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FATIGUE DAMAGE ESTIMATE COMPARISONS FOR NORTHERN EUROPEAN AND U.S. WIND FARM LOADING ENVIRONMENTS

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ABSTRACT

Typical loading histories associated with wind turbine service environments in northern Europe and within a large wind farm in the continental U.S. were recently compared by Kelley (1995) using the WISPER [Ten Have, 1992] loading standard and its development protocol. In this study, an equivalent load spectrum for a U.S. wind farm was developed by applying the WISPER development protocol to representative service load histories collected from two adjacent turbines operating within a large wind farm in San Gorgonio Pass, California. The results of this study showed that turbines operating in the California wind farm experience many more loading cycles with larger peak-to-peak values for the same mean wind speed classification than their European counterparts.

In this paper, the impact of the two WISPER-protocol fatigue-load spectra on service lifetime predictions are used to compare and contrast the impact of the two loading environments with one another. The service lifetime predictions are made using the LIFE2 Fatigue Analysis Code [Sutherland and Schluter, 1989] with the fatigue properties of typical fiber glass composite blade materials. Additional analyses, based on rainflow counted time histories from the San Gorgonio turbines, are also used in the comparisons. In general, these results indicate that the WISPER load spectrum from northern European sites significantly underestimates the WISPER protocol load spectrum from a U.S. wind farm site; i.e., the WISPER load spectrum significantly underestimates the number and magnitude of the loads observed at a U.S. wind farm site. We conclude that there are fundamental differences in the two service environments.

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 farms. The Wind turbine reference SPEctRum, WISPER,, 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 employed for commercial power production have been installed in multi-row wind farms located in continental sites dominated by complex terrain (i.e., mountain passes). While the WISPER spectrum was intended to be a loading standard that reproduces the general character of flap loads on a wind turbine blade, the question arises whether the same methodology can be used to create a loading sequence more representative of a multi-row wind park in complex terrain. Kelley (1995) found that the WISPER development protocol could be successfully applied to the U.S. wind farm operating environment. As one might expect, the load spectrum from the wind-park analysis differed significantly from the WISPER spectrum, with the former containing many more and larger loading cycles than the latter.

A logical extension of this work is to examine the predicted lifetime for these two load spectra. In this paper, we discuss the impact of the two operating environments on the predicted lifetime of two typical turbine blade materials. The lifetime predictions are also compared to the rainflow counted load spectrum on two Micon 65/13 turbines in San Gorgonio Pass, California. A brief discussion of what we believe to be the source of the differences is also included.

THE WISPER REFERENCE-LOADING SPECTRUM

The WISPER reference-loading spectrum was developed by an international working group composed of thirteen different European research institutes and manufacturers [Ten Have, 1992]. The objective of the effort was 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). These features imply that the standard is to be used for comparative purposes only.

The WISPER load spectrum is derived from eight load cases that are called “classes” or “modes”. The first two classes are the loads for discrete events, specifically turbine start-up (Class 1) and stopping (Class 2). The six remaining classes, 3 through 8, are based upon 10-minute load histories obtained during continuous operation of the turbines over their operating wind speed range. Mode 3 contains representative data for mean wind speeds below 9 m/s. Modes 4 through 7 contain data for mean wind speeds of 9-11, 11-13, 13-15, and 15-17 m/s, respectively. Finally, Mode 8 describes the loads for mean wind speeds exceeding 17 m/s.

The WISPER spectrum is based on a large population of load measurements from nine turbines whose rotor diameters ranged from 11.7 to 80 m. A total of 65, rainflow counted load cycle matrices (sorted by WISPER Wind Speed Class) were used to construct the WISPER spectrum. For Modes 3-8, the individual matrices from each turbine were normalized by the magnitude of the load cycle occurring once per 1000 revolutions. The normalized matrices for each wind speed class were then averaged together to reduce the influence of individual turbines. Using this approach, six normalized load cycle matrices were obtained; one each for Wind Speed Classes 3 through 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.

The WISPER protocol uses the six normalized load spectra as representative samples for the operation of the turbine. The total load spectrum is obtained by adding each of these representative samples together in proportion to the number of hours the turbine will operate during a two-month period. The hours of operation used in the WISPER protocol are based on the long-term wind statistics from two different sites along the coast of northern Germany.

