Using a New Characterization of Turbulent Wind for Accurate Correlation of Wind Turbine Response with Wind Speed

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September 1987

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SUMMARY

The turbulence encountered by a point on a rotating wind turbine blade has characteristics that in some important respects are different from those measured by a stationary anemometer. The conventional one-peaked continuous spectrum becomes, broadly, a two-peaked spectrum that in addition contains a set of narrow-band spikes of turbulence energy, one centered on the frequency of rotor rotation and the others centered on multiples of that frequency.

The rotational sampling effect on wind spectra is quantified using measurements of wind velocity by anemometers on stationary crosswind circular arrays. Characteristics of fluctuating wind are compared to measured fluctuations of bending moments of the rotor blades and power output fluctuations of a horizontal-axis wind turbine at the same site.

The wind characteristics and the correlations between wind fluctuations and wind turbine fluctuations provide a basis for improving turbine design, siting, and control.

CONTENTS

SUMMARY	iii
1. INTRODUCTION	1
2. MEASUREMENTS OF THE WIND AT A CROSSWIND PLANE	3
3. ROTATIONALLY SAMPLED AXIAL WIND SPEED TIME SERIES	7
4. A COMPARISON OF TIME SERIES OF MOD-OA WIND TURBINE RESPONSE AND ROTATIONALLY SAMPLED VPA WIND	9
5. POWER SPECTRAL DENSITY OF THE ROTATIONALLY MEASURED WIND SPEED AT THE VPA	11
6. CORRELATION OF ROTATIONALLY SAMPLED WIND SPEED WITH ROTOR FLAPWISE BENDING MOMENT	17
7. A HIERARCHY OF APPROXIMATIONS TO THE WIND SPEED ROTATIONALLY SAMPLED AROUND THE VERTICAL PLANE ARRAY	23
8. CONCLUDING REMARKS	27
9. REFERENCES	31
APPENDIX A - AN AERODYNAMIC DERIVATION OF AN APPROXIMATE RELATION BETWEEN A CHANGE IN THE FLAPWISE FORCE ON A ROTOR BLADE AND AN INCREMENT OF ROTATIONALLY SAMPLED AXIAL WIND SPEED	A.1
APPENDIX B - A PRELIMINARY ANALYSIS OF TURBINE BLADE RESPONSE SPECTRUM CUTOFF FREQUENCIES IN RELATION TO THE SIZE OF TURBULENCE EDDIES THAT FORCE ROOT BENDING	B.1

FIGURES

1a	A Photograph of the Vertical Plane Array of Anemometers and the MOD-OA1 Wind Turbine at Clayton, New Mexico	4
1b	Plan View of Clayton Site	5
2	A Set of Time Series of Axial Wind Speeds Measured at Each Anemometer on the Vertical Plane Array for the Same 4.27-min Period of Time	6
3	A Comparison of Rotationally Sampled VPA Axial Wind Speed With Hub-Height and Disk-Average Axial Speeds for the Same 9-s Time Interval	8
4	Comparisons of Single-Blade Flapwise Root Bending Moment and Generator Output Power with Rotationally Sampled Axial Wind Speed for a 6-Revolution Period of Time	10
5	Examples of Power Spectral Density Function of Rotationally Sampled Axial Wind Speed at the Vertical Plane Array for Stable, Neutral, and Unstable Layering of the Atmosphere	12
6	Vertical Profiles of Mean Properties of the Wind for the Stable, Near-Neutral, and Unstable Cases	13
7	Power Spectral Density Functions for the MOD-OA1 Wind Turbine Response to the Wind for Stable, Neutral, and Unstable Atmospheric Layering	18
8	Comparison of the Spectral Density Function of the Two-Blade Rotationally Sampled Wind Speed that Corresponds to the Power Into an Idealized Two-Bladed Turbine Rotor	19
9	Frequency Response Functions Between Rotationally Sampled Axial Wind Speed and Turbine Response	21
10	A Comparison of Spectra of a Hierarchy of Approximation to the Full-Disk Rotationally Sampled Axial Wind Speed	24
A.1	A Cross Section of an Airfoil of a Rotor Blade and the Aerodynamic Forces of Lift and Drag and the Flapwise Component of the Force Due to Steady-State Unstalled Airfoil Flow	A.2
B.1	Frequency Response Functions Between Wind Speed and Turbine Fluctuations	B.2

1. INTRODUCTION

Wind turbines that have been field tested often have been found to be inadequately designed to withstand the effects of wind fluctuation. For example, turbine fatigue caused by wind fluctuations has been found to be greater than expected. Further, attempts to correlate the actual fluctuating response of a wind turbine to the measured wind velocity have been unsuccessful, because the characterizations of the wind have not included the high-frequency turbulence encountered by a wind turbine in the actual environment. Here we report the first successful correlation of winds and turbine response that includes the high-frequency region of the rotor response, where fatigue effects are critical.

Two misconceptions about turbulent wind are commonly expressed in the wind turbine industry. One misconception is that the rotor averages fluctuations in wind velocity over the area of the disk of the rotor. The important fluctuations of the wind that remain after disk averaging are said to be due to "engulfing gusts." Thus, aerodynamic force fluctuations along the rotor blades are assumed to be heavily filtered by the blades. A typical cutoff frequency that represents this filtering effect is used in analogy to the eddy-shedding frequency from a crosswind disk in an Eulerian (or nonmoving) frame of reference. The rule of thumb is expressed by a formula relating the disk diameter, D , and the mean wind speed upwind of the disk, U , to the cutoff or half-power frequency of wind fluctuations, which are sufficiently coherent to affect a rotor, as follows:

$$n_c^1 = U/D \quad (\text{Eulerian, disk-averaged wind}) \quad . \quad (1)$$

This formula will be shown to give the wrong numerical values for the observed high-frequency cutoff, although it may correspond to an actual low-pass frequency filtering effect. Further, the physical reasoning from which Equation (1) is obtained does not come from rotor blade aerodynamics and mechanics.

