

# A Comparison of Measured Wind Park Load Histories with the WISPER and WISPERX Loading Spectra

Neil D. Kelley

*Prepared for  
ASME Wind Energy Symposium  
January 29–February 1, 1995  
Houston, Texas*



National Renewable Energy Laboratory  
1617 Cole Boulevard  
Golden, Colorado 80401-3393  
A national laboratory of the U.S. Department of Energy  
Managed by Midwest Research Institute  
for the U.S. Department of Energy  
under contract No. DE-AC36-83CH10093

Prepared under Task No. WE418350

January 1995

## **NOTICE**

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available to DOE and DOE contractors from:

Office of Scientific and Technical Information (OSTI)  
P.O. Box 62  
Oak Ridge, TN 37831

Prices available by calling (615) 576-8401

Available to the public from:

National Technical Information Service (NTIS)  
U.S. Department of Commerce  
5285 Port Royal Road  
Springfield, VA 22161  
(703) 487-4650



# A COMPARISON OF MEASURED WIND PARK LOAD HISTORIES WITH THE WISPER AND WISPERX LOAD SPECTRA

**Neil D. Kelley**  
Wind Technology Division  
National Renewable Energy Laboratory  
Golden, Colorado

## ABSTRACT

The blade-loading histories from two adjacent Micon 65/13 wind turbines are compared with the variable-amplitude test-loading histories known as the WISPER and WISPERX spectra [1]. These standardized loading sequences were developed from blade flapwise load histories taken from nine different horizontal-axis wind turbines operating under a wide range of conditions in Europe. The subject turbines covered a broad spectrum of rotor diameters, materials, and operating environments. The final loading sequences were developed as a joint effort of thirteen different European organizations. The goal was to develop a meaningful loading standard for horizontal-axis wind turbine blades that represents common interaction effects seen in service.

In 1990, NREL made extensive load measurements on two adjacent Micon 65/13 wind turbines in simultaneous operation in the very turbulent environment of a large wind park located at the San Geronio Pass, California. Further, before and during the collection of the loads data, comprehensive measurements of the statistics of the turbulent environment were obtained at both the turbines under test and at two other locations within the park. The trend to larger but lighter wind turbine structures has made an understanding of the expected lifetime loading history of paramount importance. Experience in the U.S. has shown that the turbulence-induced loads associated with multi-row wind parks in general are much more severe than for turbines operating individually or within widely spaced environments. Multi-row wind parks are much more common in the U.S. than in Europe.

In this paper we report on our results in applying the methodology utilized to develop the WISPER and WISPERX standardized loading sequences using the available data from the Micon turbines. While the intended purpose of the WISPER sequences were not to represent a specific operating environment, we believe the exercise is useful, especially when a turbine design is likely to be installed in a multi-row wind park.

## INTRODUCTION

A considerable amount of interest has developed in the identification of factors that are responsible for increased fatigue loading of wind turbine blades installed in multi-row wind parks. Also of interest are testing techniques which can simulate the loading seen by blades in an operating environment through the use of servo-hydraulic testing equipment. The first step was taken in Europe in 1988 with the development of a loading standard known as WISPER (WInd Turbine Reference SPECTrum) [1]. The WISPER loading spectrum was formulated to represent the stochastic interaction effects present in service loading, but not to represent any particular or site-specific operating environment.

The WISPER spectrum, in our opinion, represents a more or less homogeneous view of the service environment seen by turbines operating individually in near-uniform terrain and in proximity to the ocean. In the U.S., the majority of wind turbines installed for commercial power production have been installed in multi-row wind parks located in continental sites dominated by complex terrain features. While the WISPER spectrum was intended to reproduce the general character of service loading, the question arises whether the same methodology can be applied to create a loading sequence more indicative of a multi-row wind park. In this paper we have strived to do that. We have taken the development up through defining the loading spectra as a function of wind speed class. The regeneration of a characteristic sequence of wind classes or operating modes and the synthesis of the actual load-time histories have yet to be accomplished.

## APPROACH

Our methodology has been to

- closely apply the protocol used to develop the WISPER reference spectrum using blade loads measured on two adjacent wind turbines towards the rear of a 41-row wind

park at San Geronio Pass, California;

- compare the results and highlight the differences, and;
- compare the results with previous work defining turbulent inflow parameters that scale with the larger, more damaging fatigue loads.

## **THE WISPER AND WISPERX REFERENCE-LOADING SPECTRA**

The WISPER and WISPERX (an abbreviated version of WISPER) reference-loading spectra have been developed by an international working group comprised of thirteen different European research institutes and manufacturers [1]. The objective of the effort has been to specify variable-amplitude (or spectral) test-loading histories that incorporate the major features seen in the root flapwise (out-of-plane) bending of horizontal-axis wind turbine (HAWT) blades. These features include exhibiting a spectral shape that is characteristic of the type of structure under test, while also providing the interactions thought to be important in such a stochastic environment. Great care was taken to ensure that the final loading spectra did not represent any particular turbine design or operating environment (e.g., no attempt was made to provide for a realistic time correlation). This was done to allow the standard to be used for comparative purposes only. It is this last context that is the subject of this paper. The final outputs are loading sequences expressed over an amplitude range of 1 to 64 (referred to as WISPER Levels), with zero load equal to 25. This definition is intended to be used to scale the variable-amplitude loads applied to a blade under test via a servo-hydraulic fatigue-testing apparatus.