SAN GORGONIO DATA SET

During 1990, an operating data set was collected from two adjacent Micon 65/13 horizontal-axis wind turbines that were simultaneously operated at Row 37 of a 41-row wind farm 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 turbine locations within the wind farm. The turbines were identical except for their rotors. One turbine had a 17-m rotor that was based on the NREL (SERI) thin-airfoil family, and the other had a 16-m rotor consisting of reconditioned, original-equipment AeroStar blades. [see Tangler et al. (1990) for a complete discussion of these tests.] In all, 397 10-minute records were collected over a wide range of inflow conditions during the late wind season (late July and early August).

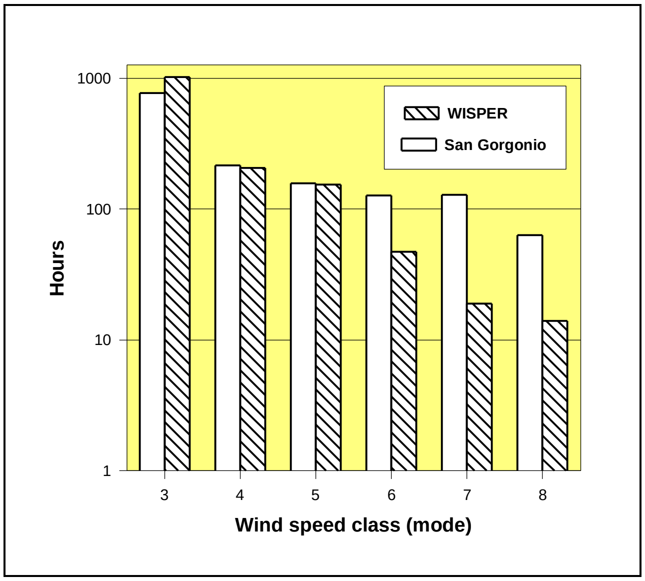

FIGURE 1. REFERENCE 2-MONTH WIND CLASS DISTRIBUTIONS

The wind speed distribution at the San Gorgonio site is significantly different from the distribution at the WISPER sites. As shown in Figure 1, there are many more hours of operation in the higher wind speed classes at San Gorgonio than are included in the WISPER distribution.

Kelley (1995) followed the WISPER development protocol to form the load cycle matrices for Modes 3 through 7. Data from both the NREL and AeroStar loads data were used to determine these matrices. The normalized load cycle matrices were then combined with the San Gorgonio wind speed distribution to form an equivalent WISPER spectrum for the San Gorgonio site. The two distributions are compared with one another in Figure 2. As shown in this figure, the San Gorgonio spectrum has many more cycles than does the WISPER spectrum.

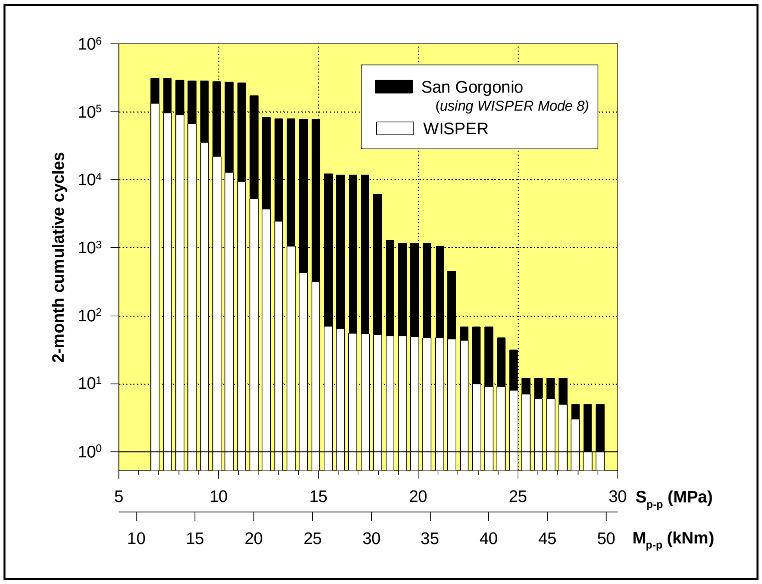

FIGURE 2. CUMULATIVE 2-MONTH REFERENCE ALTERNATING LOAD SPECTRA

The available load histograms in the San Gorgonio data set did not include information for Class 8 wind speeds. For this analysis, we have had to infer these loads. We used various approaches to extrapolate a Class 8 load spectrum from the available data. In the end, however, we found our extrapolated spectrum agreed almost exactly with that of WISPER Class 8. As a result, we have chosen to use the WISPER Class 8 load spectra, suitably adjusted for time of operation in San Gorgonio.