A second misconception is that most of the high-frequency input from the wind to the rotating rotor is caused by nonlinearity in the mean wind shear

that could be measured from a single meteorological tower. This will be shown in Section 7 to be inaccurate for almost all wind conditions.

If the disk filter concept of rotor response to high-frequency forcing of a rotating rotor is replaced by the concept of a blade rotating rapidly across turbulence elements passing through the plane of rotation, the resulting concept of a rotationally sampled wind makes accurate wind velocity characterization possible. In this report, turbulence measurements of wind at a crosswind plane immediately upwind of a horizontal-axis 200-kW wind turbine in relation to the measured response of the turbine are analyzed. Measurements for three wind conditions are separately analyzed to provide examples of three distinct representative cases for the turbine site.

The rotationally sampled wind speed is characterized herein in terms of its power spectral density function. The methods and results of analysis of the wind and of correlation with wind turbine response are described in the next three sections. In Section 7, a set of simple empirical models of the wind are compared to the full rotationally sampled wind measured in a crosswind plane array of anemometers. The major issues and conclusions of this study are summarized in the last section.

2. MEASUREMENTS OF THE WIND AT A CROSSWIND PLANE

A vertical plane array of anemometers (VPA) was operated by the authors for about one year in conjunction with operation of a 200-kW wind turbine (the MOD-0A1) at Clayton, New Mexico^(a). The wind turbine was well instrumented for turbine response research. A photograph of the VPA and the MOD-0A1 turbine is shown in Figure 1a. The VPA contained a set of 12 three-dimensional propeller anemometers attached to towers at 30° intervals around a circle in a vertical plane that was orthogonal to the direction 205° from geographic north. The radius and center height of the circle were identical to those of the MOD-0A1 rotor, 19 m and 30 m, respectively. The horizontal axis of the VPA circle intersected the vertical axis of the wind turbine tower. Another anemometer was placed at the center of the circle (at hub height). An additional anemometer was mounted at the 60-m height on the center tower of the array, 11 m above the highest anemometer on the circular array, to improve the representation of the vertical shear of the wind.

The wind data were analyzed only for times when the mean wind direction was within $\pm 20^\circ$ of the 205° direction, that is, when the VPA was close to directly upwind of the wind turbine. The VPA and wind turbine locations are shown on a map of the site in Figure 1b. The VPA was in the best position to measure wind characteristics that were statistically, though not instantaneously, identical to free-stream values that would exist at the location of the turbine. These southwest winds blew across terrain that had a uniformly low roughness over an upwind fetch of greater than 400 m. The component of the wind that was parallel to the 205° line is called the axial wind speed.

The variation of the axial wind speed at each of the anemometers on the VPA is shown for a 4.27-min period in the array of graphs in Figure 2. The wind speed time series are for measurements from the nonmoving anemometer positions. The time-average value of the axial wind speed, U , at each location is printed inside the top boundary of each graph. If the mean wind shear were to be excluded from consideration in the wind and wind turbine correlation

(a) The MOD-0A1 was operated by the National Aeronautics and Space Administration (NASA) for the U.S. Department of Energy (DOE).

FIGURE 1a.

A Photograph of the Vertical Plane Array of Anemometers and the MOD-0A1 Wind Turbine at Clayton, New Mexico. Only the circular ring of anemometers was used for the reported results.

FIGURE 1b. Plan View of Clayton Site. Distance from turbine yaw axis to towers in both 205° and 25° wind directions is 76.2 m, or 2 rotor diameters.

analyses, it would only be necessary to subtract these local mean values from their corresponding instantaneous time series plotted in the graphs.

The single time series of the axial wind speed corresponding to the wind experienced by a point at the tip of the rotating turbine blade is derived from the twelve Eulerian time series for points around the ring such as plotted in Figure 2. The method of rotational sampling and the characteristics of the wind time series that results from it are described in the next section.

VPA Wind Speeds
Nov. 25, 1981

FIGURE 2. A Set of Time Series of Axial Wind Speeds Measured at Each Anemometer on the Vertical Plane Array for the Same 4.27-min Period of Time

3. ROTATIONALLY SAMPLED AXIAL WIND SPEED TIME SERIES

A rotating rotor of a wind turbine experiences wind fluctuation whose special character is determined by the fact that it passes cyclically around a set of locations on concentric circles in the disk of the rotor. The cyclic motion has two significant features: it traverses rapidly across fluctuating two-dimensional gradients of velocity due to turbulence, and it repeatedly passes through persistent gradients. This means that turbulence eddies, which when they pass by a stationary anemometer produce a low-frequency fluctuation in the wind speed measurements, will produce higher frequencies of fluctuation when experienced by a point on a wind turbine rotor having a speed ratio of greater than one. The cyclic motion also tends to organize the sufficiently persistent fluctuations of wind energy into spikes or bands centered upon the frequency of rotation of the rotor and multiples of that frequency.

One important implication of the shift to higher frequency of fluctuation in the rotating frame of reference relates to turbulence eddy sizes. For a given frequency in the rotating frame of reference, the size of the coherent structure or eddy causing it is much larger than previously assumed. Thus, wind fluctuations experienced at one radius apply in a coherent manner to a much larger radial segment than previously thought possible. The measurements made at the tip radius of the MOD-0A1 represent with reasonable approximation the wind that produces force on much of the outer part of the blade.

The rotational sampling of the VPA data was tailored to the MOD-0A1 rotor as follows. The cyclic rate of the sampling corresponded to the rotation frequency of the blade, $2/3$ Hz, and a period of 1.5 s. The wind speed data were recorded 4 times per second from all anemometers. The VPA data were sampled successively at each of the 12 anemometer locations around the circle using a time step of $1.5 \text{ s}/12$ so that the time series would contain accurate spectral energy in fluctuations out to 6 times the rotation frequency of the rotor. Since this involves time steps from one spatial location to the next that are smaller than 0.25 s, some interpolation of wind speed in space and time was required.