### **Sources of Data**

Two fundamental sources of data were required for the development of WISPER. One was the specification of a representative operating wind regime, and the other was characterization of a range of representative load histories. The first was derived from two long-term wind records (10 and  $\approx 6$  years) available from two sites on and just off the coast of northern Germany. The latter was formulated from loading time histories collected from nine, rigid-hub horizontal axis turbines that incorporate both two- and three-bladed rotors ranging from 11.7 to 80 m in diameter. The turbines were installed in northern Europe, within the territories of Denmark, Sweden, the Netherlands, Great Britain, and Germany.

### **The Development Protocol**

The WISPER developers identified two primary sources of fatigue damage accumulation in a wind turbine blade. These are the wind inflow characteristics (the ultimate source of the stochastic loads or excitation) and the design of the turbine itself (blade geometry and materials, turbine geometry, control system, and operating procedures). Thus, the WISPER protocol consists of the two primary steps of evaluating the inflow or wind data

and observed turbine loads during starts, stops, and continuous operation. In this paper we only address the loads encountered under continuous operation. A general overview of the protocol is given below. The reader is directed to Reference [1] for more detail.

**Wind Regime Classification.** The WISPER wind regime definition utilizes eight wind speed classes. The first two are connected with discrete events, specifically turbine start-up (Class 1) and stopping (Class 2). Classes 3 through 8 are associated with 10-minute mean wind speeds in which continuous operation of the turbine is assumed. The WISPER mode of operation corresponds to these eight classes with Mode 3  $< 9 \text{ ms}^{-1}$ . Modes 4 through 7 are defined by mean wind speeds of 9–11, 11–13, 13–15, and 15–17  $\text{ms}^{-1}$ , respectively. Finally, Mode 8 is specified by means exceeding 17  $\text{ms}^{-1}$ .

To synthesize a representative wind class sequence, the long-term wind distribution derived from the two German stations was rainflow counted as 6x6 Markov From/To matrices with a resolution of 2  $\text{ms}^{-1}$ . The matrix elements then contained the expected annual number of hours for a particular wind class pair. Later this matrix was reduced from an annual to a 2-month equivalent to correspond to the final WISPER loading sequences of the same length.

**Loading Classification.** A large population of load measurements was available from the nine turbines. This data (in rainflow From/To format and accompanied by the corresponding WISPER Operating Mode) formed the basis from which the final load spectra expressed as load cycles per revolution were derived. A total of 65 matrices were extracted from the population. These selected matrices allowed absolute load spectra per turbine and operating mode to be realized. The individual spectra from each turbine were made comparable by applying a normalization scheme. For Operating Modes 3–8, the loads occurring once per 1000 revolutions were used. These normalized levels were then averaged per mode of operation to reduce the influence of individual turbines. Using this approach, it was possible to obtain a series of six normalized loading spectra representing Operating Modes 3–8. The normalization of Operating Modes 1 and 2 (start-up/stop) was handled somewhat differently but is not germane to this paper and is therefore not discussed.

By adopting a reference rotation rate of 45 rpm, an annual load-time history was synthesized using a wind class distribution expressed in hours per year from the two long-term station records. The sequence of wind classes used in the synthesis was derived from a regeneration of a randomly chosen sample from the 6x6 Wind Class From/To matrix. This sequence represented a single sample of the available population of reconstituted annual wind class vectors. The resulting load spectrum was truncated by extrapolating the once-per-1000-revolution level to a normalized range size of 2.9. It is expected that this level corresponds to a normalized range

size occurring annually. To further reduce the number of loading cycles, normalized range sizes less than 0.6 were eliminated. A 2-month spectrum was then specified by decimating the annual one by a factor of 6. Finally, the normalized loading range was discretized by expressing the test levels over a range of 1 to 64 (WISPER Levels), with a value of 25 representing the zero-load condition.

To shorten the testing time, a modified version of the final WISPER sequence, called WISPERX, was defined. The WISPERX spectrum was obtained by retaining only those cycles with a WISPER Level of 17 or larger. As a consequence, the WISPERX spectrum has only about 1/10th the number of cycles of the original while maintaining the extreme peaks and valleys in tension as well as compression. It, in effect, concentrates the loading in what we have referred to previously in Reference [2] as the "low-cycle, high-amplitude or LCHA range."

### APPLYING WISPER PROTOCOL TO SAN GORGONIO WIND FARM LOADS

The WISPER and WISPERX reference-loading spectra were developed based on operating conditions prevalent in northern Europe. Further, as far as we know, the loads data came from turbines operating individually, or at most in pairs. The contrast between operating conditions in the U.S. and those of this region of Europe is very marked. In the U.S., the majority of the wind turbine operating experience has been in multi-row wind parks located in complex terrain. The WISPER spectrum is based on loads measured on turbines operating in quasi-homogenous terrain, often not far from the influence of the ocean. The availability of an extensive set of measurements taken from two nearly identical turbines deep within a 41-row wind park was seen as an opportunity to compare the influences of the two operating environments.

### Available San Gorgonio Data Sets

During 1990, we simultaneously operated two adjacent Micon 65/13 horizontal axis wind turbines located at Row 37 of a 41-row wind park in San Gorgonio Pass, California. This location is near the center of a group of turbines that is characterized by low energy production and higher fatigue damage relative to other positions within the park. The turbines were identical except for the rotors. We operated one with blades based on the NREL (SERI) thin-airfoil family, which had a rotor diameter of 17 m. The other turbine was fitted with a 16-m rotor consisting of reconditioned, original-equipment AeroStar blades. See Tangler et al. [3] for a more complete discussion of these tests. We collected a total of 397 10-minute records over a wide range of (but representative) inflow conditions during late July and early August. We also processed the inflow wind data and blade root flapwise loading signals, following the WISPER protocol as close as is practical to compare the two loading environments.