FATIGUE LIFETIME PREDICTION

The LIFE2 code [Sutherland and Schluter, 1989] is a PC-based, menu-driven package that leads a user through the steps required to characterize the loading and material properties. Miner's rule or a linear crack propagation rule is then used to calculate the time to failure. Only Miner’s rule is used here.

The LIFE2 code requires four sets of input variables: 1) the wind speed distribution for the turbine site as an average annual distribution, 2) the material fatigue properties required by the damage rule being used to predict the service lifetime of the component, 3) a joint distribution of mean stress and stress amplitude (stress states) for the various operational states of the turbine, and 4) the operational parameters for the turbine and the stress concentration factor(s) for the turbine component. The third set of input variables are "cycle count matrices" that define the operational states of the turbine. Each one of these matrices can be obtained from simulated or measured time series data (using rainflow counting techniques) or from analytical/numerical models. See Sutherland, Veers and Ashwill (1994) for a complete description of the techniques and typical inputs for the fatigue analysis of a wind turbine.

The WISPER protocol yields a load block that is based on 2 months of turbine operation. For consistency, we report our service lifetime predictions as the number of 2-month load blocks to failure.

For the analysis presented here, we conducted a parameter study to investigate the influence of each of the first three variables, cited above, on the predicted lifetime of the turbine.

Wind Speed Distribution: As discussed above, two wind speed distributions are available for this analysis. The first distribution is for the San Gorgonio test site, and the second is the German data used in the development of the WISPER spectrum. The significant difference between the two distributions, see Figure 1, is that the San Gorgonio distribution has significantly more time in the upper wind speed classes than the WISPER protocol distribution.

Material Fatigue Properties: The fatigue life analysis used here is based on Miner's rule. In this linear damage rule, the accumulated damage from each stress cycle requires that the number of cycles to failure be described as a function of cycle mean and amplitude. For many materials this function, typically called an S-n diagram, may be posed mathematically using Goodman or Gerber models or graphically using a Goodman diagram. For this analysis, two Goodman diagrams were used. The first is included in the FAtigue of Composites for wind Turbines (FACT) database [DeSmet and Bach, 1994]. Here we use the Goodman diagram for “GP 0/45 laminates that is based on the mean value fits of the fatigue diagrams.” The second is the cubic spline fit for another 0/45 laminate developed by Kensche (1992). Both material descriptions are based on the strains-to-failure.

Operational Loads: We have four sets of the operational loads available for this analysis: the two load spectra obtained by rainflow counting the data taken from the two Micon turbines, the standard WISPER load spectrum obtained from northern European turbines and the San Gorgonio load spectrum obtained by applying the WISPER protocol to the Micon data.

The load spectra on the two Micon turbines were obtained by rainflow counting the 397 10-minute records obtained at the San Gorgonio test site. Typical cycle count distributions from these data, for wind speed Classes 5 and 7, are shown in Figure 3. The Class 5 distribution is based on almost 80,000 seconds of data (134 10-minute records) and Class 7 is based upon approximately 600 seconds (only one 10-minute record is available in this wind speed category). These data are shown here for reference. To insure a consistent analysis of these turbines based on the WISPER protocol, the rotational rate of both turbines