An example of the resulting time series of the rotationally sampled wind speed is compared in Figure 3 with the corresponding time series from a single anemometer, and with the average time series from all 12 anemometers, of the VPA. Plots of the rotationally sampled time series for the longer time interval shown in Figure 2 are included in the upper left graph for a point on the tip of a single blade, and in the upper right graph for the sum of the wind at corresponding points on the two blades. Conventional practice in turbine design is to consider either the wind at a single anemometer or the average wind throughout the disk in conjunction with the mean wind shear. The rotational sampling of the mean wind shear would result in a large sine wave of wind speed variation upon which the Eulerian turbulence wind signal in Figure 3c would be superposed. We show in Section 7 that, for most design purposes, this is not an adequate approximation to the full rotationally sampled wind speed, such as is displayed in Figure 3a.

FIGURE 3. A Comparison of Rotationally Sampled VPA Axial Wind Speed With Hub-Height and Disk-Average Axial Speeds for the Same 9-s Time Interval. The time scale is marked in number of nominal revolutions of the turbine rotor blade.

4. A COMPARISON OF TIME SERIES OF MOD-OA WIND TURBINE RESPONSE AND ROTATIONALLY SAMPLED VPA WIND

Since the method of correlating the wind turbine response with the wind deliberately does not include the use of a tested dynamical and aerodynamical model of wind turbine response, the turbine variable must be especially carefully chosen. The flapwise root bending moment of a single blade has been selected as the primary variable to be compared with the rotationally sampled axial wind speed at the tip radius. (Flapwise bending is that which is perpendicular to the chord and the radial axis of the blade. It is usually nearly perpendicular to the plane of rotation.) The aerodynamic derivation that leads to this choice is included in Appendix A. The flapwise aerodynamic force fluctuations are shown to be proportional to the magnitude of the axial wind speed fluctuations experienced at the radial location on the blade under consideration. A brief explanation is that the lift fluctuations on the rotor airfoil are approximately proportional solely to the angle of attack fluctuations, which in turn are mainly a result of the axial wind speed fluctuations.

The graph in Figure 4a of measured flapwise root bending moment as a function of time shows that the flapwise bending has characteristics similar to the corresponding rotationally sampled axial wind speed time series shown in Figure 4c. The generator produces output power fluctuations as shown in Figure 4b. The character of the power output time series is expected to reflect the inplane, mostly chordwise, aerodynamic forcing summed from both blades. The simple model of that aerodynamic forcing, composed of the sum of the axial wind speed measured at points 180° apart around the circle of the VPA, is plotted in the time series in Figure 4d. The power and the "two-blade" rotationally sampled axial wind speed have very similar time series.

To demonstrate how well the rotationally measured wind at the VPA correlates to turbine response, it is necessary to use a method of comparison that is more accurate and detailed than visual comparison of two time series. An average of an instantaneous correlation function of wind speed and a turbine response variable is not a suitable method in the present case, because the wind was measured at two rotor diameters upwind of the turbine. This is not

FIGURE 4. Comparisons of Single-Blade Flapwise Root Bending Moment and Generator Output Power with Rotationally Sampled Axial Wind Speed for a 6-Revolution Period of Time

appreciably improved by forming a lagged cross-correlation since turbulence elements are not "frozen" and are modified as they move from the location of the array to the location of the rotor.

Thus, the analysis must be restricted to correlation of a discriminating statistical function of the wind speed fluctuations with the same statistical function of the fluctuations of a turbine response variable. We might have chosen the time-domain probability density function of gust amplitude for testing the degree of correlation. Instead, we chose the power spectral density function (frequency domain) because it has broad usage in both atmospheric science and engineering research. The power spectra of rotationally sampled wind speed at the VPA are described in the next section.

5. POWER SPECTRAL DENSITY OF THE ROTATIONALLY MEASURED WIND SPEED AT THE VPA

The relation between the Eulerian reference spectrum and the rotationally sampled spectrum has been described in physical terms in other reports (Connell 1980, 1981, 1982). A mathematical model of the rotationally sampled wind spectrum was presented by Connell (1982) without benefit of a comparison with turbine response data. A comparison of empirically derived rotationally sampled wind with turbine response is taken as the next step beyond these reports. A larger set of examples and more detailed analyses are given by George and Connell (1983).

Power spectral density curves for three cases of rotationally sampled measured axial wind speed are shown in Figure 5a, b, and c. Each case represents different mean wind shear and turbulence conditions in the atmospheric boundary layer flow. These wind conditions are typically related to specific categories of temperature layering in the same layer of the atmosphere. For simplicity, we label the three cases "stable," "near-neutral," and "unstable." The atmospheric boundary conditions that characterize these three cases are tabulated in Table 1. The vertical profiles of mean wind speed, turbulence variance, and mean wind direction for the three cases are plotted in Figure 6.

The regular spikes of energy in the rotationally sampled wind speed spectra, with each center frequency equal to the frequency of blade rotation or a multiple of that frequency, are of particular importance for turbine design. Resonant modes of the rotor and of other components of the turbine lie within this range. [See, e.g., Sullivan (1983)]. The measured wind spectra indicate that in this high-frequency range more energy in the wind fluctuations exists than was previously expected, by factors of 2 to 10,000. Furthermore, the distribution of the wind fluctuation energy within the high-frequency region varies among the three cases shown.

The distinction between the effects of turbulence and of shear in the average wind speed can be demonstrated quantitatively by removing the mean wind speed value from each anemometer time series of the VPA before rotationally sampling the time series. The spectra in Figure 5d, e, and f exclude the

FIGURE 5. Examples of Power Spectral Density Function of Rotationally Sampled Axial Wind Speed at the Vertical Plane Array for Stable, Neutral, and Unstable Layering of the Atmosphere. The top row of graphs (a), (b), and (c) is for wind speeds that include the mean wind speed. In (d), (e), and (f) it is removed from each anemometer record before being rotationally sampled. Graphs (g), (h), and (i) show band-integrated spectral energy, or partial variances, for the same 3 cases.

