Simulation of Winds As Seen By a Rotating Vertical Axis Wind Turbine Blade

R. L. George

February 1984

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SUMMARY

The objective of this report is to provide turbulent wind analyses relevant to the design and testing of Vertical Axis Wind Turbines (VAWT).

A technique was developed for utilizing high-speed turbulence wind data from a line of seven anemometers at a single level to simulate the wind seen by a rotating VAWT blade. Twelve data cases, representing a range of wind speeds and stability classes, were selected from the large volume of data available from the Clayton, New Mexico, Vertical Plane Array (VPA) project. Simulations were run of the rotationally sampled wind speed relative to the earth, as well as the tangential and radial wind speeds, which are relative to the rotating wind turbine blade. Spectral analysis is used to compare and assess wind simulations from the different wind regimes, as well as from alternate wind measurement techniques. The variance in the wind speed at frequencies at or above the blade rotation rate is computed for all cases, and is used to quantitatively compare the VAWT simulations with Horizontal Axis Wind Turbine (HAWT) simulations. Qualitative comparisons are also made with direct wind measurements from a VAWT blade.

Major conclusions from this study are as follows:

- The characteristic rotationally sampled spectrum, containing spikes at all harmonics of the blade rotation frequency, occurs for VAWT as well as HAWT simulations.
- The rotationally sampled wind speed variance due to turbulence is a roughly linear function of wind speed for neutral and unstable wind conditions. For nighttime stable wind conditions, this relationship is probably nonlinear.
- For tangential and radial winds, the cyclic wind component, due to the upwind and downwind motion of the (simulated) VAWT blade, creates variance in the wind speed spectrum about 100 times greater than the variance due to turbulence in the wind. All of this variance occurs near the blade rotation frequency.

- Spectra of winds measured directly from a VAWT blade show more energy at higher harmonics of the blade rotation frequency than our wind turbulence simulations. This is presumed to be due to blade wake and aerodynamic effects, which are not being simulated in this study.

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1.0 INTRODUCTION

The influence of the turbulent wind on a moving wind turbine blade has recently emerged as a significant consideration for wind turbine design. The stresses on the rotating blade caused by instantaneous wind shears encountered by the blade within each revolution have been found to be more severe and more difficult to understand than previously expected. Since 1977, the Pacific Northwest Laboratory (PNL) has been conducting a program of measuring the wind as seen by a rotating Horizontal Axis Wind turbine (HAWT) blade, using fixed arrays of towers and anemometers (Verholek 1978, Connell 1981). In the most elaborate of these studies, an array of towers and anemometers was placed two blade diameters upwind of a large HAWT, which was the MOD-OA at Clayton, New Mexico (Connell and George 1982, 1983a). Good correlation was observed between the spectrum of the rotationally sampled wind and the stresses on the rotating MOD-OA blade. As part of the Clayton data set, a large amount of data was obtained from a line of seven anemometers, all at the same level (30.5 m above ground level). A major purpose in setting up the seven anemometers was to provide a data set which can be used to simulate the winds seen by a rotating Vertical Axis Wind Turbine (VAWT) blade.

The purpose of this study is to estimate and characterize the turbulence effects on a rotating VAWT blade using data from the seven anemometers. The expected wind as seen by the rotating VAWT blade, due only to the free stream mean wind and turbulent wind fluctuations, will be synthesized. This simulation will not attempt to show the effects of blade wakes, wind turbine structure wakes, or blade stall on the wind turbine blade. Spectral analysis techniques will be used to characterize the turbulence observed by the imaginary VAWT blade, with the emphasis on frequencies equal to or higher than the blade rotation frequency. Since no VAWT existed at the site, no attempt can be made to compare wind turbine stress directly with the rotationally sampled wind. However, our results will be compared with wind measurements obtained from a moving VAWT blade.

The organization of this report is as follows. Chapter 2 starts with a physical description of the Clayton Vertical Plane Array (VPA) and the

anemometers used there to measure the wind. Then a description of the technique of VAWT simulation follows, using a sequence of wind speeds appropriately led and lagged in time to simulate the motion of the wind turbine blade. Examples of the time series of rotational and fixed-point wind speed are given as aids in understanding the process. Then, a description of the use of spectral density is given, along with features of the fixed-point, one-blade simulation, and two-blade simulation spectral plots. These plots are characterized by spikes in the spectra, occurring at multiples of the wind turbine rotation frequency. A method is then presented to estimate the variance in the wind speed contained in each spike.

In Chapter 3, 12 data cases, belonging to four distinct wind regimes at Clayton, are selected for spectral analysis. Comparison is made of the rotationally sampled spectra and the fixed point, or Eulerian spectra, among the four categories of wind. The variances due to each spike are tabulated for all the cases. Relationships between the spike variance and wind speed are discussed, along with the relative sizes of the spikes. In the last chapter, we express conclusions about the Clayton VAWT analysis. We then compare our results with another VAWT study, a wind measurement from a rotating VAWT blade (Akins 1983).

2.0 VERTICAL PLANE ARRAY: DESCRIPTION AND DATA ANALYSIS

A Vertical Plane Array (VPA) of anemometers was operated by PNL between May 1981 and August 1982 at Clayton, New Mexico. The VPA was operated in conjunction with the MOD-OA1, a 200 kW wind turbine operated by the National Aeronautics and Space Administration (NASA) for the U.S. Department of Energy (DOE). In this chapter, we will describe the physical configuration of the VPA and the wind sensors used to take the wind data. We will also describe the data taking procedures used at Clayton, and the process of selecting data cases. Finally, we will discuss the analysis of the wind data using rotational sampling techniques and spectral analysis.