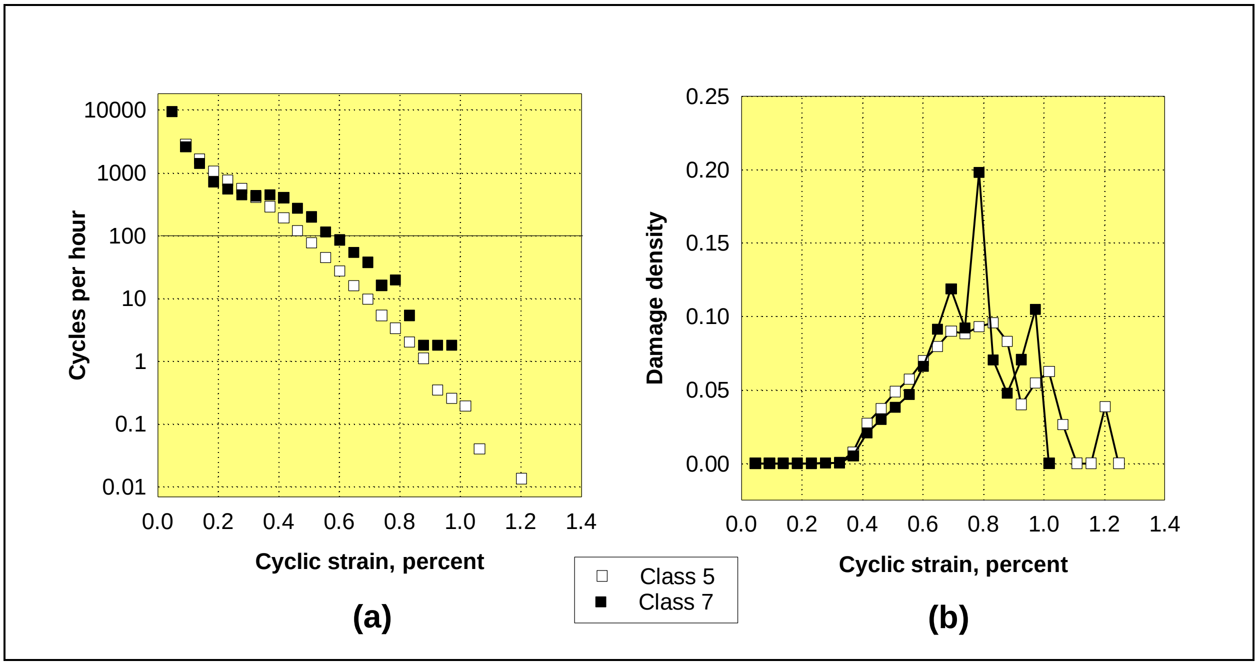

FIGURE 3. (a) STRAIN and (b) DAMAGE SPECTRA FOR THE NREL-BLADED MICON

was adjusted to 45 rpm. The NREL-bladed turbine was adjusted from 45.4 rpm and the AeroStar-bladed turbine from 41.9 rpm. Here, we refer to these data as the NREL and the AeroStar load spectra.

The other two load spectra are the normalized WISPER and San Gorgonio load spectra, both obtained using the WISPER protocol. The former being representative of a European site and the latter of a U.S. wind farm site. For this analysis, both spectra were "de-normalized" by linearly scaling the loads by the largest value seen in the NREL load spectrum.

Damage Calculations: To convert the blade loads to material strains, we have *assumed* that these blades are based on a maximum strain design of 0.4 percent (commonly used in the wind industry by blade designers); namely, that the nominal strain levels are not allowed to exceed this value. We have *assumed* that this value occurs at the average value of the Class 7 load spectrum plus 4 standard deviations. Further, we have *assumed* that the nominal strain is subjected to a stress concentration factor of 2. The implication of these assumptions is to place the maximum load cycle observed in all the spectra at approximately the 500 cycles-to-failure level and the body of the distributions in the 10^7 to 10^8 cycles-to-failure range. Based on these assumptions, the predicted service lifetime of the NREL-bladed turbine in the San Gorgonio operational environment is 104 2-month loading blocks. As these assumptions have significant implications on the predicted fatigue lifetime and they were not used in the actual design of these blades, we will only report results of our parameter study as a ratio of the predicted lifetime to this initial estimate. This ratio provides the comparison we need while minimizing the effects of these assumptions.

The results of a typical damage calculation are shown in Figure 3. In this figure, Classes 5 and 7 cycle counts for the flap loads on the NREL-bladed Micon turbine are contrasted with the Miner's rule damage predictions using the FACT database [DeSmet and Bach, 1994]. The damage plot illustrates that most of the damage occurs from the relatively infrequent, high-magnitude load cycles that form the "high stress tail" of the cycle count distribution.