### Wind Classification (WISPER Mode) Comparisons.

The individual 10-minute records of mean hub-height wind speed were classified according to the WISPER protocol. In addition to

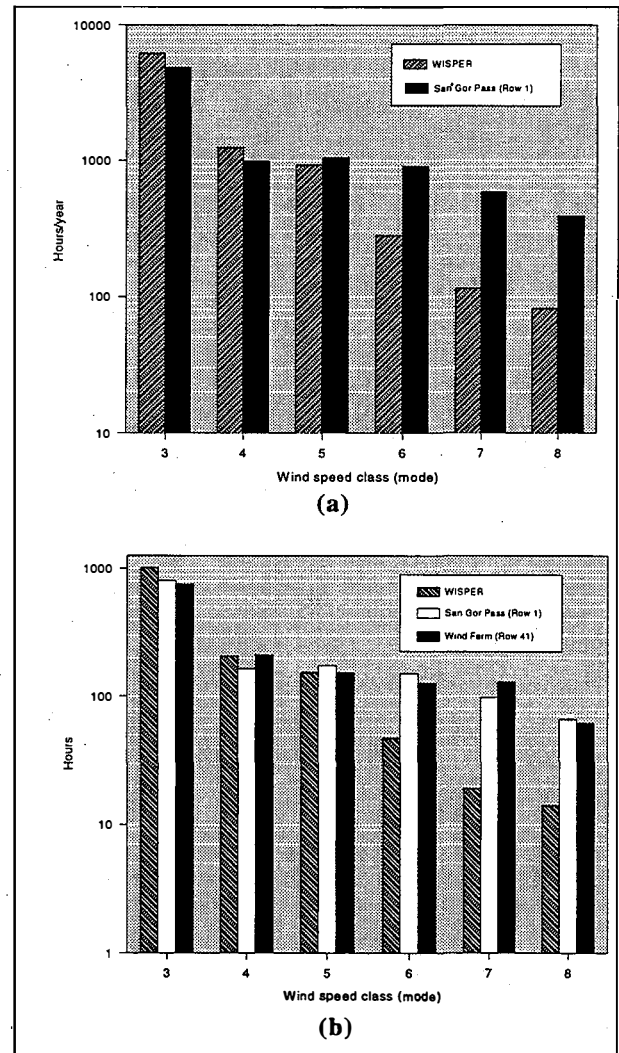


FIGURE 1. COMPARISON OF (a) ANNUAL AND (b) 2-MONTH WIND SPEED CLASS DISTRIBUTIONS

the records associated with the measured turbine loads at Row 37, longer term records were available from locations upwind of Row 1 and downwind of Row 41. The conditions seen upwind of Row 1, where more than a full year of continuous record is available, are representative of the natural flow in San Gorgonio Pass. There were no turbines upstream during the period when this data was taken. The conditions at Row 41 are representative of an operating environment within the wind park with a row-to-row spacing of 14 rotor diameters (D). Finally, the measurements at Row 37 are characteristic of conditions with a row-to-row spacing of 7D.

The full year of data from Row 1 was compared with the annual WISPER wind class distribution. The two months of record that were available from Row 41 allowed comparison with both a decimated distribution from Row 1 and the WISPER 2-month wind class distribution. Figures 1a and 1b compare these with

**TABLE 1. COMPARISON OF 2-MONTH WIND CLASS FROM/TO MATRICES**

| WISPER (10-min records)                    |      |      |      |      |      |     |      |
|--|------|------|------|------|------|-----|------|
| MODE                                       | 3    | 4    | 5    | 6    | 7    | 8   | FROM |
| 3  | 4636 | 190  | 6    | 0    | 0    | 0   |      |
| 4  | 1885 | 716  | 138  | 2    | 0    | 0   |      |
| 5  | 7    | 137  | 553  | 67   | 3    | 0   |      |
| 6  | 1    | 2    | 67   | 150  | 30   | 2   |      |
| 7  | 0    | 0    | 3    | 30   | 58   | 14  |      |
| 8  | 0    | 0    | 1    | 2    | 14   | 47  |      |
| TO   |      |      |      |      |      |     |      |
| SAN GORGONIO PASS (ROW 1) (10-min records) |      |      |      |      |      |     |      |
| MODE                                       | 3    | 4    | 5    | 6    | 7    | 8   | FROM |
| 3  | 2195 | 156  | 4    | 2    | 0    | 0   |      |
| 4  | 169  | 854  | 178  | 3    | 0    | 0   |      |
| 5  | 9    | 214  | 1116 | 223  | 4    | 0   |      |
| 6  | 4    | 2    | 244  | 1121 | 226  | 2   |      |
| 7  | 0    | 0    | 5    | 187  | 802  | 154 |      |
| 8  | 0    | 0    | 0    | 5    | 141  | 740 |      |
| TO   |      |      |      |      |      |     |      |
| SAN GORGONIO ROW 41 (10-min records)       |      |      |      |      |      |     |      |
| MODE                                       | 3    | 4    | 5    | 6    | 7    | 8   | FROM |
| 3  | 2533 | 45   | 0    | 0    | 0    | 0   |      |
| 4  | 82   | 1279 | 83   | 0    | 6    | 7   |      |
| 5  | 3    | 88   | 1103 | 28   | 0    | 15  |      |
| 6  | 0    | 0    | 80   | 1099 | 57   | 0   |      |
| 7  | 0    | 0    | 11   | 85   | 1292 | 17  |      |
| 8  | 0    | 0    | 0    | 0    | 46   | 801 |      |
| TO   |      |      |      |      |      |     |      |