2.1 VERTICAL PLANE ARRAY: PHYSICAL DESCRIPTION

The VPA consisted of seven triangular guyed steel towers, each 60.6 m (199 feet) tall (Figure 2-1). The towers were located in a straight line which was placed at right angles to a line from the center tower to the MOD-OA1 turbine. The towers were unevenly spaced in order to accommodate a ring of 12 anemometers, which were evenly spaced around a circle 38.1 m (125 feet) in diameter. The center of the circle was elevated 30.5 m (100 feet) above ground level. These dimensions correspond to the height and diameter of the MOD-OA rotor for standard rotor blades. Additional anemometers were located at 60.0 m (197 feet) on the center tower and at 30.5 m (100 feet) on the five interior towers. Data from these extra anemometers will be used in this paper to simulate the wind seen by a Vertical Axis Wind Turbine (VAWT) blade. Thus, for the present analysis, we are concerned only with the seven anemometers, one on each tower of the VPA, which were at the 30.5-m level.

The Clayton, New Mexico, MOD-OA site was chosen over the five other NASA wind turbine sites because of the flatness and uniformity of the terrain. The most frequent wind direction at Clayton is SSW or SW. The VPA was located and the anemometers exposed so as to give the best wind data in this direction. South to southwest of the VPA is also the flattest, most uniform terrain at this site. Analysis of VPA data has indicated a roughness length (used in logarithmic wind law calculations) of about 0.005 m, a length usually

FIGURE 2-1. Clayton Vertical Plane Array. The seven anemometers at the level marked "Hub Height" were used for the VAWT simulations.

associated with mown grass (Chan et al. 1983). The terrain to the west of the site is much rougher, with a rocky ravine about 100 m away.

2.2 WIND SENSORS AND DATA ACQUISITION

The wind sensors used on all the VPA towers are R. M. Young Model 27004 Gill UVW anemometers. Each anemometer consists of three small propeller anemometers mounted at orthogonal right angles to each other. All anemometers were mounted such that the primary component, known as the U direction, faced into the normal array wind direction of 205° . The cross-wind component is known as V and the vertical wind component as W. Thus, for a uniform wind direction of 205° , U is the wind speed and V is close to zero. The analysis in this report will utilize both the U and V components.

The propellers mounted on the Gill UVWs were rugged black polypropylene propellers 18 cm in diameter (referred to by R. M. Young as 'High Resolution Propeller'). The distance constant, a measure of the responsiveness of the propeller to rapid changes in the wind speed, is 3.3 m for these propellers. For rapid wind speed changes, the propeller acts as a first-order filter with a time constant equal to distance constant divided by mean wind speed (Horst 1973). Wind data from UVW anemometers require correction to account for the fact that the propellers do not respond fully to winds at high angles to the axis of the component. The raw data must be corrected to more accurately represent the wind speed. This correction was performed on all data which are presented in this report. However, the impact of correction on the measured axial wind speeds is very small. The corrections were performed with revised correction coefficients for use with the 18-cm polypropylene propeller.

The VPA was operated from May 1981 to July 1982. Several hundred hours of high speed VPA data, along with MOD-OA wind turbine parameters, were taken during this period. In addition, over 1 year's worth of climatological data from only the center tower are available. The 12 cases of high-speed VPA data used in this paper were chosen originally for a project to compare VPA data with MOD-OA blade bending moments. They have been chosen to represent different wind conditions, when the MOD-OA with blade bending signals was operating

properly. For other purposes, the amount of available data is much larger. Doran and Packard (1982) have selected data from eight different days for use in the study of wind turbine wakes. Since the MOD-OA power signal was always available, most of the data are usable for wind turbine performance evaluation, in a much more detailed manner than ever before. Miller and Formica (1983) have used the climatological data as input to a model of the MOD-OA control strategy. Chan et al. (1983) have also used the climatological data to address the problem of wind turbine array modeling. A set of full array and wind turbine data have also been provided to NASA-Lewis Research Center, designers of the MOD-OA, for use in their blade pitch optimization project.

2.3 VAWT SIMULATION TECHNIQUE

Given an imaginary VAWT with blade radius R , measured from the axis to the equator. The blade rotates at a frequency

$$n_o = 2\pi\omega$$

Thus, the blade element on the equator moves at a rotational speed

$$V_r = R\omega = R n_o / (2\pi)$$

Along this equator are 12 equally spaced imaginary anemometer locations, labeled $i=1, 12$ (Figure 2-2a). The blade is assumed to start at the leftmost position, facing northeast, and to move counter-clockwise. The blade element experiences a wind due to its motion which is equal to V_r and opposite in direction. The angle between the starting position and the present position i is thus

$$\phi_i = (i - 1)(360/12)^\circ$$

The blade moves to a new location every $1/(12n_o)$ seconds. A real anemometer $j(i)$ is associated with each imaginary location i , as shown on Figure 2-2a. We have recorded the wind speed time series $U_o(j,t)$ and $V_o(j,t)$, the along-wind

FIGURE 2-2. (a) Diagram of VAWT Simulation Using a Line of Anemometers. Blade is rotating CCW, looking down from above. (b) Vector diagram of input winds V_r , U_i , and V_i , with resultant winds W_s , U_b , and V_b , as would be seen for the imaginary blade at position 3, as shown in (a). V_r is an induced wind in the opposite direction to blade motion.

and cross-wind components, at intervals of $\Delta t = 0.25$ seconds. We use linear interpolation in time on each of these time series to get $U_0(j,t)$ and $V_0(j,t)$ for any desired time. If t_i is the time the blade passes location i , we calculate the time for the wind to advect from the anemometer to location i using the equation:

$$R \sin \phi_i = \int_{t_i}^{t_i + \Delta t_a} U_0[j(i),t] dt$$

and use a finite difference technique to solve for the advection time Δt_a . This assumes that the wind direction is close to the array direction, such that U_0 is the principal component. This is true for all the cases studied.

