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A DISCUSSION OF THE RESULTS OF THE RAINFLOW COUNTING OF A WIDE RANGE OF DYNAMICS ASSOCIATED WITH THE SIMULTANEOUS OPERATION OF ADJACENT WIND TURBINES

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ABSTRACT

The objective of this study was to provide a fatigue load comparison between two identical wind turbines employing different rotor designs. One turbine was fitted with a rotor consisting of a set of NREL (SERI) thin-airfoil blades while the other rotor included the original-equipment AeroStar blades. The data discussed are based on sample load populations derived from the rainflow cycle counting of 405, 10-minute records specifically collected over a wide range of inflow turbulence conditions. The results have shown that the statistical structure of the alternating load cycles on both turbines can be described as a mixture of three stochastic processes. We noted a high degree of load distribution similarity between the two turbines, with the differences attributable to either rotor weight or swept area.

INTRODUCTION

The expected lifetime of a wind turbine and its major subsystems is an important constituent in calculating the cost of energy (COE) by accounting for the expense of replacement equipment and major components [1]. COE calculations for a given turbine design therefore require estimates of the turbine durability. The rate of fatigue damage accumulation has been demonstrated to be strongly influenced by the characteristics of the turbulent inflow [2]. Because the bulk of wind energy development has taken place in multiple-turbine installations or wind parks, the fatigue damage associated with the higher turbulence levels seen within the parks [3] must be documented and accounted for in making lifetime estimates.

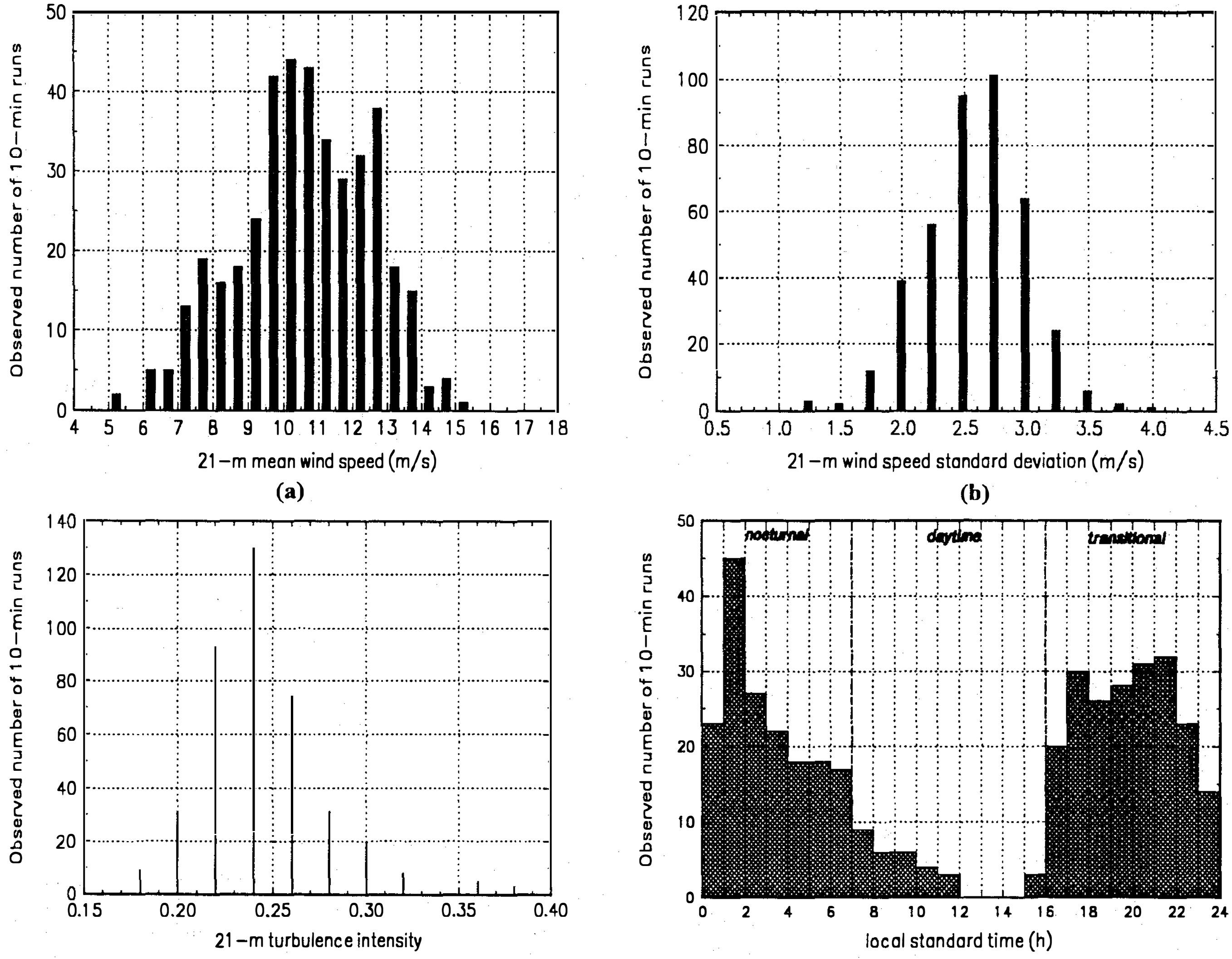
The side-by-side testing of rotors employing the NREL (SERI) thin-airfoil family and original equipment design in a wind park environment afforded us an opportunity to explore this key element of the technology. This test format allowed us to postulate that observed similarities in the response dynamics can be considered "quasi-universal" and the dissimilarities a consequence of the individual rotor designs. In this paper, we will compare cyclic load measurements based on the *total population* derived from 67.5 hours of simultaneous, on-line operation. We also make the *a priori* assumption that each turbine operated in a *statistically identical* turbulent environment over this period of record.

