1995121550

BASIC PRINCIPLES AND RECENT OBSERVATIONS OF ROTATIONALLY SAMPLED WIND

James R. Connell

Pacific Northwest Laboratory
Richland, Washington 99352

N95-27971

ABSTRACT

The concept of rotationally sampled wind speed is described. The unusual wind characteristics that result from rotationally sampling the wind are shown first for early measurements made using an 8-point ring of anemometers on a vertical plane array of meteorological towers. Quantitative characterization of the rotationally sampled wind is made in terms of the power spectral density function of the wind speed. Verification of the importance of the new concept is demonstrated with spectral analyses of the response of the MOD-0A blade flapwise root bending moment and the corresponding rotational analysis of the wind measured immediately upwind of the MOD-0A using a 12-point ring of anemometers on a 7-tower vertical plane array.

The Pacific Northwest Laboratory (PNL) theory of the rotationally sampled wind speed power spectral density function is tested successfully against the wind spectrum measured at the MOD-0A vertical plane array. A single-tower empirical model of the rotationally sampled wind speed is also successfully tested against the measurements from the full vertical plane array.

Rotational measurements of the wind velocity with hotfilm anemometers attached to rotating blades are shown to be accurate and practical for research on winds at the blades of wind turbines. Some measurements at the rotor blade of a MOD-2 turbine using the hotfilm technique in a pilot research program are shown. They are compared and contrasted to the expectations based upon application of the PNL theory of rotationally sampled wind to the MOD-2 size and rotation rate but without teeter, blade bending, or rotor induction accounted for.

Finally, the importance of temperature layering and of wind modifications due to flow over complex terrain is demonstrated by the use of hotfilm anemometer data, and meteorological tower and acoustic doppler sounder data from the MOD-2 site at Goodnoe Hills, Washington.

INTRODUCTION

Rotational sampling is a method of determining the character of the wind encountered by a segment of a rotating wind turbine blade. The concept of rotational sampling has undergone extensions in theory and observations and has been applied to wind turbine test and design. The basic principles of rotational sampling and some of our recent rotational measurements of the wind are presented in this paper.

Early in the development of the rotational sampling concept, wind measurements using vertical plane arrays of propeller anemometers in circles were analyzed to simulate the wind velocity experienced just ahead of a chordwise slice of a rotating rotor blade. Figure 1 is a sketch of the larger of those

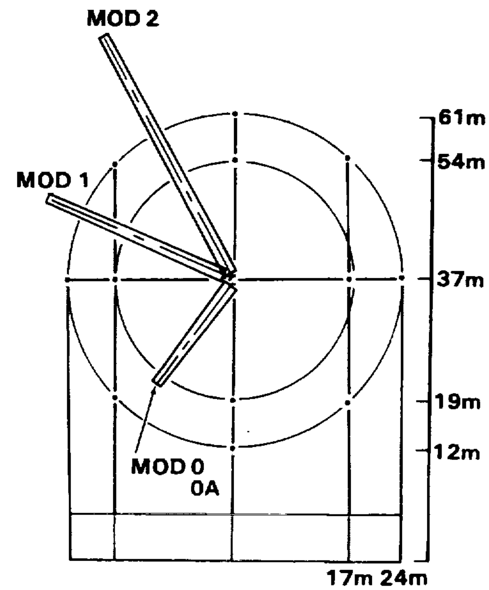

Figure 1--Sketch of the 37-m diameter vertical plane array at Hanford, Washington site

isolated vertical plane arrays, with circles of rotation, wind turbine blades and a height scale superimposed upon it.

Figure 2 shows graphs of the cross-disk (axial) wind speed as a function of time at each anemometer location on the vertical plane array (VPA) for an 8-minute period. The wind speed time series were smoothed slightly to remove the high-frequency fluctuations. Distinct similarities and differences between winds at different locations but at identical times can be seen at each of the eight locations around the circle. The wind speed fluctuations experienced by a point rotating around the circle of anemometers at the speed of a point on a rotor blade are obtained by sampling wind speed values from graph to graph around the circle and incrementing time with each change of graph (or location around the circle). This construction of a new time series of the wind speed fluctuations is called rotational sampling.

A time series of rotationally sampled axial wind speed is shown along with a time series of the axial wind speed measured at a single nonmoving point in the top graph in Figure 3. The substantial differences in character of these two time series are discussed in the next section.

CHARACTERISTICS OF ROTATIONALLY SAMPLED WIND VELOCITY

The time series of the wind speed in Figure 3 indicate qualitatively how differently the wind is seen by a stationary point and by a point revolving around a circle in a vertical plane set at right angles to the

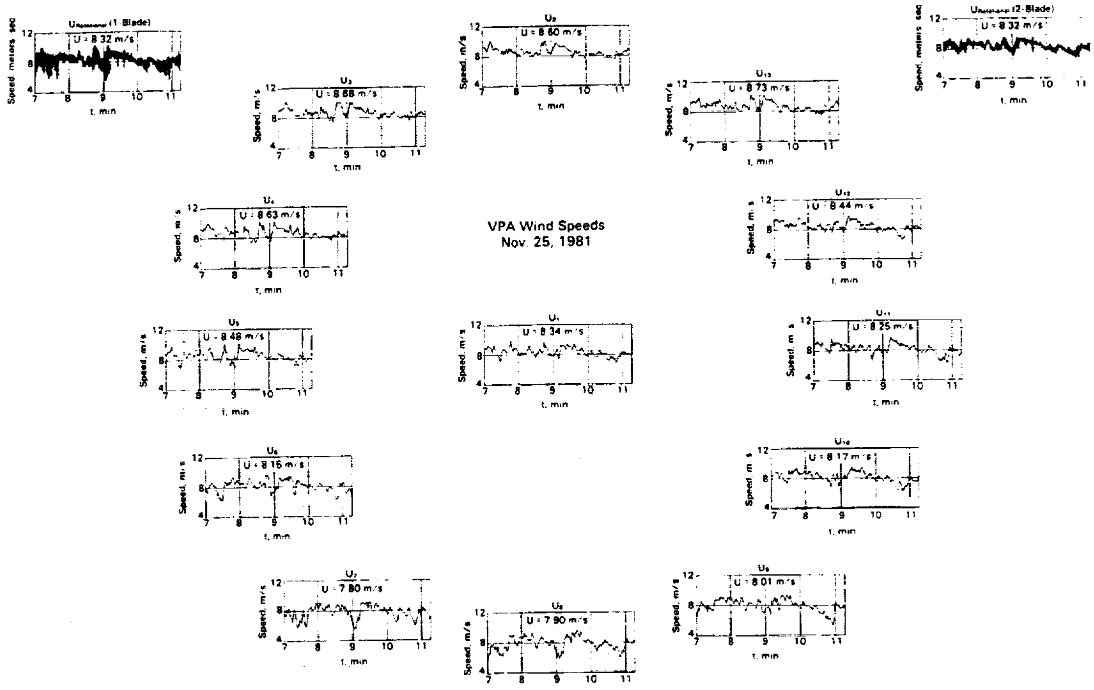

Figure 2--Graphs of axial wind speed as a function of time at each anemometer on the 37-m diameter vertical plane array