We then have the components of the observed wind at the time of blade passage of location i :

$$U(i, t_i) = U_0[j(i), t_i + \Delta t_a]$$

$$V(i, t_i) = V_0[j(i), t_i + \Delta t_a]$$

From these we will compute three different time series of rotational wind:

$$1. W_s(i, t_i) = [U(i, t_i)^2 + V(i, t_i)^2]^{1/2}$$

the observed wind speed at time of blade passage;

$$2. U_b(i, t_i) = Vr + U(i, t_i) \cos \phi_i + V(i, t_i) \sin \phi_i$$

the chordwise, or tangential wind observed by the rotating blade; and

$$3. V_b(i, t_i) = V(i, t_i) \cos \phi_i - U(i, t_i) \sin \phi_i$$

the flapwise, or radial wind observed by the rotating blade. Figure 2-2b illustrates how the known wind vectors U_i , V_i , and V_r are combined to get the desired vectors W_s , U_b , and V_b . A positive V_b indicates a net wind coming from the left side of the blade element as it moves around; that is, from the hub toward the outside.

Provision was made to model a multibladed VAWT by averaging the rotational time series taken simultaneously at the proper locations. Thus, for a two-bladed turbine, the wind observed at the opposite location was averaged with the wind from the current blade location. The results of analysis of these time series should be related to the torque and power fluctuations observed at the hub of a VAWT. No attempt was made to model any other aspects of the vertical axis wind turbine, such as the wake effects from the hub or the upwind blade. We are constrained by the geometry of the VPA to use a blade radius

$$R = 19.05 \text{ m}$$

However, we can simulate any blade rotation rate, n_0 . A rotation rate of 0.6667 Hz, or 40 rpm, was used for most of the analyses in this report.

2.4 VPA DATA ANALYSIS

Time series from the first VPA data case analyzed in this fashion are shown in Figure 2-3. These data are from November 25, 1981 at about noon standard time, a case which will be referred to in the next chapter as Case C1a. The vertical grid lines are one blade revolution apart, or 1.5 seconds for a 40 rpm rotation rate. Figure 2-3a is the W_s for a one-blade simulation. Within this short period of six revolutions of the imaginary blade, the character of this signal changed from principally one cycle of fluctuation per revolution to two-per-revolution and back again to one. Fluctuations with amplitudes of over 1 m/sec are apparent. Figure 2-3b is the observed wind speed averaged over two blades. It has a more consistent two-per-revolution character.

FIGURE 2-3. (a) Example of W_s 1-Blade Series for Six Revolutions of the Imaginary Blade, (b) Example of W_s 2-Blade Time Series, for Same Time as (a), (c) Example of U_b 1-Blade Time Series, Same Time as (a), (d) Example of U_b 2-Blade Time Series, Same Time as (a).

Figure 2-3c is U_b , the tangential wind observed by the rotating VAWT blade. It has a large sinusoidal fluctuation with a peak-to-peak amplitude of twice the mean wind speed, or over 16 m/sec in this case. Small fluctuations due to the turbulent wind are not noticeable on this plot. The average speed of U_b is 79.8 m/sec, which is V_r , the blade rotation speed. In Figure 2-3d, the two-blade average of U_b is seen to two-per-revolution character.

In Figure 2-4, the U component of the wind observed directly by the Gill anemometers is presented for the same time period as in Figure 2-3, for the leftmost, center, and rightmost array positions. This figure can be compared to Figure 2-3 to demonstrate how localized wind gusts serve to create the characteristic rotationally sampled time series.

Power spectral density (PSD) functions were chosen for data analysis in order to provide a means of comparison between wind data and wind turbine response, in a form familiar to both boundary-layer meteorologists and wind turbine engineers. PSD functions were created using a Fast Fourier Transform (FFT) routine. Variances integrated over the spectral domain are also computed using the FFT routine. The FFT spectral analysis technique requires that the input data stream consist of a number of data points equal to an integral power of 2. The data segments analyzed in this paper are 8.53 minutes long, or 512 seconds. For rotational winds, the data rate is 8 per second (one data point each 0.125 second), each spectrum contains 4096 data points (2^{12}), and the highest frequency is 4.0 Hz (Figure 2-5).

A PSD plot from the VPA for a single anemometer at the center is shown in Figure 2-5a. Atmospheric turbulence, when plotted in this manner, usually exhibits a falloff with increasing frequency which has a slope of $-5/3$ on a log-log plot, as is indicated with a diagonal dashed line on Figure 2-5. The deviation of our observed response from the theoretical is due to the lack of frequency response of the propeller anemometer. The spectra in Figure 2-5b, c and d contain spikes corresponding to the rotation rate of the wind turbine.

For one blade (2-5b and d) a spike occurs at integer multiples of the rotation frequency, which is 0.666667 Hz, referred to as 'P'. For two-blade spectra (Figure 2-5c), only even multiples of P (2P, 4P, etc.) are present.

FIGURE 2-4. The Actual Wind Speed Observed at Single Anemometer Locations for the Same Time Period as Figure 2-3. (a) Leftmost anemometer, $j=1$; (b) center anemometer, $j=4$; (c) rightmost anemometer, $j=7$.