SOURCE OF DATA

Two adjacent Micon-65/13 horizontal-axis wind turbines provided the data for this paper. The Micons were made available to NREL through the cooperation of the SeaWest Energy Group. The turbines, spaced 37 m apart laterally, were located in Row 37 of the 41-row SeaWest San Gorgonio wind park. This particular location is near the center of a group of turbines and is characterized by low energy production and higher fatigue damage relative to other locations within the park. Both turbines were equivalently and extensively instrumented for a wide range of dynamic measurements. A 31-m meteorological tower was located 32 m upwind and midway between the two turbines. The details of the instrumentation are discussed in Tangler *etal.* [4].

The Micon 65/13 turbine is a dual-speed, upwind machine featuring a three-bladed, fixed-pitch, rigid hub and an active yaw drive. The nominal rotation rate for high-speed generator operation is 48 rpm (1.25 s/rev) while the low-speed mode is ~29 rpm (~2.1 s/rev). See Tangler *etal.* [4,5] for further details on the test setup. We fitted one of the test turbines with a rotor blades based on the NREL (SERI) thin-airfoil family consisting of S805A, S806A, and S807 cross-sections. This rotor weighs 1369 kg (3012 lb) and has a diameter of 17.0 m (55.8 ft). The other machine was fitted with a reconditioned, original-equipment AeroStar rotor whose blades are based on NACA 4415-24 airfoil shapes. It has a diameter of 16.0 m (52.5 ft) and weighs approximately 1635 kg (3597 lb). The NREL rotor therefore weighs about 25% less than the AeroStar but has a 14.2% greater projected area. It also contains 3% more blade projected surface area.

We collected the data during a three-week period in late July and early August of 1990. A total of 405, 10-minute records (67.5 hours) are available for detailed analysis. We specifically designed the test procedure to ensure that the turbines operated in the wide range of inflow turbulence conditions experienced in San Gorgonio Pass. These included periods when unstable, near-neutral, and stable atmospheric boundary layer conditions were known to be prevalent. Totals of 67, 70, and 267 10-minute records were associated with each of these conditions respectively. Figures 1(a-c) are histograms summarizing the mean, standard deviation, and turbulence intensity of the horizontal wind speed at an elevation of 21 m (hub elevation of 23 m). Figure 1(d) summarizes the number of runs associated with the hour (local standard time) of the day and the boundary layer characteristic (i.e., *daytime*, *nocturn*al, or the *transition* between).