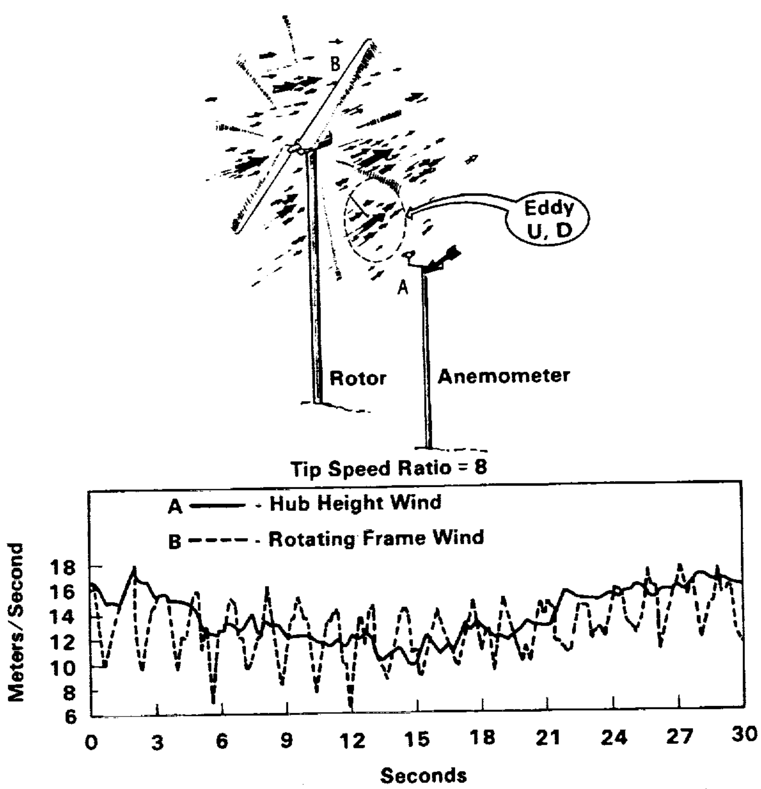

Figure 3--Schematic of wind at a wind turbine along with sample time series of real rotationally sampled wind speed

mean direction of the wind in the atmospheric boundary layer. To characterize a complicated time series of rotationally sampled wind speed fluctuations quantitatively, it is possible to separate the time series into a large set of long time series of simple sine waves, each with a distinct single frequency of fluctuation and each with a specific constant amplitude of fluctuation.

If the values of all of these sine waves are added together at each instant the resulting single time series is exactly the original complicated time series.

It is relatively easy to see the contribution of the sine wave components to the total turbulence because the frequency and amplitude of oscillation of each time series are easily and unambiguously quantified. The amplitude associated with each frequency is often given as the amount of fluctuating wind energy per unit mass of air per unit span of frequency-of-fluctuation. This is called the power spectral density of the wind speed. A single curve of the power spectral density of the wind, covering all frequencies of sinusoidal components, characterizes the original wind time series in a distinct and quantitative manner. Schematic examples of the power spectral density plots for wind at a single point at the hub height of a wind turbine and for the rotationally sampled wind at a point moving in a vertical circle around the hub are shown by the solid curve in Figure 4.

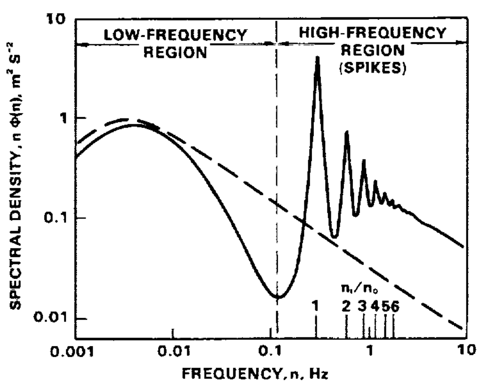

Figure 4--Schematic example of power spectral density graphs of single point wind speed (dashed curve) and rotationally sampled wind speed (solid curve)

The high-frequency region of the spectrum extends from half the frequency of rotation, 0.5 n(0), to the highest frequencies. In a more detailed classification, a midfrequency region surrounding the dip at the boundary between the low and high frequency regions of the spectrum is included. The regular set of spikes in the high frequency region is often labeled according to their center frequency, nondimensionalized by the frequency of the rotation rate of the rotor. These frequencies are called the 1-P, 2-P, ... [n(i)/n(0)]-P frequencies corresponding to the nondimensionalized frequencies marked and labeled in the lower right portion of the graph in Figure 4.

The main difference between the spectra for nonmoving and rotational sampling points is that the rotational spectrum has much more energy throughout the high frequency region. For rotational sampling, additional energy is concentrated in narrow bands, producing spikes at characteristic frequencies in the spectrum. Since rotational sampling does not produce turbulence, the total energy represented by the spectrum must not be different than the average of the energy of turbulence at the nonmoving points on the circle. This means that the fluctuations that are experienced at lower frequencies by nonmoving points are "shifted" to higher frequencies in specific ways by the rotational sampling. Of course the rotational sampling does incorporate energy of fluctuation relative to the blade due to movement through the mean wind shear, but, as we shall see, even the rotational spectrum for turbulence and no wind shear looks like that shown in Figure 4.

The drawing of the wind turbine rotor in Figure 3 indicates the complex wind distribution the rotor experiences. The demonstrated character of the rotationally sampled wind led us to assert that measured response of a wind turbine was quite different than previously supposed and would correlate well with rotationally sampled wind, whereas it would not correlate well with wind measured at nonmoving points. An experiment set up at the MOD-OA turbine site in Clayton, New Mexico, confirmed the expectation and placed the concept of rotationally sampled wind on a firm foundation of observation and theory.

CORRELATION OF ROTATIONALLY SAMPLED WIND TO MEASURED MOD-OA RESPONSE

A vertical plane array of propeller anemometers on seven towers was installed two rotor diameters upwind of the MOD-OA wind turbine as shown in Figure 5. The circle of anemometers was centered on hub height with a radius equal to the rotor radius. Electrical signals representing time series of a few rotor response variables and generator power output were provided by NASA to be recorded digitally at fast sampling rates by PNL. The wind velocity data from the VPA were also recorded digitally at suitable rates on the same magnetic tape.

The flatwise root bending was expected to reflect most directly the fluctuations of the axial wind. (In fact we suggested the idea that the wind turbine should be its own best anemometer through flatwise root bending of the blades, torque of the rotor, and power out of the generator.) The spectra of the flatwise root bending moment for three different wind conditions are shown in the top row of Figure 6. The corresponding spectra for the power out of the generator are shown in the bottom row of Figure 6. The detailed similarity of the bending moment spectra to the rotationally sampled wind speed spectra previously discussed is strong. Figure 7 contains the spectra for the rotationally sampled wind corresponding to the three cases of Figure 6. The upper row of graphs is for the wind as measured; the lower row of spectra have the effect of mean wind shear removed. If one were to overlay the upper row of wind spectra on the flatwise root bending moment spectra of Figure 6, the two would appear to be nearly identical out to at least four times the rotation frequency of the rotor, and to be similar at higher frequencies. In the lower set of wind graphs, the mean wind shear appears to have the greatest effect for the case with a stably stratified atmosphere. In the neutral and unstable cases, the mean wind shear apparently has a much more moderate role in wind fluctuation effects on the turbine rotor.

This direct correlation between turbine and wind, without benefit of a transformation of the wind into turbine rotor response through an aerodynamic model and a mechanical model of the MOD-OA, is quite instructive, but less complete than desired. Efforts initiated by PNL to compute a suitable transformation from the wind have not yet been brought to a satisfactory completion. However, we have brought