**TABLE 2. SAN GORGONIO MICON 65 LOAD TABLE**

| Turbine Rotor | Wind Class/ Mode | Mean RPM | Normalizing Value (nv) (kNm) | Load Matrix Boundaries |             | Class Width (kNm) | Record Length (s) |
|---------------|------------------|----------|------------------------------|------------------------|-------------|-------------------|-------------------|
|               |                  |          |                              | Lower (kNm)            | Upper (kNm) |                   |                   |
| NREL          | 3                | 45.40    | 24.96                        | -14.24                 | 41.07       | 1.73              | 46800             |
| NREL          | 4                | 46.92    | 29.14                        | -14.24                 | 41.07       | 1.73              | 88200             |
| NREL          | 5                | 47.18    | 32.36                        | -14.24                 | 41.07       | 1.73              | 79200             |
| NREL          | 6                | 47.28    | 33.82                        | -14.24                 | 41.07       | 1.73              | 23400             |
| NREL          | 7                | 47.26    | 35.09                        | -14.24                 | 41.07       | 1.73              | 600               |
| AeroStar      | 3                | 41.93    | 24.39                        | -14.24                 | 41.07       | 1.73              | 46800             |
| AeroStar      | 4                | 46.89    | 28.57                        | -14.24                 | 41.07       | 1.73              | 88200             |
| AeroStar      | 5                | 47.13    | 31.42                        | -14.24                 | 41.07       | 1.73              | 79200             |
| AeroStar      | 6                | 47.23    | 33.02                        | -14.24                 | 41.07       | 1.73              | 23400             |
| AeroStar      | 7                | 47.22    | 36.96                        | -14.24                 | 41.07       | 1.73              | 600               |

**TABLE 3. RELATIVE SEVERITY COMPARISON**

| Mode | WISPER | San Gorgonio |          |
|------|--------|--------------|----------|
|      |        | NREL         | AeroStar |
| 3    | 0.76   | 0.86         | 0.85     |
| 4    | 1.00   | 1.00         | 1.00     |
| 5    | 1.11   | 1.11         | 1.10     |
| 6    | 1.19   | 1.16         | 1.16     |
| 7    | 1.34   | 1.20         | 1.29     |
| 8    | 1.01   | n/a          | n/a      |

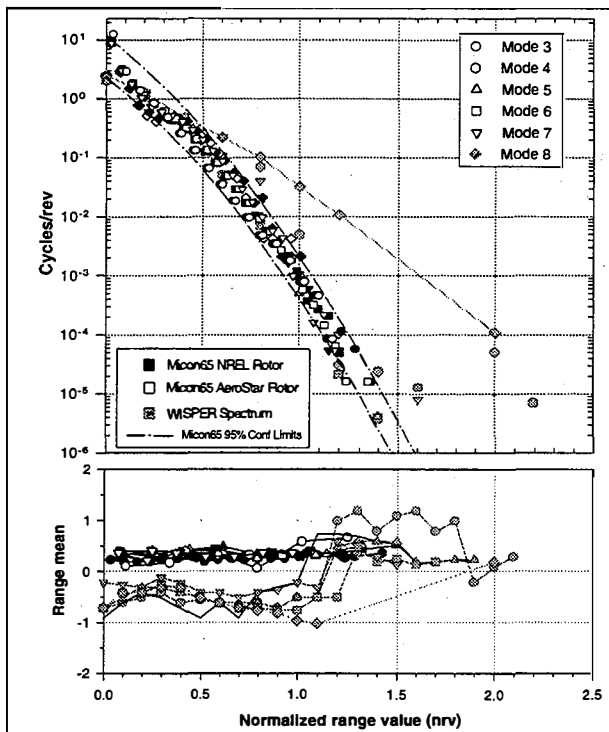
the corresponding WISPER distributions. Figure 1a shows that there is a higher frequency of occurrence of the more energetic wind classes in San Gorgonio Pass than in the WISPER. Figure 1b indicates only slight differences in the 2-month distributions at Rows 1 and 41. Table 1 summarizes the 2-month From/To matrix distributions derived from the rainflow counting of the WISPER and the two San Gorgonio wind statistics. There are significant differences between the WISPER and San Gorgonio matrices that will influence the ordering of the sequence of wind classes on wind class event regeneration.

**Loading Spectra Comparisons**

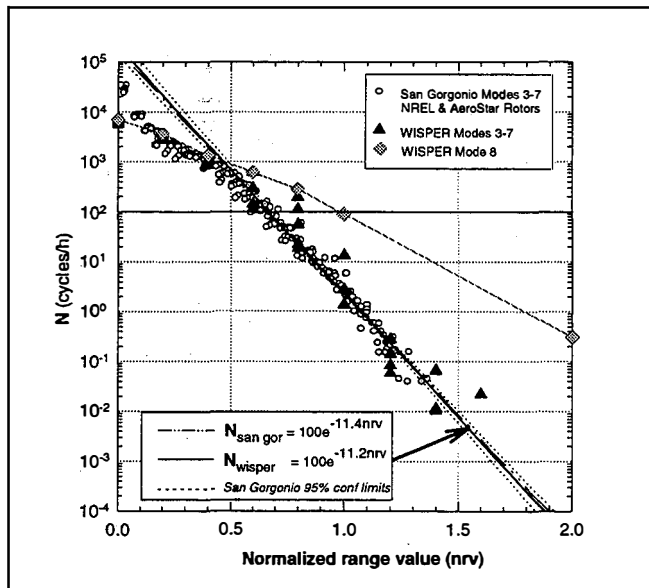
Table 2 summarizes the loading data for the two Micon 65 turbines for each wind class or WISPER operating mode available in the data set. There were no records in the Mode 8 classification. Table 3 compares the operating-mode severity for each turbine with the WISPER data. There is less mode-to-mode variation in the San Gorgonio data.