FIGURE 6. Vertical Profiles of Mean Properties of the Wind for the Stable, Near-Neutral, and Unstable Cases. (a) Mean wind speed, (b) standard deviation of turbulence speed, and (c) mean wind direction

TABLE 1. Parametric Description of Wind Conditions for the Three Cases Analyzed for This Report

Name of Parameter Static Stability	Value of Parameter		
	Stable	Near Neutral	Unstable
Average shear of the mean wind between 11.4 m and 60.0 m above ground	0.070 s^{-1}	0.020 s^{-1}	0.015 s^{-1}
Standard deviation of the fluctuation of horizontal wind speed, σ	0.2 ms^{-1}	0.8 ms^{-1}	0.85 ms^{-1}
Intensity of horizontal turbulence, σ/U	0.04	0.10	0.09
Disk-average axial wind speed, U_{rot}	5.6 ms^{-1}	8.2 ms^{-1}	9.3 ms^{-1}
Date of observation	12/18/81	11/25/81	3/22/82
Local standard time of day	1622	1149	0944

effect of the mean wind shear. They correspond to the spectra that include the effect of the mean wind shear in Figure 5a, b, and c. The average wind shear appears to have a noticeable role in the spectral peak at $n = n_0$ and to a lesser degree at $2n_0$, but at no other frequency band. In the case of the stable atmosphere the effect of the mean wind shear is predominant at these two frequencies, but turbulence is important for the higher frequencies. The existence of strong spectral spikes does not depend upon the existence of a mean wind shear!

Because the rotational sampling of the mean wind shear is a linear process, removing the mean wind shear from the rotationally sampled turbulent wind is the exact equivalent of removing the azimuthally specific average wind. Thus, the azimuthal averaging procedure need not be employed in this report. Graphs that more simply quantify the relative importance of mean wind shear and turbulence in the high-frequency energy of the wind, for the same three cases, are shown in Figure 5g, h, and i. Each set of three bars represents the energy of wind fluctuation within a spectral band of frequency

associated with a harmonic of the rotor rotation frequency from $1 n_0$ through $5 n_0$. The energy in the frequency band below the frequencies of the spikes is represented by the left-hand set of three bars. Each of the three bars gives, respectively, the energy that exists if (1) the wind is averaged over the whole rotor disk and is not rotationally sampled, (2) the wind is rotationally sampled without removal of mean wind shear, and (3) the wind is rotationally sampled after the mean wind shear has been removed from the VPA data. The magnitude of each bar is the magnitude of the variance within a frequency band that is $\pm n_0$ wide, or the "partial variance" associated with a center frequency, n_i .

The partial variance of turbulence for disk-averaged wind in the non-rotating frame of reference is only of significance at the low-frequency band for all three wind conditions. The rotationally sampled wind shows major contributions of the mean wind shear only for the $1 n_0$ band and lesser effect (less than 6%) for the $2 n_0$ and $3 n_0$ bands. Higher frequencies show negligible contribution from the mean wind shear.

Because the mean wind speed and the turbulence make distinct contributions to rotationally sampled wind characteristics, the vertical profiles of mean wind speed and of the standard deviation of turbulence wind speed are useful in describing the wind conditions at a site. These two variables are plotted for the three cases being studied in Figure 6.

The spectra of wind speed presented for the near-neutral and unstable conditions do not differ greatly from each other. However, for simple terrain, it is known that unstable conditions can produce a greater variety of turbulent wind characteristics than can neutral conditions. Therefore, we anticipate that more radical differences between neutral and unstable cases of rotationally sampled wind spectra than presented in this report may be observed.

In the next section it is demonstrated that the rotationally sampled wind speed correlates strongly with turbine rotor bending and generator power output.

associated with a component of the rotor relative frequency from 1 through 5. The energy in the frequency band between the components of the rotor is represented by the left-hand set of three bars. Each of the three bars gives, respectively, the energy that exists in (1) the wind is averaged over the whole rotor disk and is not rotationally smoothed, (2) the wind is rotationally smoothed without removal of mean wind shear, and (3) the wind is rotationally smoothed after the mean wind shear has been removed from the VPA data. The magnitude of each bar is the magnitude of the variance within a frequency band that is the width of the partial variance associated with a center frequency, ω .

The partial variance of a variance for disk-averaged wind in the non-rotating frame of reference is only of significance at the low-frequency band for all three wind conditions. The rotationally smoothed wind shows a contribution of the mean wind shear only for the 1 Hz band and lesser effect (less than 5%) for the 2 Hz and 4 Hz bands. Higher frequencies show negligible contribution from the mean wind shear.

Because the mean wind speed and the turbulence make distinct contributions to rotationally smoothed wind characteristics, the vertical profiles of mean wind speed and of the standard deviation of turbulence wind speed are useful in describing the wind conditions at a site. These two variables are plotted for the three cases being studied in Figure 2.

The spectra of wind speed presented for the best-neutral and unstable conditions are not shown in this report. However, for stable conditions it is known that unstable conditions can produce a greater variety of turbulent wind characteristics than can neutral conditions. The rotor wake is a source of rotation that may reduce differences between neutral and stable cases of rotationally smoothed wind spectra than presented in this report may be observed.

In the next section it is demonstrated that the rotationally smoothed wind speed correlates strongly with turbine rotor bearing and generator power output.

6. CORRELATION OF ROTATIONALLY SAMPLED WIND SPEED WITH ROTOR FLAPWISE BENDING MOMENT

Changes in characteristics of atmospheric flow and of the tip speed ratio of the rotation cause changes in the spectral character of the rotationally sampled wind fluctuations at frequencies greater than about half the frequency of rotation of the rotor (Connell 1982). The spectrum of the blade bending fluctuations will change correspondingly if the rotor is responsive at those frequencies. The power spectral density curves for the flapwise root bending moment of one blade of the MOD-0A1 turbine are plotted in Figure 7a, b, and c for the stable, near-neutral, and unstable wind cases, respectively. A very great similarity between these curves and the corresponding rotationally sampled wind speed spectra in Figure 5a, b, and c is evident. The wind and the blade bending spectra are very dissimilar to the spectra of wind speed measured in the nonrotating frame of reference.