(a)

(b)

(c)

(d)

Figure 1. Histogram summaries at 21m: (a) mean wind speed, (b) wind speed standard deviation, (c) turbulence intensity, and (d) time of day for the 405 data records used in this study

We processed the original binary data records using a CRAY Model Y-MP8/864 computer operated by the National Center for Atmospheric Research (NCAR). We applied a total of six processing passes to the data set using a combination of NREL-developed codes and the GENPRO (**GEN**eral Dynamic Data **PRO**cessor) developed by NCAR and enhanced by NREL. Measurement parameters associated with the turbine rotating and non-rotating frames of reference were recorded and processed at data rates of 32/s. The three-components of the wind were derived from a sonic anemometer located at an elevation of 21 m. They were collected at a rate of 32/s but were processed at 16/s because of instrument's narrower response bandwidth of 5 Hz. The remainder of the meteorological measurements were also recorded initially at 32/s but processed at 8/s because of the slow response of the sensors.

RAINFLOW CYCLE COUNTING

The accumulation of fatigue damage of turbine subassemblies is a consequence of the complex loading derived from both deterministic and stochastic sources. We used the *rainflow counting* method, as described by Downing and Socie [6], to quantify the observed load time histories from various high-stress locations in the Micon turbines. The rainflow algorithm provides a method for counting cyclic loads that are described as closed stress/strain hysteresis loops. This process produces a cycle count matrix consisting of means and alternating stress levels from which fatigue damage accumulations can be calculated. This paper only discusses the alternating (p-p) load cycles. We present alternating cycle sample populations for the following turbine dynamics:

- Flapwise and edgewise root bending moments
- Low-speed shaft bending and torque
- Axial and inplane thrust components
- Yaw drive torque
- Horizontal and vertical wind components.

We rainflow counted the load history for each parameter and accumulated the alternating cycles into 17 evenly spaced bins plus one bin each for defined-range under and overflow. The 405 individual count spectra were summed into a single vector representing the entire available record. We normalized this sample population by the observed total number of rotor revolutions for each turbine (i.e., 188,022 for the NREL and 185,197 for the AeroStar). The normalization allowed us to make direct comparisons between the two machines because the AeroStar-equipped turbine spent more time in the low-speed range. The sample population distributions are therefore expressed in terms of the number of *alternating cycles per revolution*. We iteratively fitted a series of continuous statistical models to each of the normalized population distributions.

ALTERNATING (P-P) CYCLE DISTRIBUTION MODEL

We found that ***all*** of the turbine dynamics listed above, plus several others, could be described as a *linear mixture of distributions* consisting of the sum of a Gaussian and two lognormal shapes, or

$$N(x) = \alpha_{G_o} \exp\left[-1/2\left(\frac{x-\beta_G}{\eta_G}\right)^2\right] + \alpha_{LN_1} \exp\left[-1/2\left(\frac{\ln\left(\frac{x}{\beta_{LN_1}}\right)}{\eta_{LN_1}}\right)^2\right] + \alpha_{LN_2} \exp\left[-1/2\left(\frac{\ln\left(\frac{x}{\beta_{LN_2}}\right)}{\eta_{LN_2}}\right)^2\right] \qquad (1)$$

where N(x) represents the expected number of alternating cycles per rotor revolution of parameter x and the scale, location, and width for the Gaussian, mid-, and high-range lognormal distributions, respectively. The three-distribution mixture for the AeroStar rotor flapping moment is pictured in Figure 2 as an example. Table 1 lists the correlation coefficients for each of turbine dynamics using Equation (1).

Cyclic stresses in wind turbine components arise from the coupling of deterministic forces associated with the rotor rotation and stochastic fluctuations (turbulence) in the inflow. One would therefore expect cyclic variations in the wind to induce cyclic responses in the stresses measured on the wind turbine. We verified this hypothesis by rainflow counting the horizontal and vertical wind components. We found that the three-distribution mixture described by (1) fitted the wind component rainflow spectra with a high degree of correlation. Figure 3 plots the fitted distributions for each component. As a result, we believe the consistency of (1) applying to all of the turbine alternating stress distributions is a direct reflection of the statistical structure of the wind.

MODEL INTERPRETATION

Atmospheric turbulence is often thought of to be a near- or quasi-Gaussian process. Various investigators have shown that, while distributions of velocity in the atmospheric boundary layer can be considered Gaussian, small rates of change are not [7]. This is clearly demonstrated in Figure 3, where the larger gusts are ascribed to the lognormal processes. A Gaussian process arises from the *linear* summation of many small contributions. In contrast, a lognormal process results from the *product* or *nonlinear* combining of small contributions. Thus, the areas under the lognormal distributions of Figure 3 represent the degree to which the statistical structure of the turbulent inflow is non-Gaussian.