FIGURE 2-5. Spectral Density Plots, All for the Same 8.53 Minute Period (Case C1a), (a) Eulerian, or Fixed Point Wind Speed, (b) VAWT 1 Blade Simulation, Wind Speed, (c) VAWT 2 Blade Simulation, Wind Speed, (d) U_b , the Wind Tangential to the Blade, for 1 Blade. The vertical scale of this plot is shifted downward by 10 to accommodate the large spike. The diagonal dashed line is the maximum theoretical spectral density for a fixed-point anemometer. The vertical dashed lines are the 1P and 2P frequencies.

On this plot and all other wind spectral plots in this report, the 1P and 2P frequencies are marked by vertical dashed lines.

The spectrum of VAWT wind speed in Figure 2-5b is reduced below the spectrum of Eulerian wind in the frequency range 0.05 - 0.5 Hz. A roughly equal amount of energy is distributed among the five spikes at frequencies above 0.5 Hz. This result is consistent with previously reported Horizontal Axis VPA results (Connell and George 1982). The entire structure of this spectrum above 0.5 Hz is attributable to wind turbulence, since no mean wind shears are present. The spikes in Figure 2-5c, the two-bladed simulation, have the same magnitude as the spikes in 2-5b, for the even-numbered values of P only. Spectral density at odd-numbered values of P is eliminated by two-blade averaging.

The spectrum of U_b , the tangential velocity of winds as seen by the rotating turbine blade, is fundamentally different from other rotational spectra we have seen. An enormous spike, reflecting the one-per-revolution cycle of U_b as seen in Figure 2-3c, dominates the spectrum in Figure 2-5d. However, the spikes at 2P through 5P are similar in size to those present on the VAWT wind speed spectrum (Figure 2-5b). At low frequencies, the U_b spectrum is greatly reduced compared to the wind speed spectrum. The spectrum of V_b is very similar to that of U_b .

The plots of spectral estimates in this paper are of $S(n)$ versus $n_0 \cdot S(n)$ has the units of $(m^2/sec^2)/Hz$. When the spectral density $S(n)$ is integrated over a range of frequency, an estimate is obtained of the variance in the time series due to fluctuations whose frequencies fall within that range. If n_0 is the rotational frequency of the (imaginary) VAWT blade, then we define a variance σ_i^2 such that

$$\sigma_i^2 = \int_{(i-0.5)n_0}^{(i+0.5)n_0} S(n)dn \quad \text{for } i = 1, 2, 3, 4, 5$$

is the variance associated with each harmonic of the rotational frequency (each "spike" on the rotationally sampled spectrum), and

$$\sigma_0^2 = \int_0^{0.5n_0} S(n)dn$$

is the variance due to low frequency wind fluctuations. These variance values will be calculated and used in the next chapter to compare the rotationally sampled spectra from various wind cases and various simulation types. This technique has previously been used to assess single tower simulations of various sized HAWTs (Connell and George 1983b).

3.0 VAWT SIMULATION DATA ANALYSIS

The data analysis techniques presented in the previous chapter were applied to 12 separate data cases from the Clayton VPA data set, each case being 8.53 minutes long. These cases were originally chosen for a Horizontal Axis Wind Turbine (HAWT) study. Thus, simulations of the wind rotationally sampled in the vertical plane are available for all cases, for comparison with the VAWT simulation data.

3.1 CHARACTERIZATION OF WIND DATA CASES

The 12 cases are listed in Table 3-1.

TABLE 3-1. Summary of Characteristics of 12 Data Cases Used in VAWT Simulations

<u>Case #</u>	<u>Date</u>	<u>Time MST</u>	<u>Mean WS M/Sec</u>	<u>σ/WS</u>	<u>Tip Speed Ratio</u>	<u>VAWT Spike σ^2 M²/S²</u>	<u>HAWT Spike σ^2 M²/S²</u>
C1a	11/25/81	1211	7.66	0.089	10.4	0.286	0.411
C1b	06/28/82	1350	6.82	0.120	11.7	0.263	0.406
C1c	06/28/82	0818	7.68	0.089	10.4	0.322	0.521
C2a	01/01/82	1231	9.87	0.077	8.1	0.301	0.913
C2b	11/27/81	1455	10.56	0.101	7.6	0.435	1.046
C2c	11/27/81	1143	13.61	0.077	5.9	0.483	1.505
C3a	07/01/82	0124	5.95	0.100	13.4	0.255	0.632
C3b	12/18/81	1608	5.90	0.052	13.5	0.082	0.827
C3c	12/14/81	1624	5.70	0.036	14.0	0.034	0.701
C4a	01/01/82	1803	12.52	0.086	6.4	0.700	2.568
C4b	01/01/82	1546	12.32	0.083	6.5	0.662	2.266
C4c	01/01/82	1825	14.00	0.072	5.7	0.732	3.392

The turbulence intensity, Column 5 in the Table, was computed by taking the standard deviation of the wind speed after removing all fluctuations longer than about 2 minutes, and dividing by mean wind speed. Tip speed ratio

(Column 6) was obtained using the tip speed of a 19.05-m radius blade rotating at 40 rpm, which was 79.8 m/sec, and dividing by the mean wind speed. The total variance in the 1P through 5P spikes of the wind speed simulation is given for both VAWT (Column 7) and HAWT (Column 8).

Case C1 consisted of daytime, neutral-to-unstable, low-wind speed cases. These cases at Clayton were characterized by very low vertical wind shears. The turbulence intensities of 0.09 to 0.12 are typical for a flat site. Total variance in the five spikes is 60-70% of that observed using a full ring of anemometers (see Figure 2-1) to simulate a HAWT.