TABLE: PREDICTED NORMALIZED LIFETIMES USING THE FACT GOODMAN DIAGRAM

Load Spectra			*Wind Speed Distribution*	
Reference Name	**Number of Turbines**	**Cycle Analysis**	**WISPER (German Coast)**	**San Gorgonio (U.S. Wind Farm)**
NREL	1	Rainflow Counted	2.43	1.00
AeroStar	1		3.02	1.03
WISPER	9	WISPER Protocol	6.04	1.44
San Gorgonio	2		0.91	0.74

This observation has been made previously by several authors, e.g., see the general discussions by Sutherland and Butterfield (1994). Winterstein and Lange (1995) have shown that the damage contained in the high stress tail is a function of the material properties. For composite materials (which have high fatigue exponents), they conclude that most of the damage is contained in the tail of the distribution. Kelley (1994) has previously analyzed the spectral content of the data used here. Based on that analysis, Kelley has postulated that the bulk of damage is contained in the low-cycle, high-amplitude or LCHA load range, i.e., the high stress tail of the distribution. For this data set, he observes that the damage becomes important for those load cycles with return rates equal to or less than 100 cycle/hr. The calculations cited here verify his postulate. And, they demonstrate that the majority of the blade damage is associated with the load cycles that have return rates of approximately 1 cycle/hr.

RESULTS

The table summarizes the normalized lifetime predictions using the four loading spectra and the two wind speed distributions. In general, these results indicated that the WISPER load spectrum from northern European sites significantly underestimates the WISPER protocol load spectrum from a U.S. wind farm site, i.e., the WISPER protocol overestimates the service lifetime at this U.S. site.

Spectral Content

As can be seen by comparing the predicted lifetimes in the first two rows of the table by columns, the rainflow-counted time series data for the NREL and the AeroStar bladed turbines are in very good agreement with one another. They are not in very good agreement with the WISPER and the San Gorgonio load spectra obtained using the WISPER protocol (the last two rows of the table). As discussed above and described by Ten Have (1992), the WISPER protocol selects and averages the load cycles that form its load spectrum. As reflected in these calculations, the resulting load spectrum does not duplicate the spectrum used to create it. Our calculations demonstrate that the WISPER load spectrum for U.S. wind farms (labeled the San Gorgonio load spectrum in the Table) is more damaging than the WISPER load spectrum for the European environment (labeled the WISPER load spectrum). However, this limited set of data does not permit us to determine if the WISPER protocol always produces a conservative bias in its load spectrum.

Also, one should remember that the WISPER spectra was never intended to duplicate the actual load spectrum on a turbine blade. This spectrum is a fatigue test *loading standard* based on variable amplitude load cycles for flap bending of HAWT blades on multiple turbines.