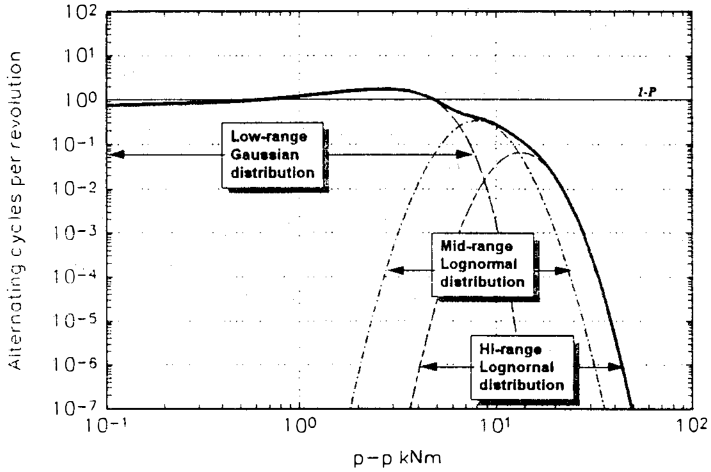


Figure 2. Sum of three-distribution mixture for the alternating flapwise moment measured on the AeroStar rotor

Dutton and Panofsky [7] have suggested that mixed processes such as those evidenced in Figure 3 are the result of a combination of several turbulent regimes. This could easily be the case within the internal flow of the San Gorgonio wind park. We have observed that the location is clearly affected by the surrounding complex terrain as well as gravity-induced (drainage) flows during the transition and nocturnal

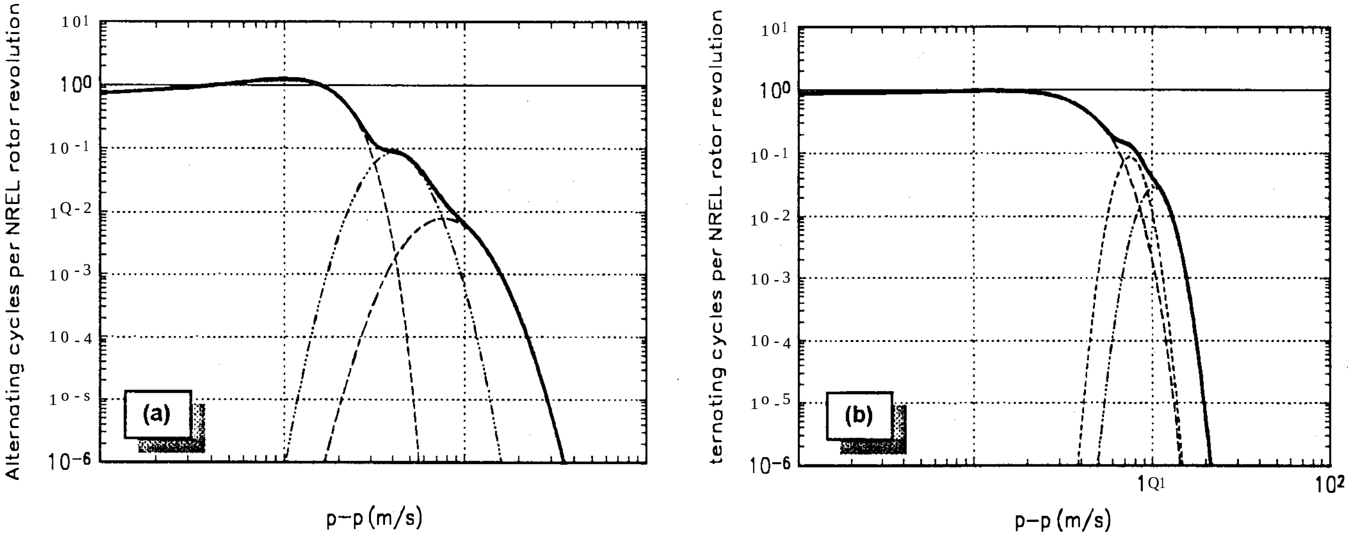


Figure 3. Observed population three-distribution mixtures for the 21m (a) horizontal and (b) vertical wind speeds

periods [3]. Turbines within the park are also exposed to turbulent wakes from upwind machines. Kelley [8] has identified a definite, small-scale contribution from the wakes in the turbulent spectra. This contribution, as would be expected, is particularly discrete during stable flow conditions.