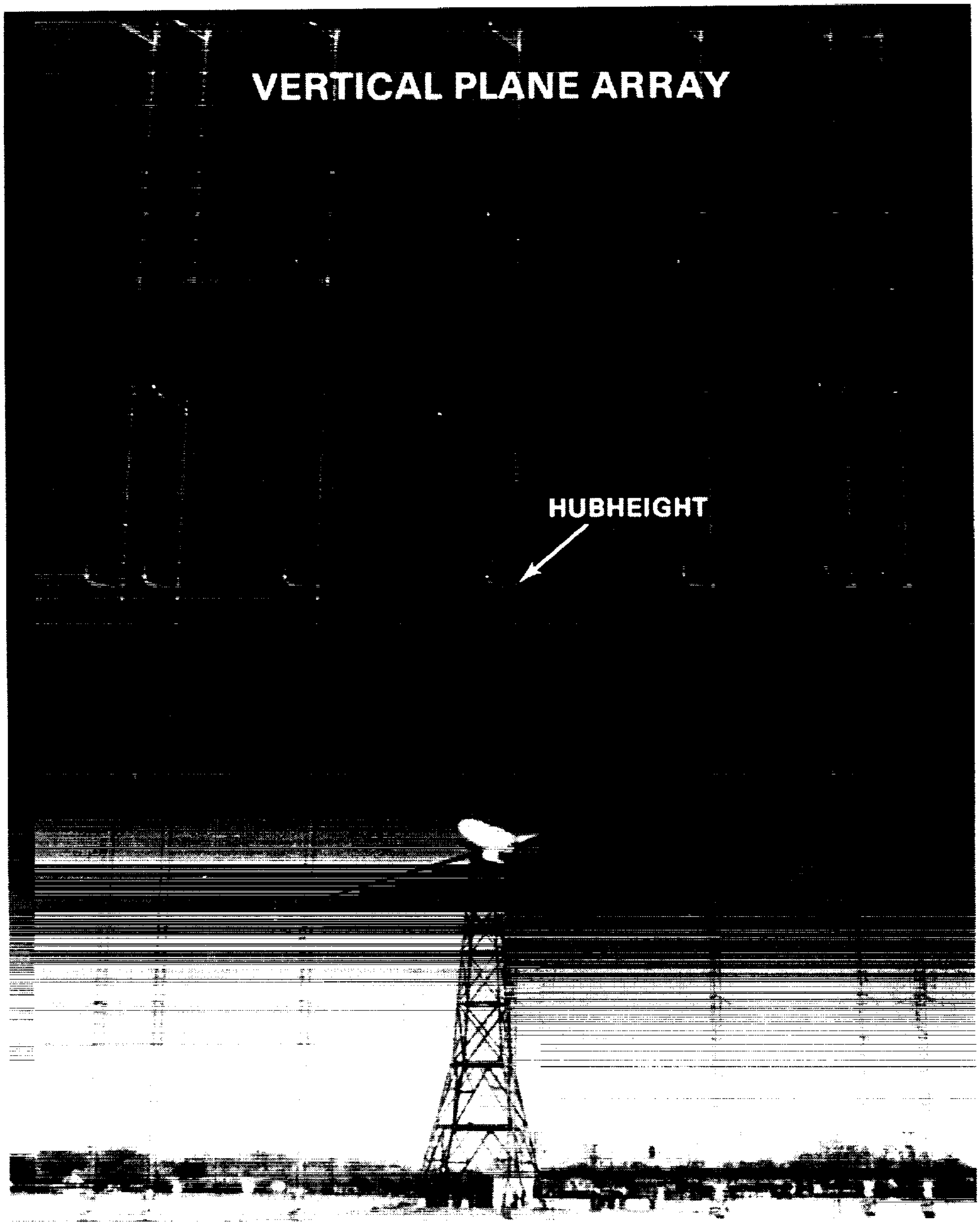

Figure 5--Photograph of PNL seven-tower vertical plane array near the 200 kW MOD-OA at Clayton, New Mexico

wind theory far enough that a test of the theory against the wind measurements using the Clayton VPA has been fruitful. The theory of the rotationally sampled wind spectrum is discussed in the next section.

THEORY OF THE SPECTRUM OF ROTATIONALLY SAMPLED WIND SPEED FLUCTUATIONS

A theoretical description of the rotationally sampled wind speed is useful for verifying the rotational analysis of measurements from the VPA or direct rotational measurements of the wind. The theory is especially helpful if there is concern that the effect of measurement or analysis errors on the character of the measurement-derived wind time series is significant. A tested wind theory is also a potentially convenient and low-cost tool for use in design and analysis of wind turbine response. Three approaches were initiated to develop a theory of the rotationally sampled wind speed spectral density function. Two of them represent the relation between the wind simultaneously at several radial locations but with, as yet, inadequate accuracy.

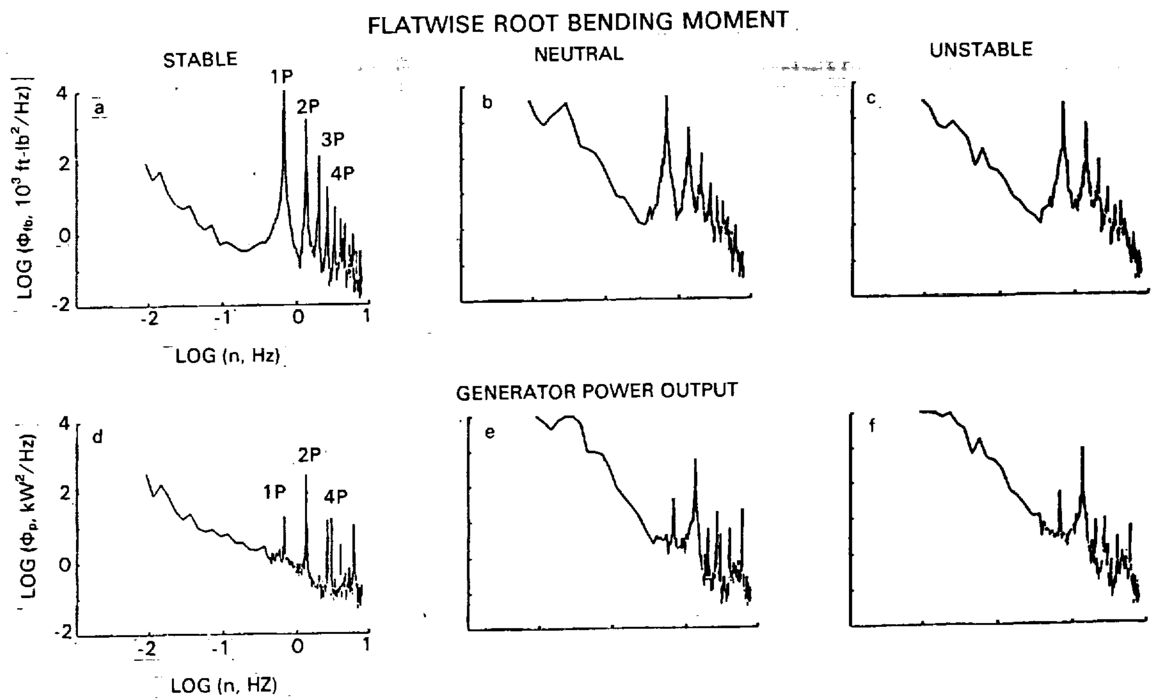

Figure 6--Power spectral density graphs of MOD-OA response to wind for three wind conditions. Top row: flapwise root bending moment. Bottom row: generator power output.

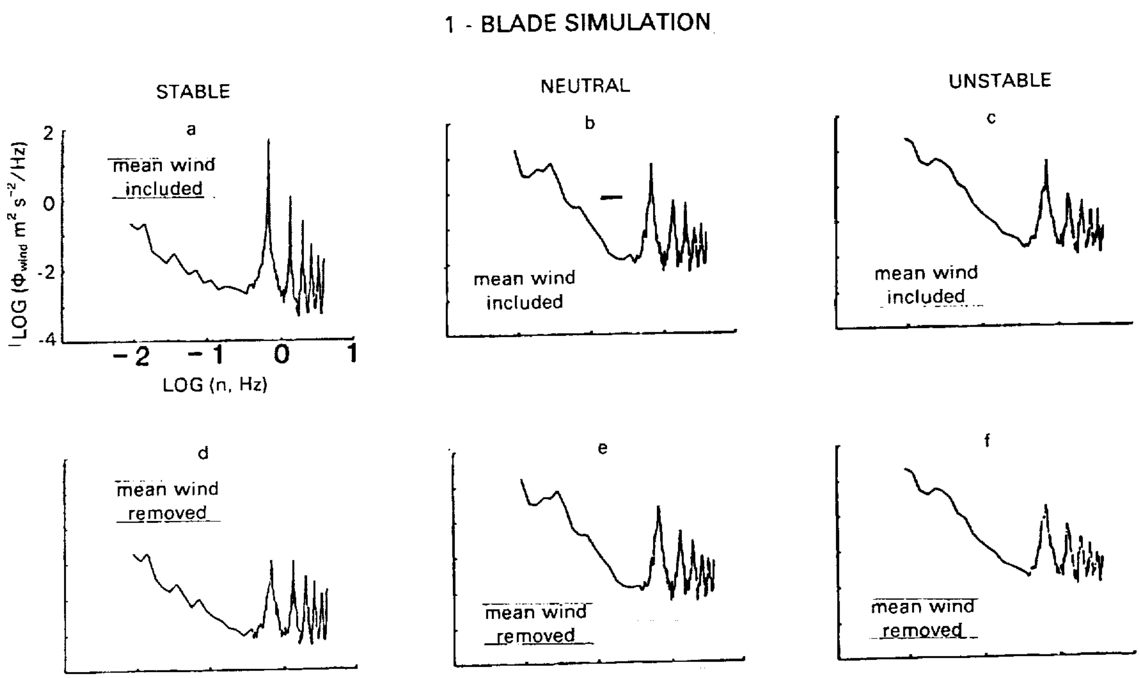

Figure 7--Power spectral density graphs of rotationally sampled axial wind speed corresponding to the MOD-OA response graphs in Figure 6. Top row: complete wind. Bottom row: mean wind shear effect removed.