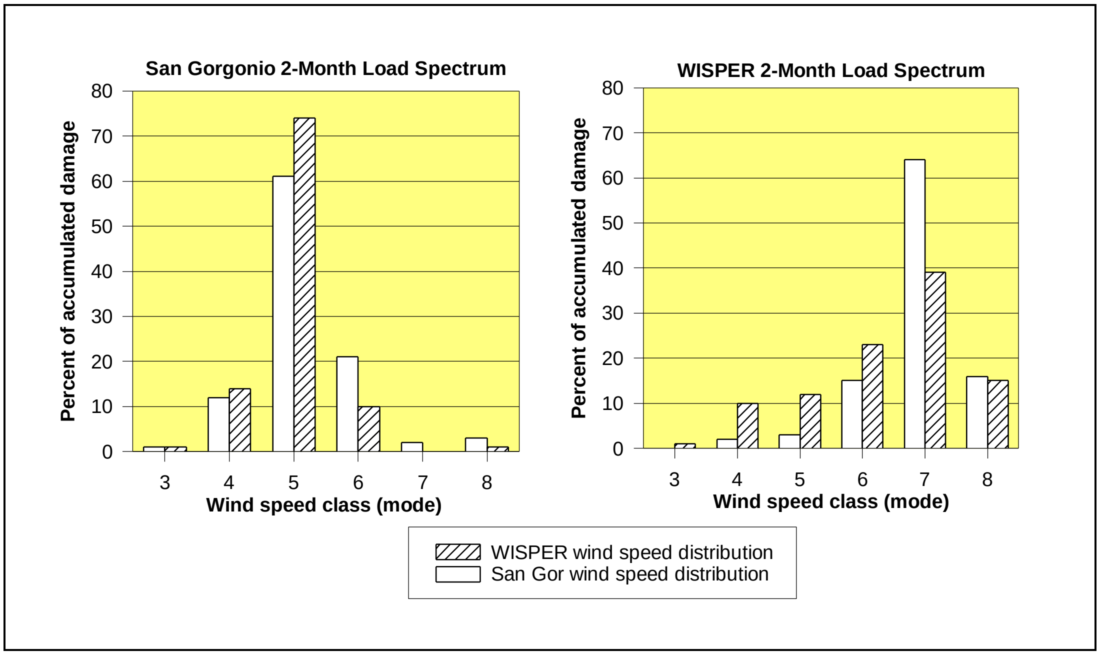

FIGURE 4. COMPARISON OF ACCUMULATED DAMAGE BY LOAD SPECTRUM AND WIND SPEED DISTRIBUTION

Wind Speed Distribution

As can be seen in the table by comparing the predicted lifetimes in each row with one another, the damage associated with the San Gorgonio wind speed distribution is significantly more severe than that associated with the WISPER wind speed distribution (i.e., the predicted service lifetime for the WISPER wind speed distribution is larger than the predicted lifetime for the San Gorgonio distribution). As noted above and shown in Figure 1, the former has many more hours in the energetic Wind Speed Classes 6, 7, and 8. The increased operation in these load states lowers the predicted lifetimes of the turbine in all cases examined here, albeit with increased production of electrical power.

The contributions to the overall damage, by each wind speed class, for the WISPER and San Gorgonio load spectra are summarized in Figure 4. This figure illustrates that most of the damage occurs in Wind Class 5 (11 to 13 m/s) for the San Gorgonio load spectrum, whether the WISPER or San Gorgonio wind distribution is used. For the WISPER load spectrum, the peak damage occurs in Wind Class 7 (15-17 m/s) using either the WISPER or the San Gorgonio wind distribution. The two graphs in this Figure 4 present a fundamental difference in the two service environments.

Cyclic Loads

As can be seen by comparing the predicted lifetimes in the last two rows of the table by columns, the San Gorgonio load spectrum is more severe than the WISPER load spectrum (i.e., the predicted service lifetime for the WISPER load spectra is always larger than the predicted lifetime for the San Gorgonio loads). A detailed examination of the cyclic loads contained in the high wind-speed classes helps to define the differences. For the 2-month operation loads in either wind distribution, the San Gorgonio Class 5 load spectrum contains approximately 4 times as many load cycles as the WISPER spectrum. The larger