OBSERVED TURBINE DYNAMIC STATISTICAL DISTRIBUTIONS

The observed mixed-process population distributions for the alternating loads of the turbine dynamic parameters listed in Table 1 are summarized in Figure 4. All of the curves of Figure 4, with minor differences, exhibit the same general shape characteristic when plotted on a log-log diagram. This suggests that the underlying statistical structure of the loading responses is essentially identical for both turbines. Where differences are noticeable, they can be explained either by inertial or aerodynamic scaling. For example, the greater edgewise bending and inplane thrust loads associated with the AeroStar rotor in Figures 4(b) and 4(f) are inertial in origin because of its greater mass. The slightly higher loads experienced by the NREL-equipped turbine in Figures 4(a), 4(d) and 4(e) are believed to be a consequence of the larger swept area and greater aerodynamic response.

Table 1. Mixed process distribution model correlations

Turbine Dynamic	Correlation Coefficients (r^2)	
	NREL	AeroStar
3-blade root flapwise bending	0.996	0.997
3-blade root edgewise bending	0.950	0.945
Low-speed shaft bending	0.997	0.996
Low-speed shaft torque	1.000	0.999
Axial thrust component	0.991	0.997
Inplane thrust component	0.992	0.929
Yaw drive torque	0.999	0.999
Horizontal wind speed	0.985	-
Vertical wind speed	0.994	-

One attribute of mixed process distribution described by (1) is that the peaks of the two lognormal distributions can be considered characteristic of the magnitude and occurrence frequency of the forcing and response. For example, Table 2 lists the value of the p-p amplitude and corresponding recurrence interval of the high-range lognormal distributions for each of the turbine parameters and wind field parameters listed in Table 1. Except where the midrange distribution dominates the large excursions, the expected recurrence intervals are of the same order of magnitude for both rotor configurations. Table 2 does indicate that large vertical wind gusts are more intense (~ ±5.1 ms^{-1}) and occur roughly three times more frequently than is characteristic with the horizontal gusts (~ ±3.8 ms^{-1}). The striking similarity between the mid- and high-range gust distributions of Figure 3(a,b) and the turbine dynamics of Figure 4 strongly suggest that the latter are the result of the former. However, this remains to be conclusively demonstrated.

Table 2. Characteristic High-Range Cyclic Amplitude (Peaks) and Corresponding Recurrence Intervals

Turbine Dynamic	NREL		AeroStar	
	p-p amplitude	time (s)	p-p amplitude	time (s)
3-blade root flapwise bending	20.4 kNm	223[a]	13.4 kNm	12.2
3-blade root edgewise bending	16.7 kNm	1.30	21.6 kNm	1.49
Low-speed shaft bending	18.1 kNm	30.3	17.7 kNm	28.1
Low-speed shaft torque	16.9 kNm	286	15.0 kNm	294
Axial thrust component	12.9 kN	46.8	9.37 kN	33.9
Inplane thrust component	10.5 kN	17.1	14.1 kN	110[a]
Yaw drive torque	1.99 kNm	54.8	2.06 kNm	38.1
Horizontal wind speed	7.65 m/s	101	-	-
Vertical wind speed	10.22 m/s	27.9	-	-

[a] midrange peak is dominant and, as a result, this recurrence time may not be appropriate.