A comparison between the WISPER and San Gorgonio load spectra is presented in normalized coordinates in Figure 2. There is excellent agreement for both turbines in the normalized range values for Modes 3–7. It is not clear why the discrepancy with the WISPER Mode 8 exists. Perhaps it is related to the short records available, which makes it difficult to estimate a normalizing value at the once-per-1000-revolution frequency. The corresponding range-normalized means show a systematic variation between the WISPER and the two San Gorgonio turbines. We have interpreted this to be a consequence of the local operating environments. J. Tangler has suggested that this crossover from mean compression to mean tension in the WISPER loads may be a consequence of the occasional intense North Sea storms that affect the region [4].

Previously, in Reference [2], we have suggested that the root flapwise bending loads exhibit a decaying exponential distribution at frequencies longer than about 100 cycles/h. It is this region that we call the low-cycle, high-amplitude (LCHA) load range. We believe this behavior is a consequence of the process responsible for these loads being Poisson or Markov-Poisson (e.g., the events constituting the cycle pairs as well as the closing of a cycle are statistically independent of one another). In

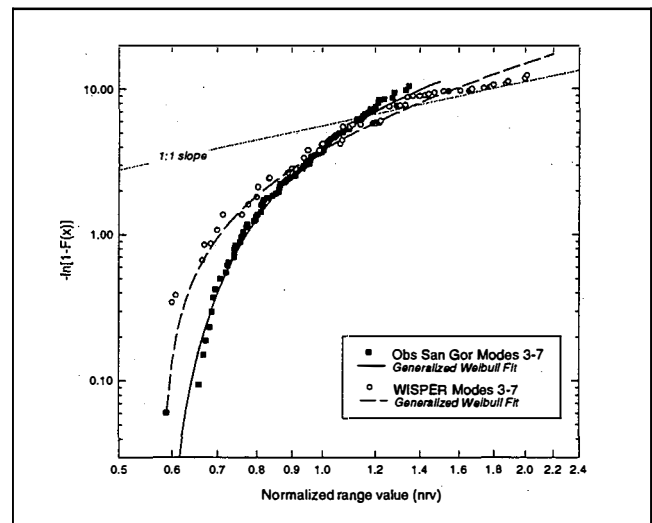


**FIGURE 2. COMPARISON OF MICON 65 AND WISPER NORMALIZED RANGE/MEANS**



**FIGURE 3. COMPARISON OF LOW-CYCLE, HIGH-AMPLITUDE RANGE NORMALIZED LOADING**

Figure 3 we have replotted normalized range values against an ordinate scaled in cycles/h. In this plot we have combined both Micon 65 rotors and WISPER Modes 3–7 into common plotting

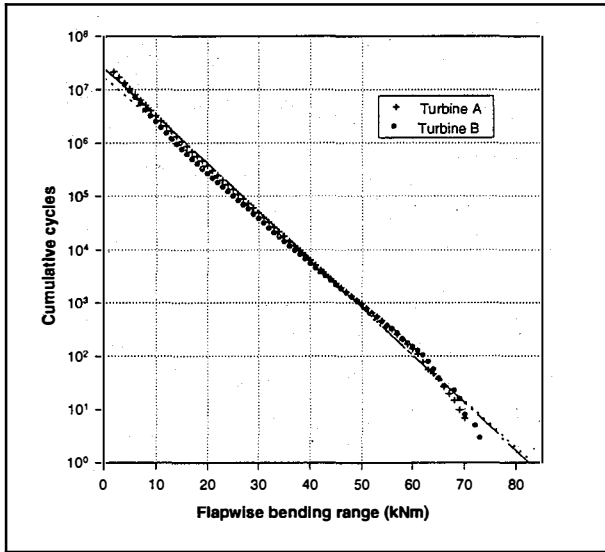


**FIGURE 4. WEIBULL COMPARISON OF LOW-CYCLE RANGE ( $N \leq 100$  cyc/h)**

symbols (open circles and filled diamonds, respectively). We have continued to plot WISPER Mode 8 separately, and have fitted a decaying exponential to both the Micons and the WISPER Modes 3–7 data points initiated at a frequency of 100 cycles/h. Both curves are almost identical with the WISPER residing within the 95% confidence limits of the Micons. The resulting slopes are within 2% of each other, suggesting the process responsible applies in both this wind park and in northern Europe.

In Figure 3 we noted the apparent similar behavior of the aggregated Modes 3–7 load spectra from San Gorgonio and WISPER in the LCHA range (e.g. an exponential decay). H.J. Sutherland suggested plotting the same data in Weibull coordinates and then applying a generalized Weibull fitting algorithm developed by Winterstein et al. [5] to better evaluate the behavior in the high-loading tail [6]. This has been done in Figure 4, where  $F(x)$  is the observed distribution function. The plot shows that, except at the normalizing value of 1.0, the WISPER and San Gorgonio data have slightly different shapes. Because the San Gorgonio data covers a smaller compass of normalized range values than the WISPER, we cannot say with certainty if it will continue with the final slope as suggested by the curve fit or become parallel with the WISPER. It is interesting to note, however, that the asymptotic approach of the extreme tail of the WISPER distribution to the 1:1 slope line suggests that the process is indeed exponentially distributed.