The spectra of the generator power output for the same three wind cases are included in Figure 7d, e, and f as further indication of the relevance of the rotationally sampled wind. Although the generator response to the wind will include drive train resonances, damping, and other factors that complicate interpretation, the strong response at even multiples of the rotor rotation rate, expected only on the basis of rotational sampling by two blades, is shown. This phenomenon is more clearly seen in Figure 8 which, unlike all the other spectral plots in this report, uses a linear frequency scale and a frequency-weighted spectral density scale to enhance the display of features of interest. Small amounts of generator energy at the odd multiples (Figure 8b), not found in the two-blade rotationally sampled wind spectrum (Figure 8a), may be caused by asymmetries in the blades as well by the tower wake and the wind gradients across the rotor disk at each instant. The generator response will not be discussed further in this report.

The correlation between wind and blade bending response is made quantitative at each spectral frequency by forming a response function. The response function is the ratio of the nondimensional spectral density functions of wind speed and blade bending moment shown in Equation (2).

FIGURE 7. Power Spectral Density Functions for the MOD-OA1 Wind Turbine Response to the Wind for Stable, Neutral, and Unstable Atmospheric Layering. Spectra for the flapwise root bending moment are in graphs (a), (b), and (c). The corresponding spectra for generator output power are in graphs (d), (e), and (f).

FIGURE 8. Comparison of the Spectral Density Function of the Two-Blade Rotationally Sampled Wind Speed that Corresponds to the Power Into an Idealized Two-Bladed Turbine Rotor. The wind speed spectrum and turbine generator output power spectrum are each plotted on a linear scale. The spectra are weighted by the frequency of fluctuation, n .

$$H^2(n) = k S'_b(n)/S'_{rot}(n) \quad (2)$$

where $H^2(n)$ is the response function, $S'_b(n)$ is the nondimensional spectral density function of the blade bending moment, and $S'_{rot}(n)$ is the nondimensional spectral density function of the rotationally sampled wind speed, and k is a dimensionless factor that adjusts the function so that it has a value of 1 at low frequency. The two nondimensional spectra are formed by dividing the spectral density functions of the blade root bending moment or the wind speed by the variance of the same variable calculated for the low-frequency region between 0 Hz and the frequency of half the rotation rate of the rotor. This form of response function, as opposed to one derived by cross-correlation of the instantaneous wind speed and blade bending moment, is necessary because the wind measurements were not made directly at the rotor blade. Turbulence does not convect, as though it were frozen, from the site of the VPA to the location of the rotor. The cross-spectrum method eliminates effects of random noise. The accuracy of the method used in this report, calculation of a ratio of auto-spectra, depends upon measurements that have sufficiently low noise levels. The response functions calculated are believed to be accurate in the essential details.

The nondimensionalized response function will have a value of unity except near frequencies of resonance or very strong damping or when the wind force fluctuations are not sufficiently coherent along the rotor blade. For this relation to be seen the wind must be properly characterized and must be associated with quasi-steady, unstalled aerodynamics. At damped resonance frequencies the response function will have a value greater than one. At the non-resonance bending and noncoherent turbulence frequencies, it will have a value less than one. The measured response functions, $H(n)$, of flapwise root bending moment for the two wind cases are plotted as solid lines in Figure 9. The detailed shape of the response functions is somewhat dependent upon the amount of filtering of the time series from which the spectra are computed. The computational filter used was a 5-point nonweighted running mean, with a 0.25-s interval between each point. A preliminary analysis of three cases of wind turbine response, leading to some interesting implications about the

FIGURE 9. Frequency Response Functions Between Rotationally Sampled Axial Wind Speed and Turbine Response. Flapwise root bending moment response is given in graphs (a) and (b) for stable and unstable atmospheric conditions, respectively. The left dash-dot vertical line is at $n = n_0$ and the next one is at $n = 2n_0$. The dashed vertical lines are at the flapwise bending resonances at $n = 1.5$ Hz and 4.3 Hz.

importance of turbulence length scales, is presented in Appendix B. One tentative conclusion is that turbulence length scales less than D/π , where D is the rotor diameter, do not cause flapwise root bending of the blade below frequencies of at least $n = n_0$.

The response curve drawn using a dash-dot line on the plots in Figure 9 represents a response function expected on the basis of test bed measurements of the MOD-0A fiberglass blade reported by Sullivan (1983). The first two natural resonance frequencies from Sullivan's report, 1.5 Hz and 4.3 Hz, were used in the two-pole model of Equation (3), where the resonance frequencies are designated by n_1 and n_2 .

$$H^2(n) = \frac{1}{\left[\left(1 - \frac{n^2}{n_1^2} \right)^2 + \left(2\zeta_1 \frac{n}{n_1} \right)^2 \right]} \times \frac{1}{\left[\left(1 - \frac{n^2}{n_2^2} \right)^2 + \left(2\zeta_2 \frac{n}{n_2} \right)^2 \right]} \quad (3)$$

The corresponding damping factors are designated by ζ_1 and ζ_2 . The values of these damping factors were prescribed by Connell and George (1983) to obtain the best fit of the resulting linear model response function to the measured

response functions. The resonance frequencies are indicated by the right-hand two vertical dashed lines in the plots of Figure 9. The damped resonance peak at $n_1 = 1.5$ Hz slopes on its high-frequency side according to the inverse of the second power of n . The measured response function appears to be broadly consistent with this model of the slope. Other nonlinearities and nonstationarity of the signal during the period of measurement may be expected to cause the measured response function to deviate from the model. Among these will be the blade twist and the rotor coning. A turbulence aspect is discussed in Appendix B. The tower wake that interacts with the blades is a complicated function of wind conditions; it is not accounted for in the rotationally sampled wind speed spectrum used in the calculation of the observed response function. Thus, the wake effect will appear as part of the response function of the blade. The two left-hand vertical dash-dot lines indicate the frequency of rotation of the rotor and twice that frequency.