Of the three theoretical constructs, at this time the simplest one results in the most accurate and complete spectrum. It is also the least costly to calculate using a digital computer. It was formulated in cylindrical coordinates with economy and accuracy for rotor problems in mind. It has the present restriction that it does not give the phase relation between the wind at several radial locations.

An example of the theoretical spectral density of the axial wind speed compared to the spectrum calculated from measurements of axial wind using the VPA at

Clayton is shown in Figure 8. The goodness of this comparison is taken to confirm the concept of the rotationally sampled wind and to indicate the accuracy of the theory for normal wind conditions. A quantitative comparison between measurement and theory is conveniently made using integrals of the spectra over small bands of frequency surrounding individual spikes of the spectra. The magnitudes of energy of fluctuation that result, called partial variances, are plotted as a function of center frequencies in Figure 9. Comparisons for the three different atmospheric stability cases are shown in the three graphs. Theory deviates the most from measurement for the case of stable stratification, for which the basic assumptions of the theory are least suited.

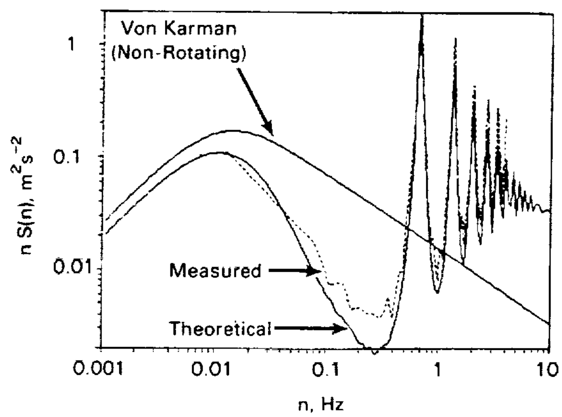

Figure 8--Comparison of theoretical power spectral density function of rotationally sampled wind speed for a MOD-0A wind turbine with rotationally sampled wind speed measured at the MOD-0A vertical plane array. Nearly neutral case.

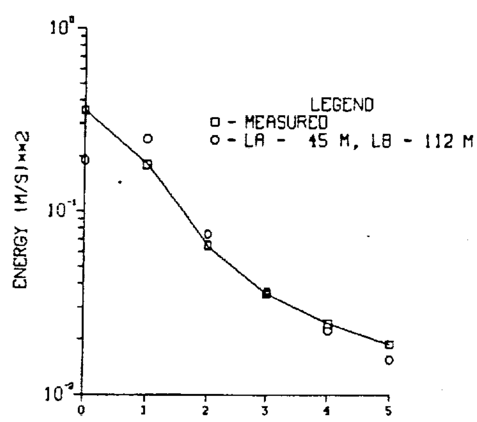

Figure 9--Theoretical variance of rotationally sampled wind speed for each spectral spike compared with the corresponding variance of wind speed measured at the MOD-0A vertical plane array. Nearly neutral case.

A SINGLE TOWER MODEL OF ROTATIONALLY MEASURED WIND SPEED

For conditions of terrain or atmospheric stability in which the present theory is unsuitable and a full rotational measurement of the wind is not possible, it would be helpful if turbulence data from several heights on a single tower could be analyzed to give a useful approximation. A model, STRS-2, was developed using wind measurements from the center tower of the VPA at Clayton.

The wind speeds at the VPA center tower were composited into the STRS-2 model of a rotationally measured time series using a special type of rotational sampling of the data from anemometers, with appropriate lead times and lag times at different heights. The result, compared to the spectra derived using the full VPA, is shown for three stability conditions in the spectra in Figure 10. The model is suitable for some purposes without correction; correction factors were also developed for the MOD-0A rotor diameter and hub height and the wind conditions at Clayton. However, the applicability of the model and correction factors to other sizes of turbines and other wind conditions is unknown.

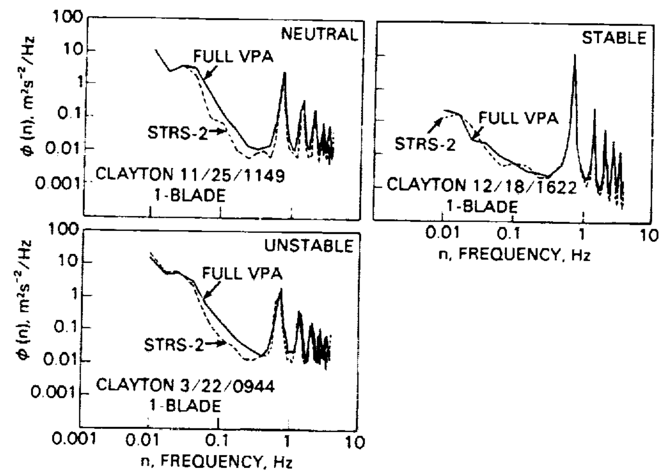

Figure 10--STRS-2 model rotationally sampled wind spectra derived from anemometers on a single meteorological tower compared to full vertical plane array rotational spectra

The need to test existing models of rotationally sampled wind characteristics scaled up for turbines larger than the MOD-0A led to additional measurement programs using wind velocity sensors whose use for the larger turbine geometries is more economical than use of propeller anemometers on arrays of towers. The remainder of this paper discusses results from the use of fast-responding hotfilm anemometers placed on rotating booms and on a MOD-2 rotor, 300 feet in diameter.

HOTFILM ANEMOMETER ROTATIONAL MEASUREMENTS OF THE WIND

To make rotational measurements of the wind at a location very near a rotating blade with acceptable economy and accuracy, the hotfilm anemometer was specialized and tested using a rotating boom apparatus similar to the one shown in Figure 11. The tiny wind velocity sensor is placed on a probe extending ahead of the leading edge of the boom, which is rotated at known speed using an electric motor. The three components of the wind relative to the moving sensor, which were measured under light wind conditions, are characterized by the three spectra shown in Figure 12. These spectra are for the horizontal axis

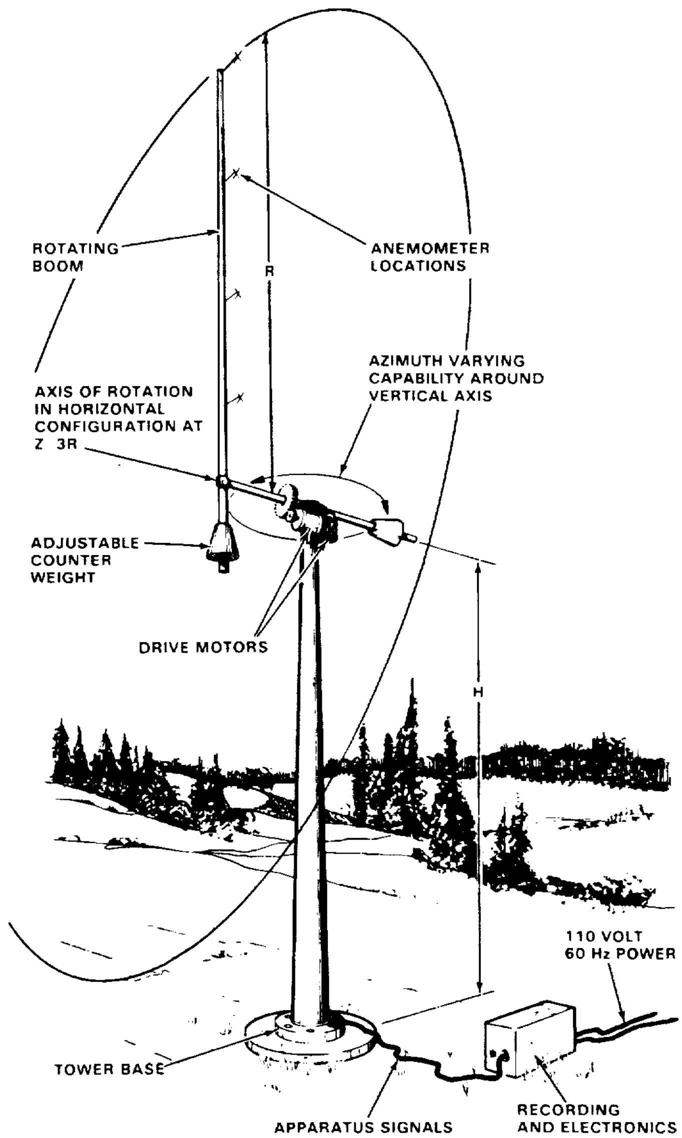

Figure 11--Picture of a rotating boom apparatus for rotational measurement of wind velocity and testing of turbulent wind velocity sensors