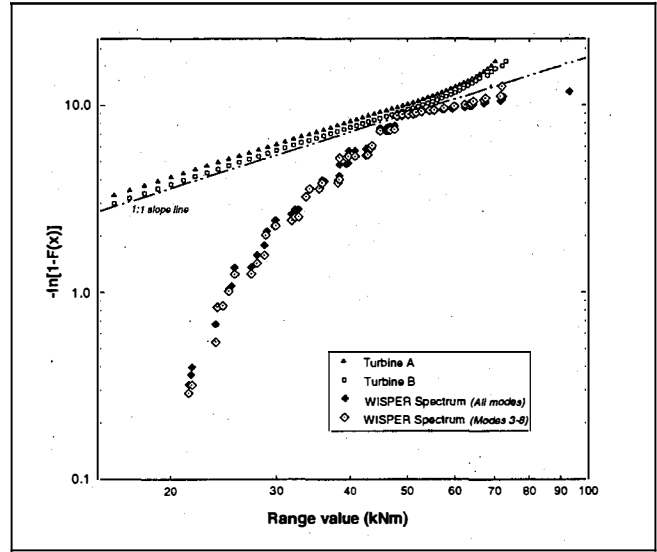
Recently, H. Seifert has made available two range or peak-to-peak rainflow load spectra collected for 6 months from two turbines in northern Germany [7]. The spectra are summarized in Figure 5 with an exponential trend line fitted through each. Again, the two exponential trend lines are almost identical in the high-loading tail, though the data exhibits curvature at values larger than about 50 kNm. This can be seen more clearly in the Weibull plot of Figure 6. We believe the curvature the long-term data in the high-loading tail is an artifact brought about by



**FIGURE 5. SIX-MONTH RAINFLOW SPECTRA FROM TWO TURBINES IN NORTHERN GERMANY WITH EXPONENTIAL TREND LINE**

the closing of all open (or half-cycles) at the conclusion of a recording period. Typically, when an open cycle is closed prematurely, its true amplitude will be underestimated and counted in a class associated with a lower value. To see this, we have plotted the WISPER spectrum in Figure 6 which has been scaled by using the value of the largest observed rainflow load class. The WISPER spectrum in the high-loading tail for Modes 3–8 does not exhibit the same degree of curvature as the long-term German data because it was derived from *full cycles only*. We believe that the overall agreement of the long-term spectra in Figure 6 with a slope of 1 lends credibility to the hypothesis that the high-load tail or LCHA region is exponentially distributed.

From this point on, we believed it was appropriate to treat the loads from the two Micons as an aggregate sample from the six rotor blades. Using the 2-month wind speed class or operating mode distribution of Figure 1b, we calculated the final San Gorgonio loading spectrum following the WISPER protocol. In Figure 7 we compare the results by plotting the cycles accumulated in 2 months for Modes 3–7 of the WISPER, WISPERX, and San Gorgonio load spectra as a function of the WISPER Level range size. We did not include the WISPER Mode 8 in the calculations because, quite frankly, we do not know how to judge its relevance to the San Gorgonio wind park environment. It is clear from Figure 7 that a turbine blade operating at this location in the San Gorgonio wind park will exhibit more cycles in the damaging LCHA load range as compared to northern Europe. The number of loading cycles in Figure 7 for the WISPER, WISPERX, and San Gorgonio spectra are approximately 125,000, 13,000, and 118,000 respectively. It can be seen that the San Gorgonio spectrum is essentially a much more rigorous version of WISPERX.



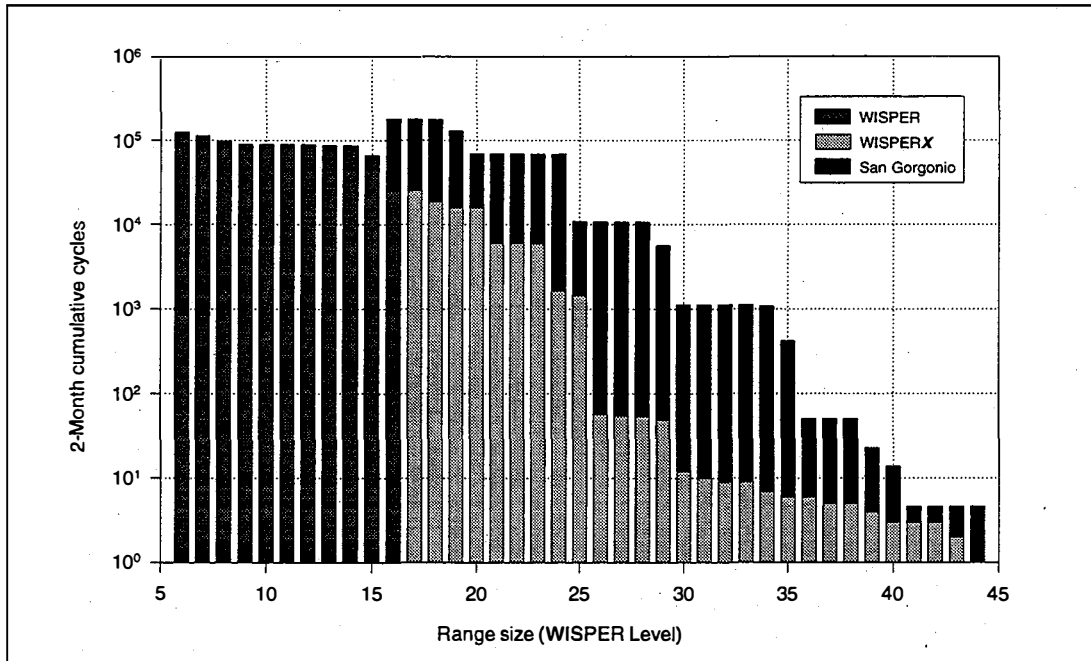
**FIGURE 6. WEIBULL PLOT OF 6-MONTH DATA PLUS WISPER SPECTRA**

