rather than the multi-value regression used in the previous studies. This analysis will be used here.

Dependent Variables

For this analysis, the blade fatigue loads for the flap and edgewise bending moment are characterized using the damage equivalent fatigue load [3,5] and by the extreme values for each 10-minute record. The Equivalent Fatigue Load (EFL) for each spectrum is determined for two fatigue exponents, m, equal to 3 and 10. The former yields an EFL appropriate for steel and the latter yields an EFL appropriate for fiberglass composites.

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Fig. 12a. Three-dimensional Plot. **Fig. 12b. Two-dimensional Plot.**

Fig. 12. Regression of the Primary Inflow Parameters on the EFL in Edgewise Bending.

Inflow Parameters

A total of eighteen inflow parameters were examined. The first two are the "primary" parameters of mean and standard deviation of the hub-height, horizontal wind speed. An additional sixteen "secondary" parameters were examined: the vertical wind shear exponent, standard deviations of wind speed in the cross-wind and vertical directions, turbulence kinetic energy, three orthogonal Reynolds stresses, local friction velocity, Obukhov length, a stability parameter, the gradient Richardson number, turbulence length scales in three orthogonal directions, and the skewness and kurtosis of horizontal wind speed. Sutherland [5] provides a mathematical description of these variables.

Regression Procedure

The analysis used here starts with a bi-variate linear regression on the two primary variables. After the initial regression is performed, the residual is regressed on each inflow parameter from the secondary inflow parameter list. The particular parameter that produces the best correlation coefficient is chosen as the next most important parameter.   The residual is then recomputed and the process repeated on the remaining 15 secondary inflow parameters.

Results

The dependence of the EFL on wind speed is shown in Fig. 12 for a fatigue exponent m of 10. In this figure, the dependence on mean wind speed and turbulence is depicted in the three-dimensional plot and the dependence on mean wind speed is highlighted in the two-dimensional plot.

As shown in Fig. 12, the EFL for each 10-minute record varies widely. There does appear to be some banding below 14 m/s, see Fig. 12b, but some of the highest EFL occurs at the lowest mean wind speeds.

The analysis of these data will proceed along two paths. In the first, the entire data set will be analyzed and in the second, only the high wind speed data will be analyzed.

The Entire Data Set

The results of the regression analysis on the two primary inflow parameters of mean and standard deviation of the hub-height, horizontal wind speed are shown in Fig. 12. The resulting residuals are shown in Fig. 13.
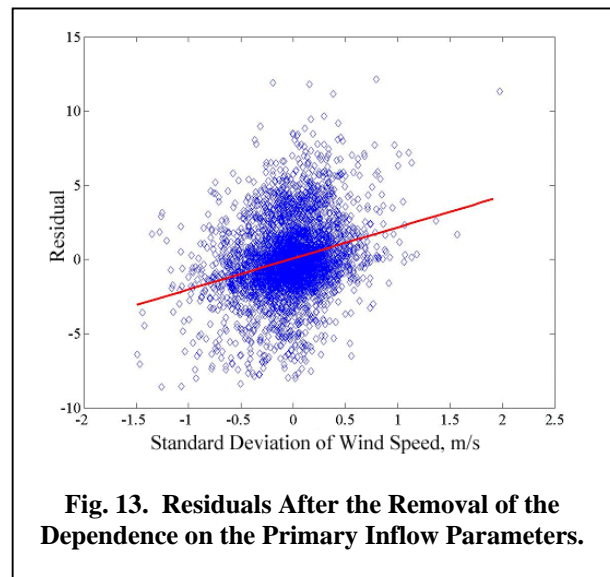
Fig. 13. Residuals After the Removal of the Dependence on the Primary Inflow Parameters.
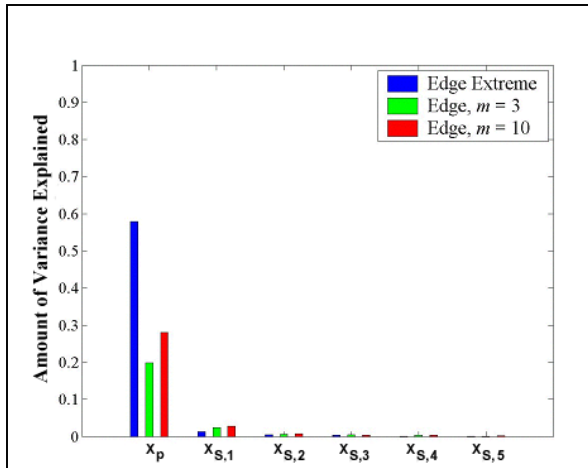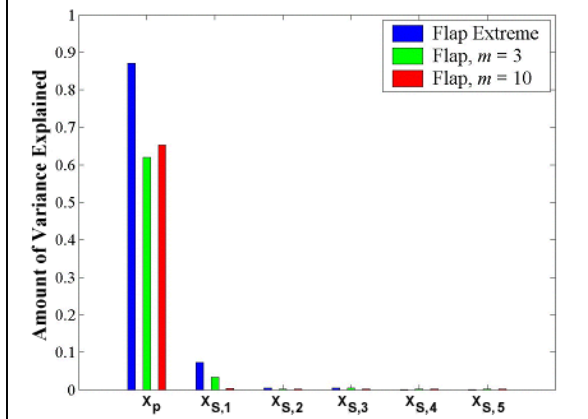
Fig. 14a. Edgewise Bending.