of rotation configuration. The results verify the earlier rotational sampling results from the VPAs. The hotfilm measurements require precise calibration and data reduction to achieve the required accuracy of measurement. One useful demonstration of the accuracy that may be achieved is the comparison of wind measurements made using two hotfilm anemometers placed 6 inches apart at the tip of the rotor on the rotating boom apparatus. The results for one example are shown in Figure 13. The axis of the rotating boom was vertical for this example. Thus the sensors traveled in a horizontal circle, moving with and against the wind at opposite sides of the circle. The mean wind speeds relative to the sensors for a 6-minute period are identical for the two sensors with an error of less than 0.5%. They also agree with the relative wind speed calculated as the product of boom radius and rotation angular velocity.

The time series of speed of the tangential wind speed for the two anemometers shown in the top graph of Figure 13 indicate that the measurements are nearly identical at each instant. The cross-disk or transverse velocity time series are also nearly identical. The main difference is due to slight differences in angle of attack of the two anemometers as indicated by the nonzero magnitudes of the mean transverse velocities. These geometrical problems may be resolved in the computational data reduction phase of the wind data analysis.

With the knowledge that highly accurate rotational measurements of the wind velocity could be made with the hotfilm anemometers, we initiated measurements of the wind at the blades of a MOD-2 wind turbine, 300 feet in diameter. Some results from a pilot study at Goodnoe Hills, Washington, are discussed in the next section.

ROTATIONAL MEASUREMENTS OF THE AXIAL WIND SPEED OF A MOD-2 WIND TURBINE ROTOR

Pilot measurements at the MOD-2, unit number 2, at Goodnoe Hills were made in August 1983. The location

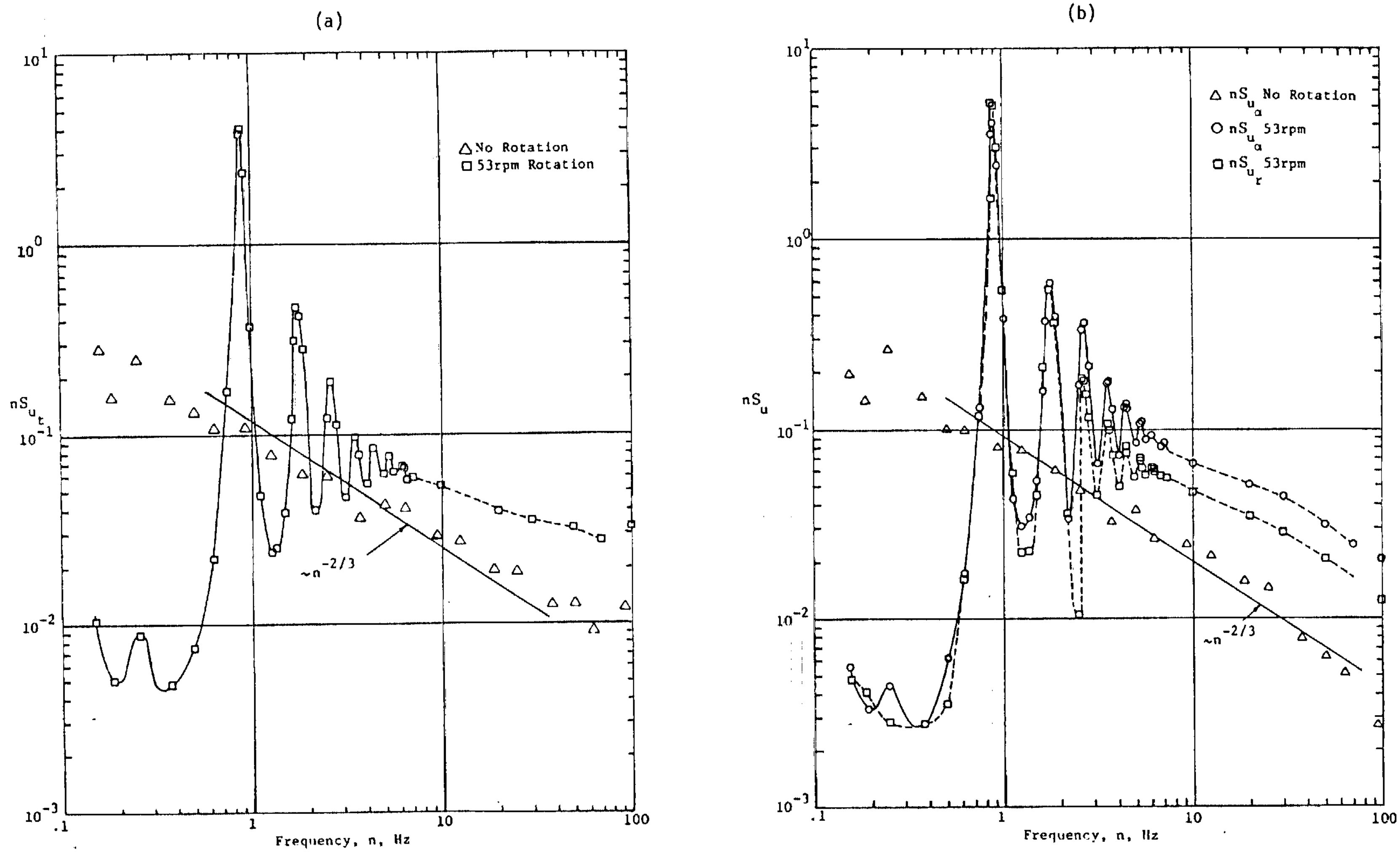

Figure 12--Power spectral density curves of three orthogonal components of the wind velocity rotationally measured with hotfilm anemometers on the PNL rotating boom in horizontal axis configuration a) wind tangential to sensor rotation path b) wind radial and wind axial to rotation circle