Case C2 contains higher wind speed cases of daytime, neutral-to-unstable winds. The turbulence intensity was slightly lower for these cases. Moderate vertical wind shears were present, causing the VAWT variance to be only 32-42% of the HAWT variance, which contains energy due to mean wind shear.

Cases C3 and C4 were evening and nighttime cases with more stable wind shear profiles. C3a was only slightly stable, and has higher turbulence levels more characteristic of neutral flows. C3b and C3c had extremely low turbulence levels, and correspondingly low variances in the VAWT harmonic spikes. For these two cases, the VAWT W_s simulation had only 5-10% as much variance as the HAWT simulation. Case C4 had high wind speeds, very high vertical wind shears, and levels of turbulence similar to the neutral cases. The very high values of variance in the HAWT simulations for the stable cases are due to the rotation of the HAWT blade through large vertical wind shears. Even so, VAWT spike variance was 22-29% of HAWT variance.

3.2 SPECTRAL ANALYSIS OF DATA CASES

Spectral plots are in Figures 3-1 to 3-13. Wind speed spectra (parts a and b of each figure) have been normalized by adjusting all the time series slightly so that they have the same mean wind speed at each anemometer location. This eliminates small differences in mean wind speed between anemometers, due mostly to measurement error. Even a mean wind speed error of 2%, the expected accuracy of the Gill anemometers, will produce noticeable differences in the

FIGURE 3-1. Complete Set of Spectral Plots for Case C1a, (a) W_s , 1 Blade (same as 4-5b), (b) W_s , 2 Blade (same as 4-5c), (c) U_b , 1 Blade (same as 4-5d), (d) U_b , 2 Blade, (e) V_b , the Radial Wind Component, for 1 Blade, (f) V_b , 2 Blade, (g) Wind Speed for the Horizontal Axis Wind Turbine Simulation, 1 Blade, (h) Eulerian or Fixed-Point Wind Speed (same as 4-5a).

FIGURE 3-2. Spectral Plots of Case C1a, for a Simulated 20 RPM VAWT, (a) W_s 1 Blade, Original Data, (b) W_s , 1 Blade Anemometer Data Filtered With a 15 Point (3.75 Second) Lowpass Filter Before Rotational Sampling, (c) U_b , 1 Blade, (d) U_b , 1 Blade 3.75 Second Filter, (e) V_b , 1 Blade, (f) V_b , 1 Blade, 3.75 Second Filter.

FIGURE 3-3. Spectral Plots for Case C1b. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-4. Spectral Plots for Case C1c. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-5. Spectral Plots for Case C2a. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-6. Spectral Plots for Case C2b. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-7. Spectral Plots for Case C2c. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-8. Spectral Plots for Case C3a. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-9. Spectral Plots for Case C3b. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-10. Spectral Plots for Case C3c. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-11. Spectral Plots for Case C4a. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-12. Spectral Plots for Case C4b. Vertical dashed lines mark the 1P and 2P frequencies.

FIGURE 3-13. Spectral Plots for Case C4c. Vertical dashed lines mark the 1P and 2P frequencies.

higher frequency spikes (4P and 5P). A similar smoothing of the vertical wind shear was used to produce the HAWT spectra. The VAWT U_b and V_b simulations were not similarly corrected.

A complete set of spectral plots for case C1a is given in Figure 3-1. Parts a, b, c and h were discussed in Chapter 2. The two-blade spectrum for U_b (Figure 3-1d) has somewhat higher spikes at 2P and 4P than the VAWT wind speed in Figure 3-1b. Spectra for V_b are very similar to those for U_b . The HAWT spectrum in (Figure 3-1g) is only slightly different from the VAWT spectrum in 3-1a. It is smoother in the low frequencies, and it has sharper spikes, due to the presence of mean wind shear in this time series.

Data for the same time period were used to simulate VAWT rotation at 20 rpm. This cuts the tip speed ratio in half, to 5.2 in this case. As can be seen in Figure 3-2, this produces a spectrum with a different character than in the 40 rpm case. Spectral peaks beyond 2P are not clearly resolved. Our experience with rotational sampling has shown that the level of the spectrum between spikes is related to the level of the Eulerian spectrum at the 1P frequency. For 20 rpm, the 1P frequency is 0.333 Hz. Looking at Figure 3-1h, we see that the Eulerian spectrum is about one decade higher at 0.333 Hz than at 0.6667 Hz. The level of the rotational spectrum between spikes (Figure 3-2a) is raised above the level in the 40 rpm case (Figure 3-1a) by about the same amount. This higher "noise" content in the simulated analysis can be removed by lowpass filtering of the data from each anemometer before the rotational sampling is performed. For the 20 rpm case, a lowpass filter was created on each anemometer by using a running mean of 15 consecutive data points, or 3.75 seconds of data. These heavily filtered data were then rotationally sampled using the VAWT simulation. The resulting spectrum for single blade wind speed, Figure 3-2b, looks much more like the 40 rpm spectrum (Figure 3-1a) than the original 20 rpm spectrum in 3-2a. This demonstrates that the characteristic harmonic spikes are due to relatively large turbulent wind eddies. The same effect is visible for the U_b simulations (3-2c, unfiltered and 3-2d, filtered) and the V_b simulations (3-2e and f).