### INFLOW TURBULENCE STRUCTURE AND SCALING IMPLICATIONS

Given the results of Figure 7, one might ask if there are significant structural differences in the turbulent inflows seen in northern Europe and in San Gorgonio wind parks. Figure 7 clearly indicates that for a given WISPER range size, many more high-load cycles will be experienced by a blade in San Gorgonio than in the environments from which the WISPER was derived. In Figure 8 we plot the relationship between the normalized range values and the WISPER Level range size. It is insensitive to mean wind speed (wind speed class or operating mode) for the corresponding WISPER or northern European load spectra. Within the San Gorgonio wind park, however, Figure 8 indicates a strong dependence on wind speed class. The data shows that the WISPER Level range size or peak-to-peak value from San Gorgonio increases with increasing mean wind speed for the same normalized range value.

The strong dependence of the slopes of Figure 8 on wind speed class for the San Gorgonio data and the lack of it for the northern European data suggests that some parameter other than mean wind speed may better scale the data. Previously, in Reference [2], we examined the sensitivity of rate of decay of the LCHA-range distribution to various fluid dynamics parameters of the inflow. We found that it was most sensitive to the static stability and the hub-height shearing stress,  $(-u'w')^{1/2} = u_*$  (where  $u'$  and  $w'$  are the longitudinal and vertical turbulent wind components, respectively, and  $u_*$  is defined as the friction velocity). Other bulk turbulence measures that are often used to scale loads are the standard deviation of the horizontal wind speed,  $\sigma_H$ , and the turbulence intensity  $TI = \sigma_H/U_H$  (where  $U_H$  is the mean horizontal wind speed). In Figure 9 we compare the ensemble means (denoted by the brackets) of these three parameters as a function of the WISPER wind speed

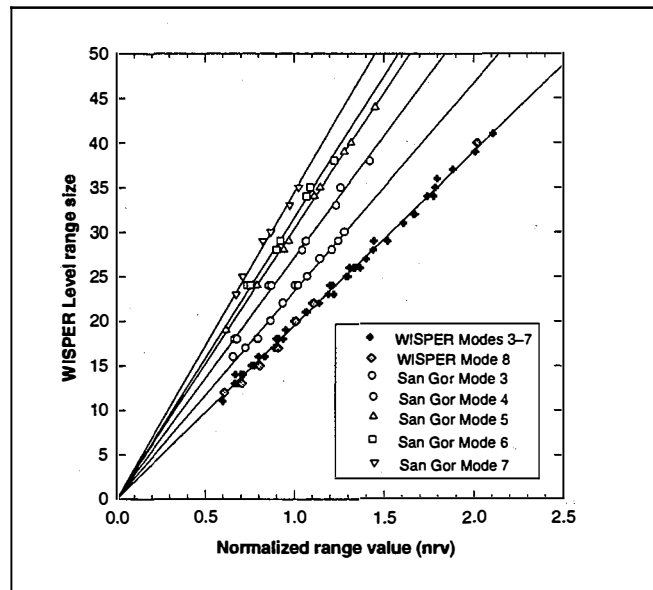




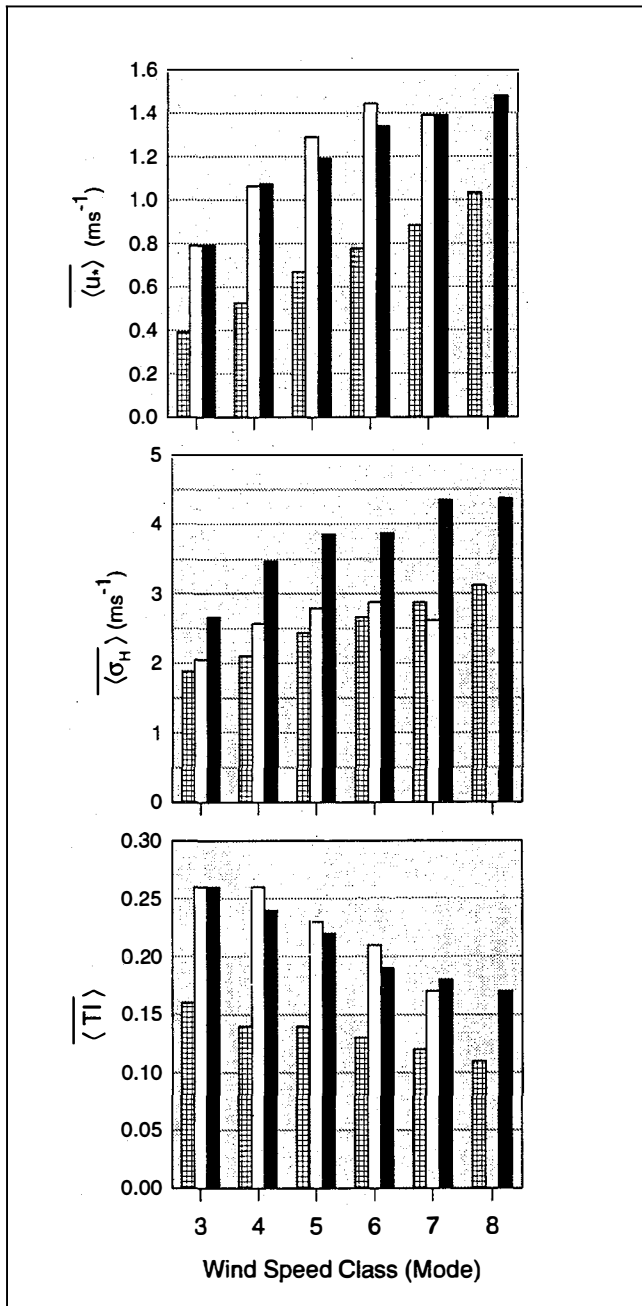
**FIGURE 7. COMPARISON OF MODES 3-7 OF WISPER, WISPERX, AND SAN GORGONIO LOADING SPECTRA**