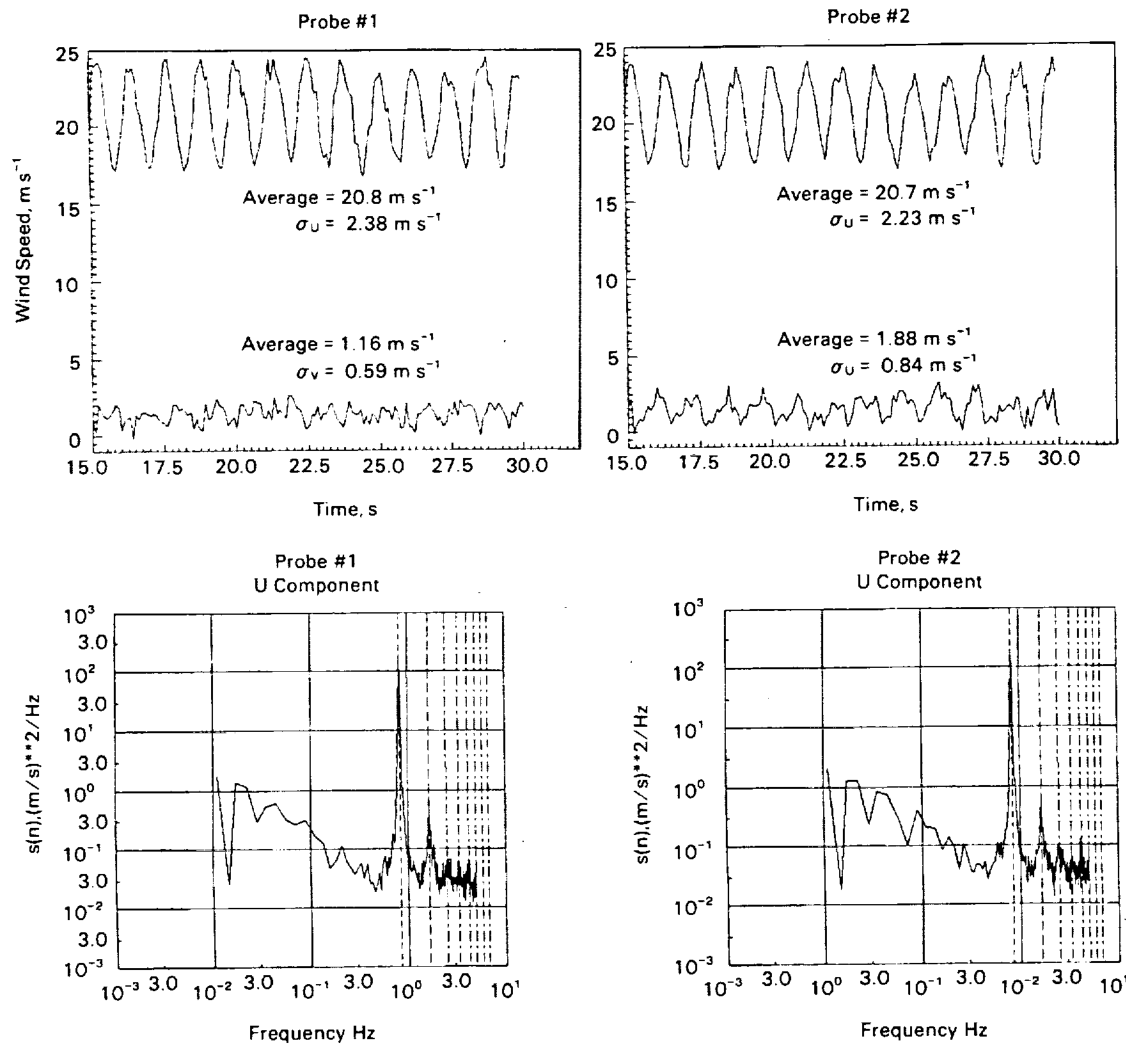

Figure 13--Comparison of time series and spectra of wind velocity components rotationally measured by two side-by-side hotfilm anemometers on a vertical axis rotating boom. Top two graphs: tangential wind speed. Bottom two graphs, axial (cross disk) wind speed.

of hotfilm anemometer booms on the rotor is shown in Figure 14. One probe was placed at the 0.7 radius position on each blade. Another pair of probes was placed at the 0.2 radius positions on the rotor. (These locations were dictated by the availability of attachment structures for use in the pilot program.) The wind velocity was thus measured relative to the motion of the rotor. That motion included rotation, teeter and blade bending.

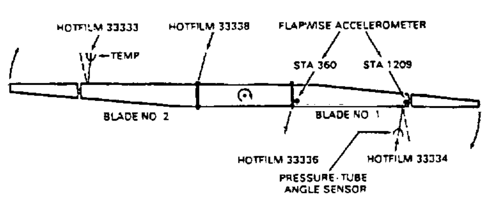

Figure 14--Location of hotfilm anemometers on the rotor blade for the 1984 pilot study at the MOD-2 #2 wind turbine at Goodnoe Hills

As we expected, we observed rotationally measured wind spectra that look somewhat like the spectra for rigid rotors discussed previously, but with some deviations in spectral energy distribution due to the teeter and flap motions. Also, we expected from theory to observe spectral shapes at an 0.7 R location distinctly different from those at an 0.2 R location. This latter expection is demonstrated in Figure 15, which contains plots of the theoretical rotationally sampled wind speed spectrum. They were calculated for 10 radial locations along a blade of a MOD-2 for typical turbulent wind conditions in simple terrain. The rotational sampling effect is diminished at the 0.1 R and 0.2 R locations especially because the linear speed of rotation of the sensor at these small radii is small.

One example of the actual spectral density functions of the axial or cross-disk wind measured rotationally from each of the four locations on the rotor is shown in Figure 16. The expection that the inner radial location would experience diminished rotational effect at frequencies higher than the rotation

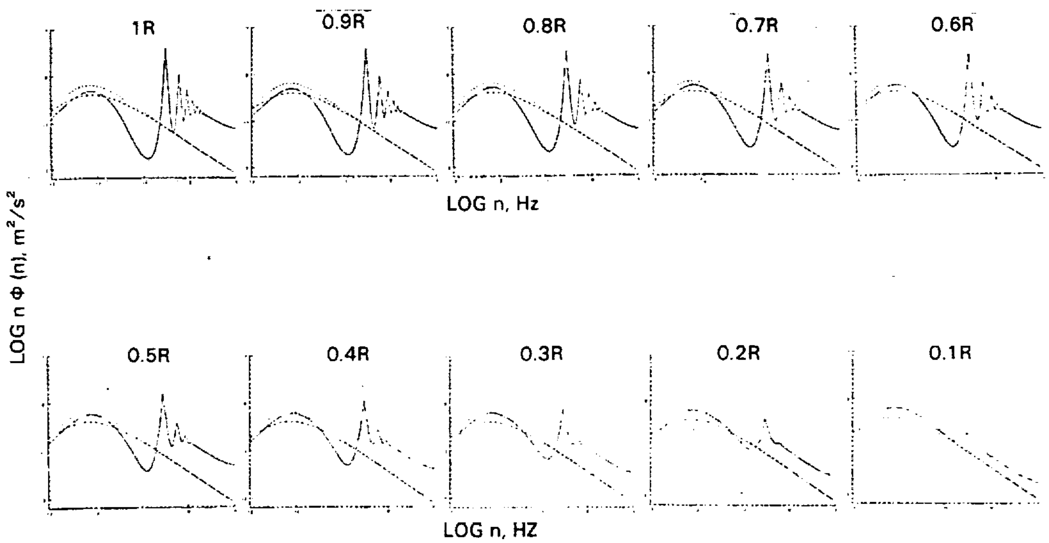

Figure 15--Expected radial distribution of power spectral density functions of the rotationally sampled axial wind speed derived from PNL theory. Neutral case.

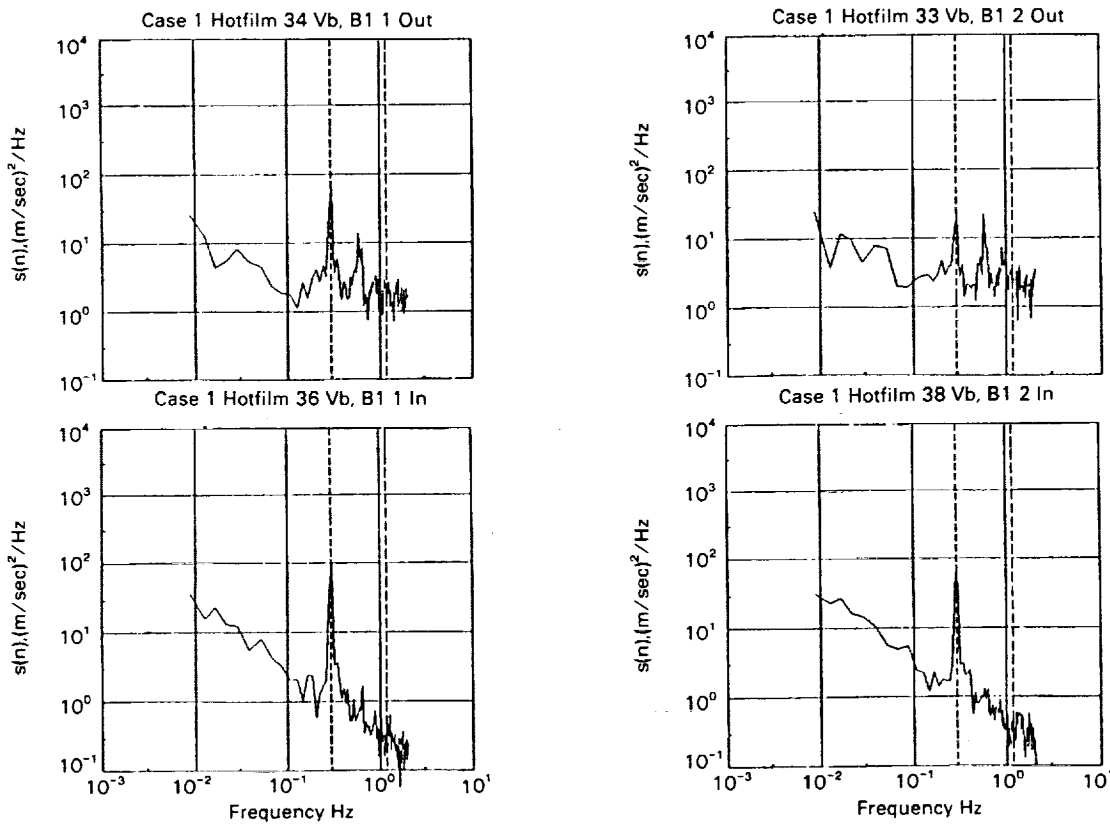

Figure 16--Power spectral density functions of rotationally measured axial wind speed at four diametral locations, for MOD-2 #2 wind turbine. Neutral case.