For the remainder of the 12 data cases, an abbreviated set of five spectral plots is presented. These plots are for 40 rpm simulations only, in

Figures 3-3 to 3-13. This set includes spectra of W_s for one-blade and two-blade simulations, U_b for one-blade and two-blade simulations, and the Eulerian spectrum. The remaining neutral low-wind speed cases, cases C1b and C1c, look remarkably similar to case C1a.

In case C2, higher wind speed neutral-to-unstable cases, the character of the spectra is somewhat different. Higher frequency peaks are not clearly resolved in the one-blade W_s case (Figures 3-5a, 3-6a, 3-7a). This can be related to the Eulerian spectrum in the same way that the 20 rpm and the 40 rpm spectra were related. Once again, the level of the Eulerian spectrum at the 1P frequency is close to the level of the 4P and 5P spikes, making the spikes more difficult to resolve. The spikes themselves seem to be broader in case C2 than in C1, for one-blade and two-blade wind speed spectra.

A somewhat objective way to compare these rotational spectra to one another is to compile a table of the integrated spectral spikes, as detailed in the previous chapter. In Tables 3-2 and 3-3, we present all the σ_i^2 s, where $i=0$ (low frequency) to 5 (5P spike), for all 12 cases, and W_s , U_b , and V_b for both one-blade and two-blade simulations. In Table 3-2, the spike variances for C1 and C2, the neutral-to-unstable cases, are shown. The large differences in low frequency variance from one case to the next are due to differences in stationarity between the various cases. The variance due to the large 1P spike in U_b and V_b one-blade simulations is approximately $(\sqrt{2}/2 \times \text{mean } W_s)^2$, or the variance of a sine wave with amplitude of the mean wind speed.

The next three figures (3-8 to 3-10) show case C3, the nighttime stable low wind case. For all these cases, the dips between spikes are much lower than any in cases C1 and C2. Case C3a, which was only slightly stable, looks similar to case C1. However, C3b and C3c have very weak spikes in the wind speeds (1P to 5P) and the blade-relative winds (2P to 5P). This is due to the near absence of turbulence in the wind for these two cases. However, the basic 5-spike structure is evident for all the cases.

In contrast, the high wind speed stable cases, in C4 (Figures 3-11 to 3-13) have higher levels of turbulence than the neutral cases. When

TABLE 3-2. Variance in Each Spike, Cases C1 and C2

Simulation Type		Case Number					
		C1a	C1b	C1c	C2a	C2b	C2c
VAWT Ws 1 Blade	Lo Freq	0.888	1.043	0.346	0.375	0.818	0.777
	1P	0.157	0.149	0.186	0.173	0.274	0.276
	2P	0.063	0.054	0.068	0.058	0.082	0.108
	3P	0.029	0.030	0.031	0.033	0.037	0.044
	4P	0.019	0.016	0.022	0.021	0.023	0.032
	5P	0.017	0.013	0.015	0.015	0.018	0.023
VAWT Ub 1 Blade	Lo Freq	0.104	0.093	0.136	0.124	0.183	0.186
	1P	30.058	23.844	29.722	49.269	56.472	94.018
	2P	0.097	0.071	0.088	0.097	0.119	0.158
	3P	0.036	0.022	0.031	0.038	0.044	0.065
	4P	0.027	0.013	0.016	0.040	0.039	0.054
	5P	0.012	0.010	0.011	0.013	0.014	0.022
VAWT Vb 1 Blade	Lo Freq	0.060	0.036	0.040	0.047	0.042	0.079
	1P	29.381	23.620	29.467	48.255	55.817	91.756
	2P	0.106	0.093	0.112	0.117	0.180	0.187
	3P	0.036	0.034	0.045	0.043	0.060	0.081
	4P	0.022	0.024	0.023	0.027	0.032	0.040
	5P	0.014	0.018	0.026	0.019	0.021	0.025
VAWT Ws 2 Blade	Lo Freq	0.885	1.045	0.347	0.374	0.824	0.772
	1P	0.002	0.001	0.002	0.004	0.004	0.007
	2P	0.061	0.054	0.066	0.056	0.076	0.099
	3P	0.002	0.002	0.002	0.004	0.004	0.008
	4P	0.018	0.015	0.020	0.018	0.020	0.022
	5P	0.002	0.001	0.002	0.004	0.005	0.009
VAWT Ub 2 Blade	Lo Freq	0.093	0.083	0.117	0.106	0.150	0.155
	1P	0.001	0.001	0.001	0.003	0.004	0.006
	2P	0.080	0.068	0.081	0.072	0.105	0.108
	3P	0.001	0.001	0.001	0.002	0.003	0.006
	4P	0.023	0.011	0.014	0.033	0.034	0.041
	5P	0.002	0.001	0.001	0.003	0.003	0.006
VAWT Vb 2 Blade	Lo Freq	0.045	0.033	0.037	0.025	0.036	0.040
	1P	0.001	0.001	0.001	0.002	0.002	0.005
	2P	0.091	0.079	0.089	0.097	0.142	0.150
	3P	0.001	0.001	0.001	0.003	0.003	0.006
	4P	0.019	0.019	0.018	0.022	0.023	0.028
	5P	0.001	0.001	0.002	0.004	0.004	0.007

compared to a neutral case with a similar wind speed (C2c, Figure 3-7), the spikes look broader, and the "floor" to which the dips between spikes drops is higher. The tabulation of σ_i^2 values for cases C3 and C4 (Table 3-3) demonstrates the higher levels of turbulence in case C4 and the very low levels in C3. Variance values for C4 are higher than C2c for practically all spikes and all simulation types.