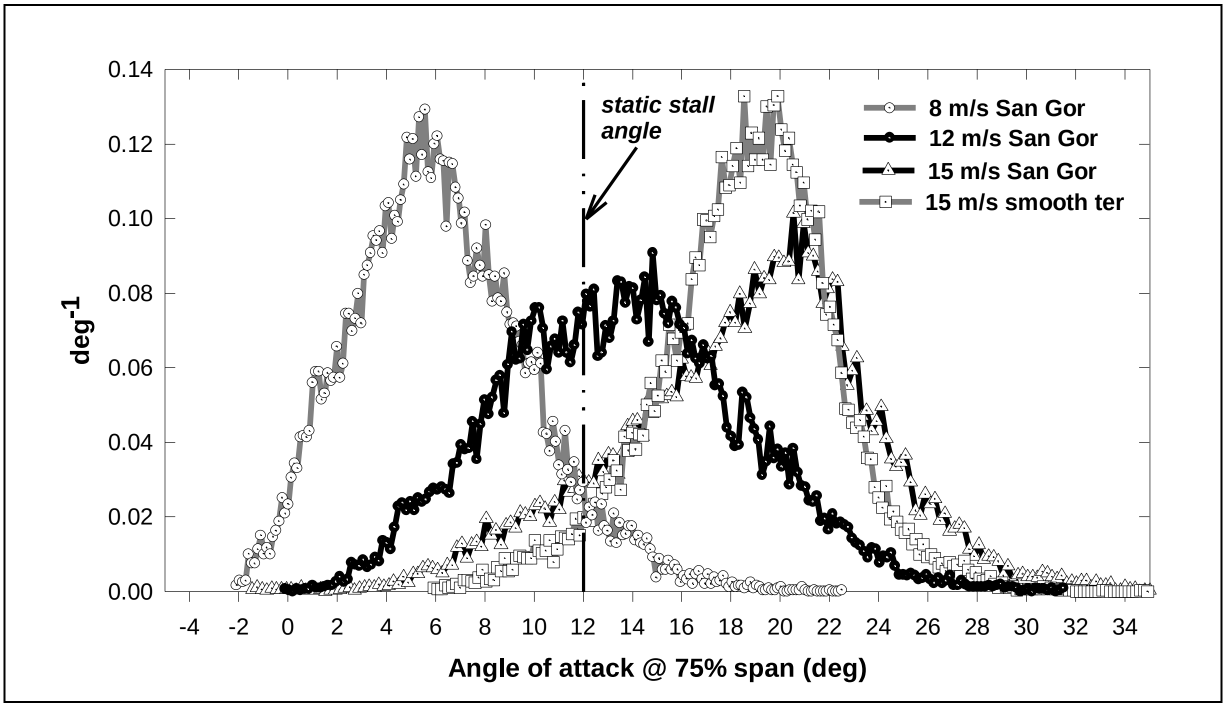

FIGURE 5. PDF OF ANGLE OF ATTACK AT 75% SPAN FOR SIMULATED INFLOWS

number of cycles in the San Gorgonio spectrum produces approximately 40 times more damage than the WISPER spectrum. The same is not true for Mode 7, where the WISPER load spectrum contains approximately 100 times as many cycles as the San Gorgonio. The damage produced by the WISPER Class 7 spectrum is approximately 10 times more damaging than the San Gorgonio Class 7 spectrum. For Class 6, the cycles contained in the San Gorgonio spectrum are approximately three times more damaging than the Class 6 cycles in the WISPER spectrum.

Material Properties

The results presented in the table are based on the FACT database [DeSmet and Bach, 1994]. Predictions were also made using the database developed by Kensche (1992). The Kensche formulation predicts a service lifetime for the NREL-bladed turbine in the San Gorgonio operational environment that is approximately four times larger than that predicted by the FACT database. As this trend is consistent throughout this parameter study, the detailed results are not presented here.

INTERPRETATION

As discussed above and shown graphically in Figure 2, the San Gorgonio load spectrum contains many more cycles than the WISPER spectrum and they are more damaging. We believe that the higher loads may be attributed to the increased turbulence in the inflow created by the complex terrain in San Gorgonio pass and by the wakes of the up-wind turbines.

To tie our current observations to the wind farm inflow, we will consider the recent work of Laino and Kelley (1995). They have performed a loads sensitivity analysis using a YawDyn model of the Micon 65. Drawing upon their work, we have plotted the probability density function (PDF) of the angle of attack at other mean wind speeds and inflow conditions. The PDF’s of the simulated angle of attack for 8, 12, and

15 m/s wind farm conditions and 15 m/s over smooth terrain are plotted in Figure 5. The data in this figure illustrate that the San Gorgonio inflow produces a broader variation in the angle of attack than that produced by the European (smooth terrain) inflow. Of particular note is the very broad distribution corresponding to the rated wind speed of 12 m/s (Wind Class 5) that straddles the static stall angle of 12 degrees. The larger range in the angle of attack shown in the San Gorgonio inflow calculations translates into the higher blade loads observed in the data.

CONCLUSIONS

In general, these results indicate that the WISPER load spectrum from northern European sites significantly underestimates the WISPER protocol load spectrum from a U.S. wind farm site; i.e., the WISPER load spectrum significantly underestimates the number and magnitude of the loads observed at a U.S. wind farm site. The damage is occurring because the U.S. sites have wind speed distributions that contain more time in the higher wind speeds and because the inflow in the wind farm environment produces more cycles and higher loads in the turbine. Thus, there are fundamental differences in the two service environments.

ACKNOWLEDGMENTS

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