The resonance frequencies are at 2.2 and 6.4 times the rotation frequency of the rotor. The response functions calculated using VPA data and corresponding MOD-OA1 blade data indicate broad resonances at the two frequencies measured by Sullivan. However, the sharp peaks in the spectra of bending fluctuations nearest the resonance frequencies actually occurred at frequencies that were multiples of the blade rotation rate as shown by the bending spectra in Figure 7. These are also the frequencies of the peaks of rotationally sampled turbulence energy. Thus, the blade bending fluctuation peaks are explained by the rotationally sampled wind that forces the bending and by damped resonances. It does not matter whether the blade experiences the same wind forces due to rotational sampling of mean wind shear or of turbulence. Effectively instantaneous gradients of wind speed are in either case what the blade experiences, because it rotates.

A strong correlation between rotationally sampled wind speed and the flapwise root bending moment, as contrasted with the poor correlation with the wind as measured in the nonrotating frame of reference, has been demonstrated in this section. The right conceptual framework (rotational sampling) for description of wind experienced by wind turbines has been found. Several approximations to the rotationally sampled wind speed, which have been reported in other papers, are described and compared in the next section.

7. A HIERARCHY OF APPROXIMATIONS TO THE WIND SPEED ROTATIONALLY SAMPLED AROUND THE VERTICAL PLANE ARRAY

In this section the importance of full-circle rotational sampling for obtaining an accurate description of the wind at a turning rotor blade is demonstrated. This is achieved by comparing the spectrum of the rotationally sampled VPA wind with the spectra of a set of successively simpler approximations to it, all derived from the same wind data set. In the simpler approximations, data from fewer anemometers or data more averaged over longer periods of time or over more anemometer locations are used. The comparisons provide a basis for decisions about the level of approximation that is acceptable in a specific design problem.

The power spectral density function of wind speed measured by a single anemometer at the hub location on the VPA is plotted in Figure 10a. Spectrum (a) represents wind fluctuation observed at a single nonmoving (Eulerian) point. Its application to a complete rotor implies that a single wind speed value exists for all points of the disk at each instant. This is one form of the engulfing gust. Another form of the fluctuating engulfing gust is represented by the spectrum of the disk-average Eulerian wind speed shown in Figure 10b.* The single-point Eulerian wind speed spectrum shown in (a) is repeated as the dashed curve in (b) to indicate how much of the energy of wind fluctuation is removed when the disk-average engulfing gust is used. This is equivalent to the assumption that the rotor smooths or filters out much of the higher frequency fluctuations in the wind. The fact that the turbine blades are rotating makes no difference in the fluctuations that the blade experiences if the engulfing gusts are taken to represent the wind.

Rotational sampling around a circle across a wind field composed of only a mean wind speed shear in the vertical direction produces a wind speed fluctuation at the blade whose spectrum is of the kind shown in Figure 10c. Notice the high-frequency spikes. The wind shear is that derived from the winds at the center tower of the VPA. The fluctuations are completely cyclic and, except for appropriate phase lags, identical for all blades of the rotor. The very small high-frequency fluctuations beyond the first spike are due to nonlinearity of the mean wind shear. The frequency content to the left of

FIGURE 10. A Comparison of Spectra of a Hierarchy of Approximation to the Full-Disk Rotationally Sampled Axial Wind Speed

the first spike is very small and represents computational error. The spectrum contains weak hints of the character of the full rotationally sampled wind speed. This model is designated STRS-0, for zero order, or simplest, single-tower rotational sampling.

The next higher order of approximation also uses data only from the single center tower of the VPA. The fluctuations of the wind shear are now included. That is, the complete turbulent wind at each anemometer on the single tower is retained and rotationally sampled. The implication of this model is that the fluctuating wind is at each instant identical at all horizontal locations crosswind from the center tower of the VPA. The model is designated STRS-1. The resulting wind spectrum is plotted in Figure 10d. Qualitatively, the spectrum is suggestive of the full VPA wind spectrum shape. The total energy of fluctuation, represented by the area under the power spectral density curve, is much larger than that for the three previous models shown in Figure 10a, b, and c. The model estimates somewhat less than the energy of fluctuation for the full VPA rotationally sampled wind speed shown in Figure 10e, but STRS-1 may be considered a first rough approximation, useful if full-circle rotationally sampled wind speed characteristics are not available. A second-order single-tower model, STRS-2, more recently has been utilized with still better approximation to the full VPA rotationally sampled wind (Connell and George 1983).

8. CONCLUDING REMARKS

The importance of the new description of the wind for understanding wind turbine response has been discussed by Connell (1982); however, because it was not possible then to use the rotationally sampled wind speed in a turbine dynamical model or to correlate the wind with measured wind turbine response, the actual importance of the new wind description could not be proven. This report and its more complete companion report (George and Connell 1983) complete that task by demonstrating that the rotationally sampled wind, and only that wind among all the wind characterizations known, explains the observed flapwise bending fluctuations of the MOD-0A1 wind turbine rotor.

We have focused attention on turbulence spectra of wind fluctuations computed as observed in the rotating-blade frame of reference, using rotationally sampled wind. By this method, we have clearly demonstrated the importance of including the crosswind variations in turbulent wind when relating turbulence to wind turbine response fluctuations. Although the important crosswind variations are associated with turbulence eddies that are fairly large with respect to the length of the wind turbine blade, they have a lot of variation that is lost in disk-averaging the wind values.

Another value of using rotationally sampled wind relates to the lesser amount of irrelevant information about the wind that needs to be processed and stored in computer modeling of turbine response to the wind. This is easily seen if one considers the small fraction of information about the wind throughout the disk of rotation that is actually used for input to the aerodynamics model of a rotor with a typical solidity. Rotational sampling at the time of wind modeling very much reduces the amount of turbulent wind data to be stored or computed. It does require that the turbine model computer program be modified to eliminate the rotational sampling that is normally included in the turbine model whose wind input is not already rotationally sampled. This may substantially reduce the computational time and cost of modeling wind turbine response.