We may wish to generalize the relationships among the various spectra as an aid in the practical application of these results. One parameter of

TABLE 3-3. Variance in Each Spike, Cases C3 and C4

Simulation Type		Case Number					
		C3a	C3b	C3c	C4a	C4b	C4c
VAWT Ws 1 Blade	Lo Freq	0.293	0.034	0.040	0.492	0.798	0.430
	1P	0.156	0.035	0.015	0.370	0.396	0.397
	2P	0.050	0.022	0.007	0.164	0.140	0.157
	3P	0.025	0.011	0.005	0.083	0.062	0.077
	4P	0.015	0.008	0.004	0.047	0.035	0.048
	5P	0.010	0.006	0.003	0.036	0.028	0.043
VAWT Ub 1 Blade	Lo Freq	0.090	0.024	0.016	0.234	0.250	0.261
	1P	18.020	17.601	16.455	77.145	76.176	96.654
	2P	0.066	0.024	0.014	0.179	0.183	0.186
	3P	0.019	0.013	0.009	0.077	0.073	0.086
	4P	0.011	0.014	0.010	0.053	0.069	0.060
	5P	0.008	0.005	0.004	0.029	0.022	0.032
VAWT Vb 1 Blade	Lo Freq	0.019	0.012	0.007	0.087	0.088	0.085
	1P	17.782	17.246	16.058	79.825	76.168	99.458
	2P	0.089	0.027	0.022	0.252	0.227	0.244
	3P	0.030	0.014	0.009	0.111	0.088	0.107
	4P	0.017	0.010	0.006	0.058	0.052	0.065
	5P	0.014	0.007	0.004	0.038	0.031	0.041
VAWT Ws 2 Blade	Lo Freq	0.293	0.034	0.040	0.484	0.799	0.427
	1P	0.001	0.001	0.000	0.008	0.007	0.013
	2P	0.049	0.021	0.007	0.157	0.135	0.147
	3P	0.001	0.001	0.000	0.011	0.008	0.013
	4P	0.014	0.007	0.004	0.034	0.027	0.037
	5P	0.001	0.001	0.000	0.012	0.009	0.013
VAWT Ub 2 Blade	Lo Freq	0.080	0.020	0.009	0.203	0.227	0.218
	1P	0.001	0.000	0.000	0.010	0.007	0.012
	2P	0.060	0.016	0.009	0.148	0.148	0.143
	3P	0.001	0.001	0.000	0.010	0.007	0.013
	4P	0.010	0.013	0.009	0.038	0.057	0.043
	5P	0.001	0.001	0.000	0.010	0.006	0.012
VAWT Vb 2 Blade	Lo Freq	0.017	0.005	0.003	0.065	0.052	0.055
	1P	0.001	0.000	0.000	0.007	0.004	0.008
	2P	0.074	0.020	0.013	0.206	0.193	0.188
	3P	0.001	0.000	0.000	0.009	0.007	0.013
	4P	0.014	0.009	0.004	0.039	0.038	0.041
	5P	0.001	0.000	0.000	0.011	0.008	0.014

interest is the total variance due to the 1P - 5P spikes in the VAWT simulation, as listed in Table 3-1. In Figure 3-14, this sum is plotted as a function of mean wind speed for the wind speed spectra, one-blade simulation only. Cases C1 and C2 are marked as squares. The solid line is a least-squares linear fit to the six values in cases C1 and C2. This line has the equation:

$$\sum_{i=1}^5 \sigma_i^2 = -0.017 + 0.039 W_s.$$

FIGURE 3-14. Plot of Total Variance in All 5 Turbulent Spikes Vs. Wind Speed for the VAWT W_s 1-Blade Simulation. The solid line is a linear regression of the neutral-to-unstable cases, C_1 and C_2 (marked by squares). The dashed line is a regression of the stable cases, C_3 and C_4 , marked by triangles.

Since this line passes close to (0,0), and since the neutral cases all have similar turbulence properties, this line may be a useful means of predicting the spike variance, given a known mean wind speed over a flat site. A dashed line is drawn as a linear fit to cases C_3 and C_4 , shown as triangles on the plot. This line has the equation:

$$\sum_{i=1}^5 \sigma_i^2 = -0.343 + 0.080 W_s$$

However, due to the great differences in turbulence between cases C3 and C4, we do not expect this linear relationship to be a useful predictor.

Another parameter which may be of interest is the rate at which the spike variance decreases with increasing frequency. In Figure 3-15, the variance due to each spike is plotted versus frequency on a log-log plot. Most of the traces on this plot seem to be linear. The equation of a straight line on a log-log plot has the form:

$$\sigma_i^2 = K_0 (i/n_0)^{K_1}$$

where K_0 is the value for σ_i^2 at $n = 1.0$ Hz and K_1 is the slope of the line. In Table 3-4, the values of K_0 and K_1 for a linear curve fit to each case are shown. Once again, these apply only to the VAWT wind speed simulation, one blade. The lines are remarkably similar except for cases C3b and C3c. The average slope of all the other cases is -1.58. This is very close to the natural slope of a turbulence spectrum on a log-log plot, which is -1.6667.