Fig. 14b. Flapwise Bending.

Fig. 14. Correlation Coefficients for the Inflow Parameters in Order of Their Importance Using the Entire Data Set.

Fig. 15a. Edgewise Bending.

Fig. 15b. Flapwise Bending.

Fig. 15. Correlation Coefficients for the Inflow Parameters in Order of Their Importance Using the Reduced Data Set.

The bi-variate regression yields the plane shown in Fig. 12a. In Fig. 12b, the regression plane is depicted using constant standard deviation lines as they follow the regression plane. The three lines shown here correspond to standard deviations of 1, 2 and 3 m/s, respectively. The very mild slope of these lines indicates that the dependence of the fatigue loads on the standard deviation is relatively small.

As shown in Fig. 13, the residuals do not display a significant trend. This is verified with the results of the regression analysis shown in Fig. 14. In this figure, the primary parameters, x_p, have a correlation coefficient of approximately 0.2 to 0.3 in fatigue and 0.6 for the extremes in edgewise bending and approximately 0.6 and 0.85, respectively, in flapwise bending. All of the second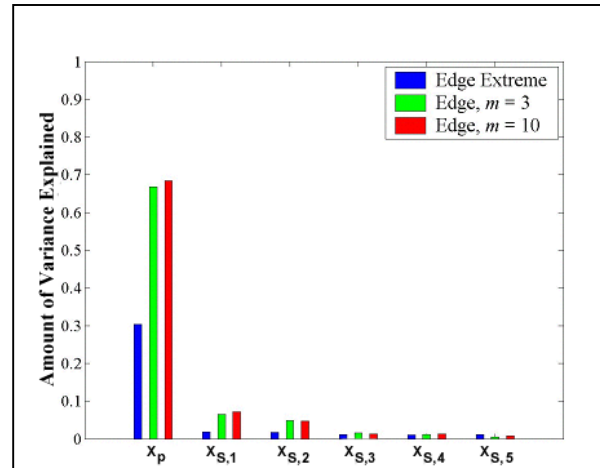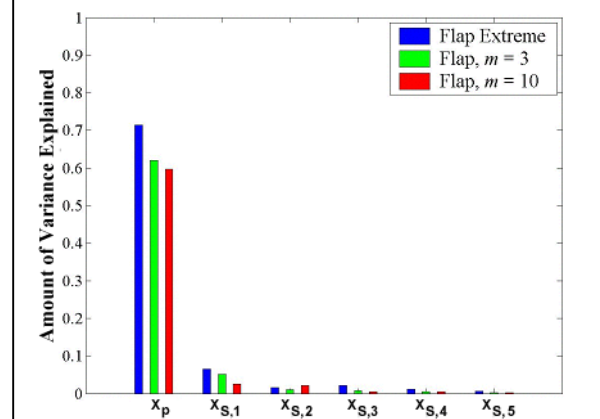ary parameters, $x_{S,1}$, $x_{S,2}$, … , $x_{S,16}$, have a correlation coefficient of less than approximately 0.05. Thus, the fatigue and the extremes show essentially no dependence on any of the secondary inflow parameters.

Reduced Data Set

Nelson, et al [6] have shown that using a reduced data set that includes only those data above rated power offers promise. The results for this reduced data set are shown in Fig. 15. As shown in the figure, there is essentially no dependence of the reduced data set on any of the secondary inflow parameters either.

SUMMARY

The recent measurement campaign on a small wind turbine at a Great Plains site using an updated data acquisition system, ATLAS, illustrates that the system

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is now very reliable and can be used successfully in a field environment to obtain continuous data 24 hours a day, 7 days a week from an operating wind turbine.

The measurement campaign used to demonstrate the capabilities of the ATLAS gathered over 1630 hours of data. These data expanded the previous data set for the test turbine, 330 hours of data, by almost a factor of five. This expanded data set is used here to illustrate long-term fatigue spectra and the dependence of fatigue on various inflow parameters.

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