The concept of rotationally sampled wind leads to several modifications in previous thinking about winds approaching wind turbines. The significant

wind at a rotating rotor is not composed of engulfing gusts with uniform wind velocity everywhere on the rotor disk and time variations that are represented by wind measured at a single nonmoving location or by an average of the wind at many such points over the disk. Further, this report shows that the variations of wind velocity at a point on the rotor blade are not due primarily to the vertical profile of the mean wind velocity or of the fluctuating wind shear along a single vertical line. The variation of the turbulence throughout a crosswind disk is the source of much of the high-frequency variation in the wind at the blade.

To put the new model of the wind into perspective, a comparison of spectra of a set of increasingly complete models of wind experienced by a rotor blade has been made. The four models provide a basis for choosing an appropriate one for specific turbine design purposes. None of the models accurately represent the full rotationally sampled wind, but the wind-shear fluctuation model is a rough approximation to it. A model under development, the STRS-2 model, is a further improvement in approximation with single-tower wind data.

The hydrostatic stability of the wind flowing toward the turbine rotor strongly affects the character of the rotationally sampled wind spectrum. In the unstable or buoyancy-mixed wind and in the near-neutral or friction-driven mixing, turbulence is nearly the sole contributor to fluctuation energy at all high frequencies except the frequency of rotation of the rotor. (See Figure 5c.) At the rotor frequency the mean wind shear and the turbulence are about equally important. In the stable wind the mean wind shear is the primary factor at the rotation rate of the rotor and at twice that frequency. Its effect diminishes rapidly at higher frequencies where the energy is due to the turbulence, although turbulence energy is small in the stable wind. The effects of stabilities or of complex terrain airflow that reach beyond the several examples in this report are likely to be substantially different and sometimes stronger.

The flapwise bending response of the MOD-0A1 to wind is for the first time explained, using measurements, to be as expected from mechanical theory and measurement of the damped resonance frequencies. This is achieved by using the rotationally sampled wind in computing the response function. The

response half-power (cutoff) frequency is found to be substantially higher than would be estimated using the concept of a rotor-disk averaging filter for which the cutoff frequency is given by Equation (1). A simple interpretation of the relation of the observed cutoff frequency to tip speed ratio leads to an estimate that the size of the smallest eddies that affect the flapwise root bending moment of a blade is about two-thirds of the radius of the blade. The instantaneous wind gradient within a turbulence eddy may be large and complex.

In conclusion, the application of the concept of rotationally sampled wind reveals that there is much more energy of wind fluctuation at high frequency than previously thought, and that the energy is coherent over a large fraction of a rotor blade in the high-frequency portion of the spectrum. Part of this energy is placed exactly at the right frequencies to account for much of the nonresonant part of the spectral response of rotor blade flapwise root bending moment. The rest of the rotationally sampled wind energy in this frequency range provides the previously unexpected energy to stimulate the blade resonance modes in this range.

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APPENDIX A

AN AERODYNAMIC DERIVATION OF AN APPROXIMATE RELATION BETWEEN
A CHANGE IN THE FLAPWISE FORCE ON A ROTOR BLADE AND AN
INCREMENT OF ROTATIONALLY SAMPLED AXIAL WIND SPEED

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AN AERODYNAMIC DERIVATION OF AN APPROXIMATE RELATION BETWEEN A CHANGE IN THE FLAPWISE FORCE ON A ROTOR BLADE AND AN INCREMENT OF ROTATIONALLY SAMPLED AXIAL WIND SPEED

The purpose of this appendix is to derive an equation that shows the relation between the fluctuating flapwise force on a segment of a rotor blade and the fluctuations of the rotationally sampled axial wind speed. The method is to describe the approximate flapwise force due to aerodynamic lift at a spanwise element of the rotor blade. The symbols and orientation of the forces are shown in Figure A.1. An alternative approximate derivation of the same result, starting from a flapwise drag hypothesis, is given following the derivation based on lift force. The derivation is for nonstalled flow and for a constant value of the slope of the curve for the coefficient of lift, $dC_L/d\alpha$.

The flapwise force on an airfoil section is written as follows:

$$F_{\text{flap}} = L \cos \alpha + D \sin \alpha \quad (\text{A.1})$$

where F_{flap} is the flapwise aerodynamic force, L is the lift, D is the drag, and α is the angle of attack of the airfoil (see Figure A.1). Following conventional aerodynamic derivation methods and symbols, where S is the plan area of the blade section, the following steps in the derivation are listed.

$$F_{\text{flap}} \doteq C_L S \rho V^2 \cos \alpha \quad (\text{A.2})$$

We introduce an expression for the simple lift coefficient curve for small angles of attack:

$$F_{\text{flap}} \doteq C_{L0} + \alpha \frac{dC_L}{d\alpha} S \frac{\rho V^2}{2} \cdot 1 \quad (\text{A.3})$$

FIGURE A.1. A Cross Section of an Airfoil of a Rotor Blade and the Aerodynamic Forces of Lift and Drag and the Flapwise Component of the Force Due to Steady-State Unstalled Airfoil Flow

Treating the fluctuations of tangential wind speed relative to the blade, v' , as negligible and writing the axial wind speed as the sum of its mean and fluctuation components, we find that

$$F_{\text{flap}} \doteq C_{L0} + C'_L \alpha \text{ (constant)} \bar{v}^2 \left(1 + \frac{\bar{u}^2 + u'^2}{\bar{v}^2} \right) \quad (\text{A.4})$$

For small angles of attack, $\alpha = (\bar{u} + u')/\bar{v}$. We substitute this expression for angle of attack into Equation (A.4) and neglect $(\bar{u} + u')/\bar{v}^2$.

$$F_{\text{flap}} \doteq \text{Constant} \left(1 + \text{Constant} \frac{\bar{u} + u'}{\bar{v}} \right) \bar{v}^2 \quad (\text{A.5})$$

Taking the difference at two successive increments of time of Equation (A.5) and treating v as constant, we give the final expression:

$$F_{\text{flap}} \doteq \text{Constant} \Delta u' \quad (\text{A.6})$$

This means that the fluctuations of flapwise force on a blade are proportional to the fluctuations of the rotationally sampled axial wind speed.