frequency of the rotor is clearly verified. The large spikes in the spectra at 0.2 R at the frequency of rotation of the rotor were not predicted by the theory. However, the theory did not include modified mean wind shear caused by flow induced by the nacelle, the tower and the inner sections of the blades of the turbine.

The spectra for the wind at the 0.7 R locations on each blade are nearly identical to each other. The differences may be due to differences in motion and orientation of the two blades. Compared to the spectra obtained from the VPA, rotating boom, and theory, the MOD-2 wind spectra at 0.7 R have substantial differences in the high frequency spikes. One reason for the differences is that the VPA and rotating boom winds were measured and analyzed relative to coordinate systems that were rigidly fixed in a single plane. Similarly, the theoretical model was applied to the rigid rotor case. However, the sensors of wind for the MOD-2 were attached to a teetering and bending rotor blade. This may be the reason why the spectra for the MOD-2 have relatively smaller spikes at 1P (teeter), 3P and 4P (flapwise or axial blade bending). Nevertheless, the sensors measure the wind experienced immediately ahead of the rotor blades, which is the correct location to describe the wind used in a time-domain aerodynamic model of the rotor.

A brief look at the MOD-2 flapwise blade bending moment spectra in Figure 17, corresponding to the wind spectra in Figure 15, is instructive. The root bending moments for the two blades are shown in the bottom two graphs. They are identical, perhaps due to the effect of rotor teetering in forcing a sharing of the effect of the bending forces on each whole blade. The moments for the tip sections are not quite identical to each other; but they are not directly coupled to each other through the teetering mechanism. The spikes of the spectra around 1P and 2P are approximately of the same relative magnitude as they are in the wind spectra at the 0.7 R locations. The 3P response is light, reflecting the smallness of the wind spectrum spike and the lack of resonance at that frequency. The 4P blade spike is substantially larger than the corresponding wind spike, reflecting the first flapwise symmetric bending mode near that frequency.

These preliminary efforts at describing the relation of the blade bending spectra to the rotationally measured wind spectra need to be replaced by accurate dynamic modeling of the response of the turbine using a model that has been tested for a simpler wind turbine and simpler conditions for rotationally sampled wind measurements. The wind and turbine data that seem to be required for this first phase are available from the VPA experiments at the Clayton MOD-0A site. Some modeling of the MOD-2 case has begun at other laboratories.

EFFECTS OF ATMOSPHERIC TEMPERATURE LAYERING

The impact of atmospheric temperature stratification and of the attendant mean wind and turbulence stratification on the character of rotationally measured wind velocity is substantial. We would be negligent in not including at least an example of the effect in this paper. Figure 18 shows time series of the voltage signals from a hotfilm anemometer on the blade of the MOD-2 for four different examples of temperature layering in the atmosphere. In each case the voltage from film 2 is closely proportional to the wind velocity crossing the disk of the rotor.

In the strong inversion case at the top of Figure 18, the wind speed fluctuates with a dominant period equal to that of the rotation of the rotor. The amplitude is rather constant from cycle-to-cycle. Sometimes the variation is so smoothly sinusoidal that there appears to be no turbulence. At other times the turbulence and nonlinearity of wind shear are so great that the waveform is ragged or even

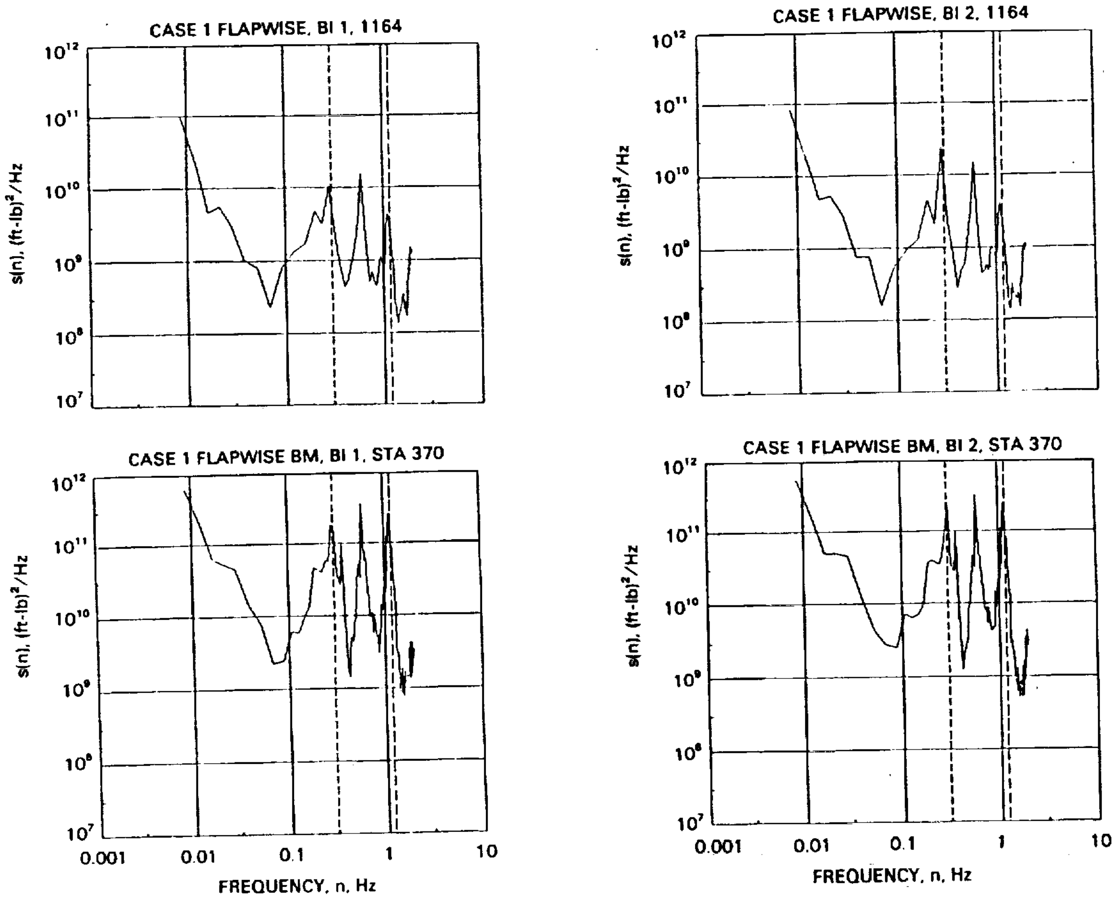

Figure 17--Power spectral density functions of blade flapwise root bending moment corresponding to the wind spectra in Figure 16.