class for three locations in and near the San Gorgonio wind park. Of the three parameters in Figure 9, only the shearing stress or friction velocity  $u_*$  exhibits a consistent monotonic increase with wind speed (or class) at all three locations.

We correlated each of these parameters with the slopes associated with each of the wind speed classes for the San Gorgonio data in Figure 8. We used the F Statistic (a large number reflecting a high degree of correlation) and the P-value (where P is the probability of being wrong) as measures of sensitivity to the slope of the curves of Figure 9. We found that  $u_*$  had the highest degree of correlation ( $F = 141.7$ ,  $P = 0.0013$ ), the turbulence intensity (TI) was next ( $F = 17.4$ ,  $P = 0.0250$ , though the correlation was actually *negative*), and  $\sigma_H$  was last ( $F = 4.56$ ,  $P = 0.1223$ ). Thus, these results are consistent with our findings in Reference [2]. We conclude that the difference between the WISPER curve of Figure 8 and the family associated with loads in the wind park is the strong dependence of the latter on the *turbulent cross-component wind statistics*. In Reference [2] we postulated that the dynamic shears present in the wakes from upstream turbines (as evidenced by high degree of *cross-axis correlation* or *coherency* in the flow) were a major contributor to the increased load levels seen in the LCHA. The lack of peak-to-peak load sensitivity with wind speed class in the WISPER spectrum suggests that the natural inflow lacks such a high degree of coherency.



**FIGURE 8. WISPER RANGE SIZE VERSUS WIND SPEED CLASS (MODE)**



**FIGURE 9. BULK TURBULENCE SCALING PARAMETERS AS A FUNCTION OF WIND SPEED CLASS IN SAN GORGONIO UPWIND AT ROW 1 (hashed), AT ROW 37 (white), AND AT ROW 41 (solid)**

## CONCLUSIONS

The application of the WISPER development protocol was proven to be successful for a specific operating environment. The normalization scheme, when applied to the San Gorgonio data set, provided consistent results. The methodology did identify some significant differences between the two service environments. The service spectrum based on the wind park

measurements contains many more loading cycles at larger peak-to-peak values. The WISPER spectrum peak-to-peak loads, as a function of the normalized range, are insensitive to increases in mean wind speed. In the San Gorgonio wind park, however, they increased monotonically. A sensitivity analysis revealed that this increase scales with an increase in the mean hub-height shear stress or friction velocity  $u_*$ , which is consistent with earlier results.

## FUTURE WORK

Our next step will be to regenerate a suitable random sample of the wind class sequence for the San Gorgonio wind park environment somehow including a Mode 8. With this sequence, we will then be able to synthesize an actual loading history in WISPER Levels for use with a servo-hydraulic fatigue-testing machine.

## ACKNOWLEDGMENTS

This work has been supported by the U.S. Department of Energy under contract number DE-AC02-83CH10093. The author sincerely appreciates the useful discussions with Jim Tangler of NREL and Herb Sutherland of Sandia National Laboratories, and thanks the latter for providing the generalized Weibull fitting of various distributions. The author also extends his appreciation to Henry Seifert of the Deutches Windenergi-Institut (DEWI) for making available the long-term load measurements.

## REFERENCES

1. Ten Have, A.A., September 1992, "WISPER and WISPERX: Final Definition of Two Standardized Fatigue Loading Sequences for Wind Turbine Blades," NLR-TP-91476U, National Aerospace Laboratory NLR, Amsterdam, the Netherlands.
2. Kelley, N.D., November 1993, "The Identification of Inflow Fluid Dynamics Parameters That Can Be Used to Scale Fatigue Loading Spectra of Wind Turbine Structural Components," NREL/TP-442-6008, National Renewable Energy Laboratory, Golden, CO.
3. Tangler, J., Smith, B., Jager, D., and Olsen, T., September 1990, "Atmospheric Performance of the SERI Thin-Airfoil Family," SERI/TP-257-3939, Solar Energy Research Institute, Golden, CO.
4. Tangler, J., September 1994, National Renewable Energy Laboratory, personal communication.
5. Winterstein, S.R. and Lange, C.H., January 1995, "Load Models for Fatigue Reliability from Limited Data," *Proc. of 14th ASME ETCE Wind Energy Symposium*, W.D. Musial (ed), ASME, Houston, TX.
6. Sutherland, H.J., September 1994, Sandia National Laboratory, personal communication.
7. Seifert, H., October 1994, Deutches Windenergi-Institut, personal communication.