TABLE 3-4. Linear Curve Fit Coefficients to Spike Profiles for 12 Data Cases Used in VAWT Simulations

<u>Case #</u>	<u>Mean Ws M/Sec</u>	<u>VAWT Spike σ^2 M²/S²</u>	<u>K₀ M²/S²</u>	<u>K₁</u>
C1a	7.66	0.286	0.088	-1.46
C1b	6.82	0.263	0.082	-1.55
C1c	7.68	0.322	0.100	-1.57
C2a	9.87	0.301	0.093	-1.51
C2b	10.56	0.435	0.133	-1.73
C2c	13.61	0.483	0.150	-1.58
C3a	5.95	0.255	0.080	-1.70
C3b	5.90	0.082	0.025	-1.13
C3c	5.70	0.034	0.010	-0.97
C4a	12.52	0.700	0.220	-1.49
C4b	12.32	0.662	0.206	-1.71
C4c	14.00	0.732	0.222	-1.45

FIGURE 3-15. Plot of Variance, σ_i^2 , in Each Individual Spike, Vs. Frequency, for All 12 Data Cases. The four types of cases are shown as different line types, as shown on the figure labels.

4.0 CONCLUSIONS AND COMPARISONS

In this study, the free-stream turbulent wind, as seen by a rotating Vertical Axis Wind Turbine (VAWT) blade, has been simulated using an array of fixed anemometers. Spectral plots of the resultant winds have been produced for a wide range of wind conditions.

4.1 GENERAL CONCLUSIONS

These results lead to some general conclusions, as follows:

- Generally, the characteristic rotationally sampled spectrum, with spikes at all harmonics of the blade rotation rate for one-blade simulations and at even harmonics only for two-blade simulations, occurs for all simulations. In all cases, parts of the high frequency spectrum exceed the theoretical fixed point Eulerian spectrum. At low tip speed ratios (high wind speeds or slower blade rotation rates), the 4P and 5P spikes are of the same magnitude as the general increase in spectral density, and thus do not stand out on the spectral plots. Lowpass filtering of the wind data before rotational sampling can be used to reveal the discrete nature of the 4P and 5P spikes.
- The variance contained in the high frequency spikes for a VAWT wind speed spectrum is only a little less than the variance for a Horizontal Axis Wind Turbine (HAWT) simulation, which contains mean wind shear effects, for low-wind speed neutral cases. VAWT variance is much less than HAWT variance for highly sheared winds.
- Neutral-to-unstable winds show a roughly linear increase in wind speed variance with increasing wind speed. The increase has a slope of about $0.039 \text{ m}^2/\text{sec}^2$ of variance per m/sec of wind speed, for a 38.1 m diameter VAWT with the equator elevated 30.5 m above the ground. We would expect the slope to be less for a smaller diameter, but greater for a wind turbine closer to the ground.
- At higher wind speeds (above 10 m/sec), more stable nighttime cases have more variance in the high frequency spikes than neutral cases with the

same wind speed. This is probably due to a slight shift in spectral energy toward higher frequencies in the more stable cases. At low wind speeds, stable cases have much less spike variance than neutral or unstable cases.

- The size of individual spectral spikes relative to each other decrease with increasing frequency in a characteristic way, for W_s spectra only. This decrease has a slope close to $-5/3$, which is the natural decrease in turbulence energy with increasing frequency.
- Generally, both U_b , the tangential wind observed at the blade, and V_b , the radial wind observed at the blade, are dominated by the 1P harmonic spike, due to rotation of the blade through the mean wind. The 2P through 5P spikes in the U_b and V_b spectra are similar in size to those on the W_s spectra.

4.2 COMPARISON OF RESULTS WITH DIRECT MEASUREMENTS

Our results can be compared with a direct measurement of the wind using pitot-static wind sensors mounted on the blade leading edge of a 17-m Darrieus VAWT (Akins 1983). Normalized spectral plots of the dynamic pressure for two different wind cases are shown in Figure 4-1. Figure 4-1a is for a wind speed of 13.3, tip speed ratios of 2-3, and wind turbine power close to rated. Figure 4-1b is for a light wind speed case, tip speed ratios of 5-6, and power about 20% of rated. Surprisingly, the lower wind speed spectrum (Figure 4-1b) resembles the rotationally sampled wind speed W_s from Clayton more so than the tangential wind speed U_b , with 2P and higher spikes only slightly smaller than the 1P spike. Figure 4-1a, the higher wind speed case, is more dominated by the 1P spike, like the U_b simulation.

In order to usefully compare these two methods of measuring the vertical axis wind, it is necessary to assess the effects of factors other than atmospheric turbulence on the results. We expect almost no outside effects on the VAWT simulation from Clayton. The Darrieus VAWT measurements, however, are strongly affected by rotation of the blade through the rotor wake on both the downwind and upwind sides of the wind turbine. The steady-state wake, as

FIGURE 4-1. Spectral Density Plots of Pitot-Static Pressure. Measured from the blade of an operating 17 m Darrieus VAWT. Figures are a) VAWT power near rated, tip speed ratio 2-3, and b) VAWT power 20% or rated, tip speed ratio of 5-6 (Akins 1983).

estimated using double multiple streamtube (DMS) models (e.g., Paraschivoiu 1981) would produce a complex velocity reduction as a function of the blade position relative to the wake. This in turn would produce spectral energy at harmonics greater than 1P, helping to explain the differences between the Clayton and VAWT measurements.

An additional component of the wind observed at the VAWT blade, however, can be estimated only by including turbulence effects in the wind. The importance of this component to the VAWT design process has yet to be determined. The resemblance of the observed spectra in Figure 4-1 to the rotationally sampled winds from Clayton would suggest an important role for turbulent wind inputs. Recent improvements to DMS models have included the use of turbulent wind inputs.

An interesting extension of this work would be to use Clayton Vertical Plane Array data as an input to an advanced DMS model. The dimensions of the VPA correspond almost exactly to the 38 m "testbed" wind turbine being proposed for the Sandia National Labs facility. Data from the entire array, rather than just from one level, would be used in this application.

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