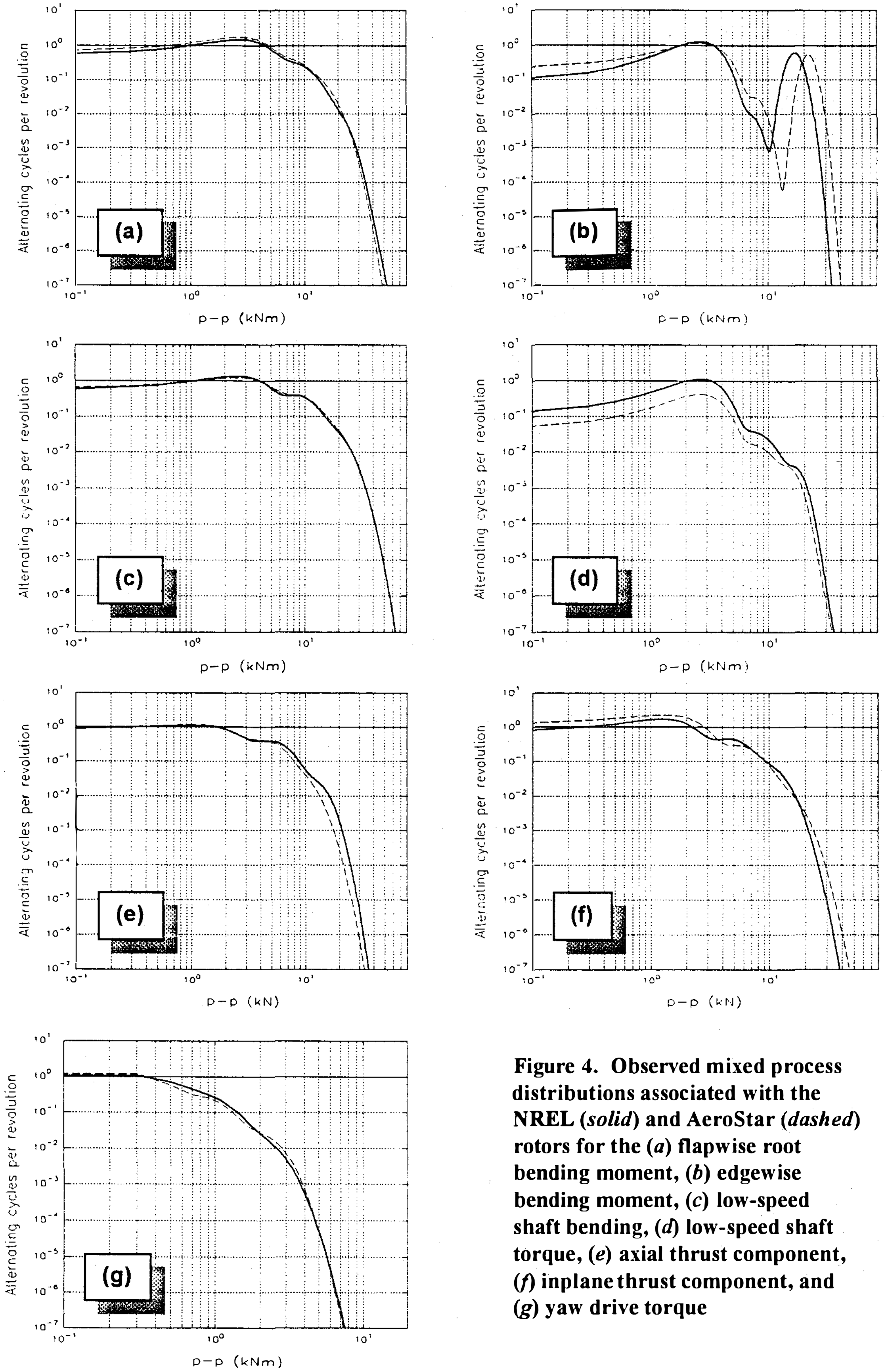


Figure 4. Observed mixed process distributions associated with the NREL (*solid*) and AeroStar (*dashed*) rotors for the (*a*) flapwise root bending moment, (*b*) edgewise bending moment, (*c*) low-speed shaft bending, (*d*) low-speed shaft torque, (*e*) axial thrust component, (*f*) inplane thrust component, and (*g*) yaw drive torque

CONCLUSIONS

The simultaneous, side-by-side operation of two identical wind turbines with substantially different blade designs over a wide range of turbulent inflow conditions has demonstrated the following:

- The statistical structure of the alternating or cyclical loads associated with high stress locations on both turbines can be described as a *mixture of three stochastic processes: a Gaussian plus two lognormal ones.*
- The inflow horizontal and vertical wind components exhibit a similar structure suggesting that their characteristics dominate the turbine dynamics.
- The observed deviations from the shape of the general model can be explained by either inertial or aerodynamic scaling considerations inherent in each of the two blade designs.

Future research needs to establish whether or not the three-process structure can be extended to other turbine configurations (i.e., teetering-rotor, horizontal-axis (HAWT) and vertical-axis (VAWT) designs. It seems reasonable to expect such an extension if the turbine component response is dominated by the statistical structure of the inflow, as is suspected. Again, such a hypothesis needs to be unequivocally demonstrated.

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