A very simplistic explanation of the relationship above can be given for heuristic purposes in terms of an equivalent flat-plate drag. The approximate derivation is presented below. If the flapwise forces were thought of as being due to drag in the direction of the mean wind specified as normal to the disk of the rotor, a flat-plate drag equation could be written as follows.

$$F_{\text{flap}} \doteq C_{\text{FD}}^2 S \bar{u}^2 \quad , \quad (\text{A.7})$$

where C_{FD} is a constant drag coefficient and the other variables are as previously defined. A series of steps in the reduction of this equation for incremental variation in force and in axial wind speed leading to the final form of the equation is shown below. Expanding u in terms of its mean and fluctuating components, as in the previous derivation, we see that

$$F_{\text{flap}} \doteq \text{Constant} \quad \bar{u}^2 + u'^2 + 2 u u' \quad . \quad (\text{A.8})$$

Taking the difference of the force equation gives

$$F_{\text{flap}} \doteq \text{Constant} (2 u' \Delta u' + 2 u \Delta u') \quad . \quad (\text{A.9})$$

For smaller variations in angles of attack, $u' \ll \bar{u}$ and Equation (A.9) becomes

$$F_{\text{flap}} \doteq \text{Constant} \bar{u} \Delta u' \quad . \quad (\text{A.10})$$

Since the average wind speed is a constant,

$$F_{\text{flap}} \doteq \text{Constant} \Delta u' \quad . \quad (\text{A.11})$$

This is the same basic equation as derived from the lift equations earlier (see Equation (A.6)). Thus it is also supportable to think of the simple flapping wind forces as being caused by drag of the axial wind on the blade of the rotor considered as a flat plate normal to the axial wind, although there is no obvious reason other than heuristic to do so.

APPENDIX B

A PRELIMINARY ANALYSIS OF TURBINE BLADE RESPONSE SPECTRUM CUTOFF FREQUENCIES IN RELATION TO THE SIZE OF TURBULENCE EDDIES THAT FORCE ROOT BENDING

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The flapwise blade root bending response functions for three cases are characterized in Table B.1 in terms of the frequencies at which the blade response appears to diminish substantially below the low-frequency value of 1. The graphs used to derive these results are shown in Figure B.1. These graphs differ from those in Figure 9 of the main text in having been derived from spectra that were slightly more heavily smoothed before calculation of the response functions. The response functions were not nondimensionalized, in further distinction to those shown in the main text. In column 4 of Table B.1, the half-power (cutoff) frequency corresponding to a disk-average filter in the nonrotating frame of reference is given for each wind case. This is the parameter defined by Equation (1) in the main text and repeated here as Equation (B.1):

$$n'_c = U/D \quad . \quad (B.1)$$

The greatest half-power frequency measured from each response function in Figure B.1 is given in column 5. The tip speed ratios are tabulated in

TABLE B.1. Half-Power Cutoff Frequencies in Root Bending for a MOD-OA1 (Clayton, New Mexico) Wind Turbine Fiberglass Blade

Case Date	Wind Speed (m/s)	Tip Speed Ratio (λ_T)	$V(\text{wind})/D(\text{rotor})$ (n'_c)	$n_c(\text{Hz})$	$\lambda_T \times n'_c$	Stability
11/25/81	8.2	10.0	0.21	2.10	2.10	near neutral
12/18/81	5.6	14.6	0.14	3.30	2.04	stable
03/22/82	9.3	8.8	0.24	2.15	2.11	unstable

Rotor Parameters: $D = 39.2 \text{ m}$, $n_0 = 2/3 \text{ Hz}$.

FIGURE B.1. Frequency Response Functions Between Wind Speed and Turbine Fluctuations

column 3. In the near-neutral and unstable wind cases, the disk-average model cutoff frequency (column 4) multiplied by the tip speed ratio shown in column 6 equals the magnitude of the measured cutoff frequency (column 5). The measured cutoff frequency (column 5) for the stable case is larger than for the other cases and the computed value (column 6) for the stable case. If the measured value (column 5) represented only rotor blade mechanical characteristics, it would have the same value for all wind conditions including stability variations.

The equation for the observed cutoff speed may be written in either of three forms as shown below, none of which involve the blade mechanics on the independent variable side of the equations. It appears that the rolloff in response at high frequency is caused in part by a lack of coherence, across the blade radius, of the wind fluctuations, rather than solely by blade mechanical damping at higher frequencies. It is the coherence aspect that the present analysis addresses. Special wind conditions could occur for which sufficient coherence in the fluctuating wind would exist at higher frequencies to force a response in the whole blade and resulting root bending moment fluctuations. This would be the case if high-frequency passage of rotor-engulfing gusts occurred. This could be approximately true in stable wind conditions.

$$n_c = n'_c \times \lambda_T \quad , \quad (B.2)$$

where n_c is the measured cutoff frequency, n'_c is the hypothetical disk-average cutoff frequency, and λ_T is the tip speed ratio of the rotor. The more direct expression of the relation in Equation (B.2) is obtained by substituting Equation (B.1) into Equation (B.2).

$$n_c = U_{tip}/D \quad , \quad (B.3)$$

where U_{tip} is the tip speed of the rotor and D is the diameter of the rotor. The physical justification for the latter relation is not much more obvious than for Equation (B.1). It implies that the highest wind fluctuation frequency experienced by the rotor is due to an eddy whose size is about D/π , or (blade radius)/ $(\pi/2)$. This relation is also further reducible as follows.

$$\pi D = U_{tip}/n_o \quad . \quad (B.4)$$

Equations (B.3) and (B.4) imply that $n_c = \pi n_o$. Clarification of the physical importance of these relations probably awaits the simultaneous measurement of rotationally sampled wind at a number of radial locations corresponding to the airflow over the whole blade.

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