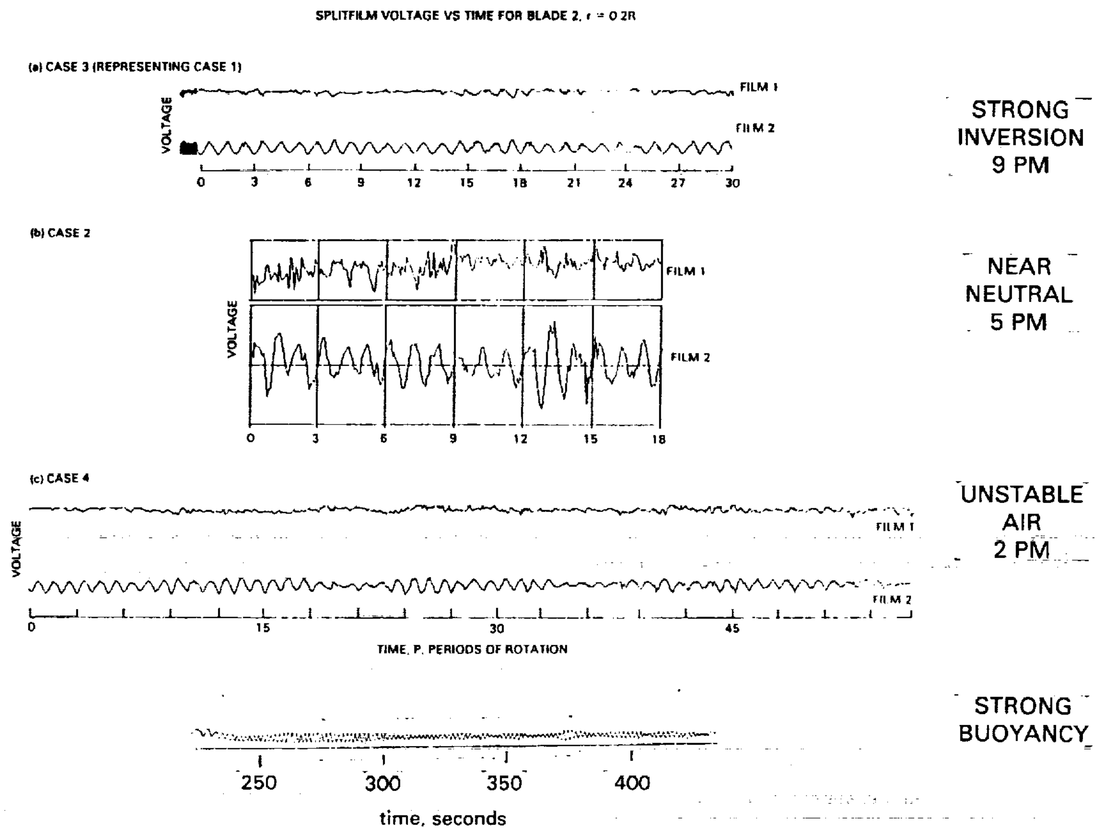

Figure 18--Hotfilm anemometer signals representing the different character of time series of rotationally measured axial wind speed for four different conditions of atmospheric static stability (temperature layering) at the MOD-2 #2 wind turbine

triangular. A more nearly neutral stability of the atmosphere results in turbulence that causes substantial random variations in the shape and amplitude of the cyclic wind time series. This is shown in the second graph, case 2. As the air becomes filled with buoyant motions during the heat of the day, the air is unstable. The character of the rotationally sampled wind then indicates the strong influence of the passage of large turbulent structures that modulate the wind fluctuations at the blade in a regular way. The last two graphs show that in unstable conditions the amplitude of the cyclic variations of the wind may occur in either of two modes. One simply appears to turn on and off the large constant amplitude fluctuations. The other produces a smoothly varying modulation of the cyclic amplitude.

Another factor that may strongly influence the character of the rotationally sampled wind is airflow over complex terrain. This is discussed briefly in the next section.

COMPLEX TERRAIN

Where airflow conditions are not simple (see topographic map of Goodnoe Hills in Figure 19), there is little information from theory or empirical models by which to estimate the character of the turbulent wind. It is not yet known how the changes in character of the wind modify the rotationally sampled wind. What can be shown are the differences in profiles of the mean wind speed and wind speed variance about the mean at different locations in the complex terrain at Goodnoe Hills, Washington. From the differences one can conclude that there is a need for further research on both complex terrain wind characteristics and rotationally sampled wind at turbine rotors in complex terrain.

In support of this conclusion, consider the vertical profiles of wind at Goodnoe Hills shown in Figure 20. The measurements were made at the three sites identified as PNL, BPA and Acoustic Sounder in the map in Figure 19. Substantial differences are indicated to be due to the separation of the measurement locations by horizontal distances of a few rotor diameters and by vertical distances of a few tens of feet. The meaning of these spatial differences for the character of the rotationally sampled wind is indicated by the theoretical spectra plotted in Figure 21.

The plotted rotational spectra are for a single turbine rotor at the same mean wind speed and same vertical profiles of mean wind and variance. The difference in wind for each spectrum is the length scale characterizing the turbulence elements comprised in the flow. Clearly, substantial effects occur that might not have been expected. Complex terrain can modify length scales of turbulence to create such deviations in character.

CONCLUDING REMARKS

The objective of this paper has been to provide some insight into the basic principles of describing the

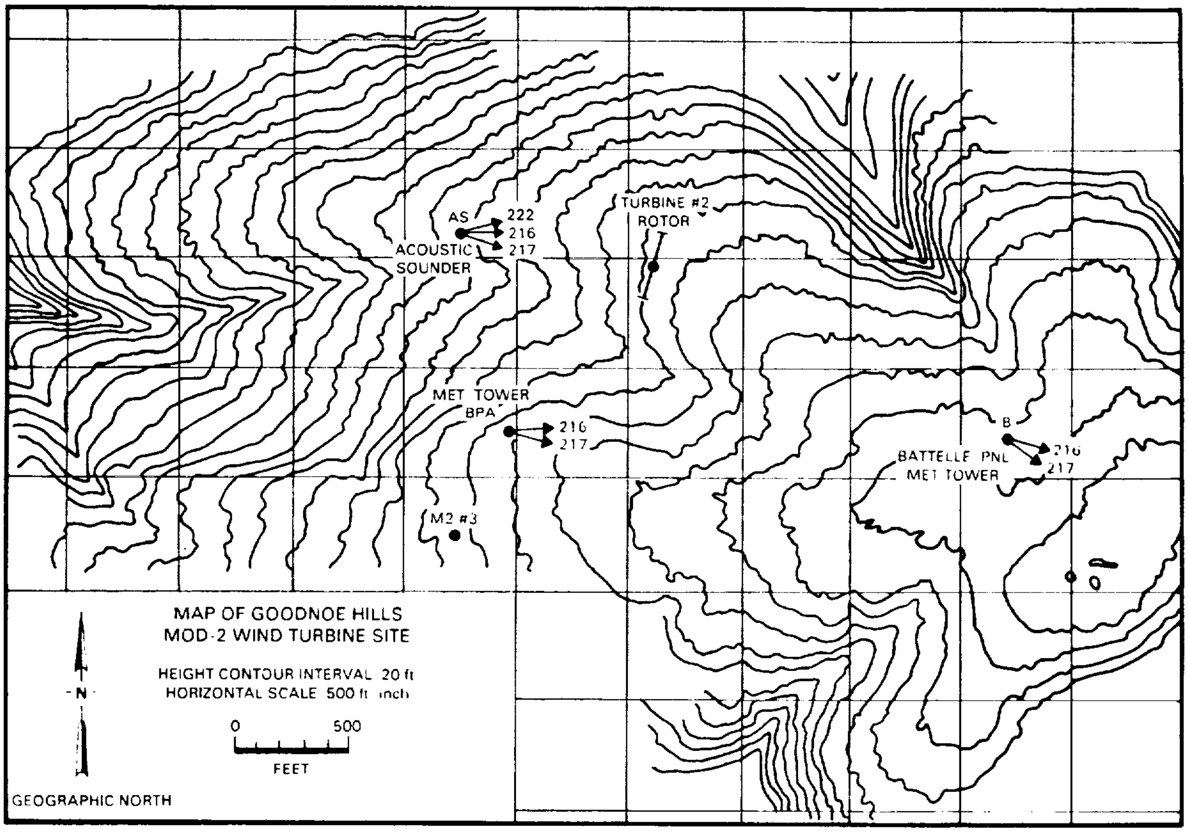

Figure 19--Topographic map of the MOD-2 site at Goodnoe Hills, Washington, showing the location of PNL and BPA meteorological towers and of the acoustic doppler wind velocity profiler relative to MOD-2 #2 location

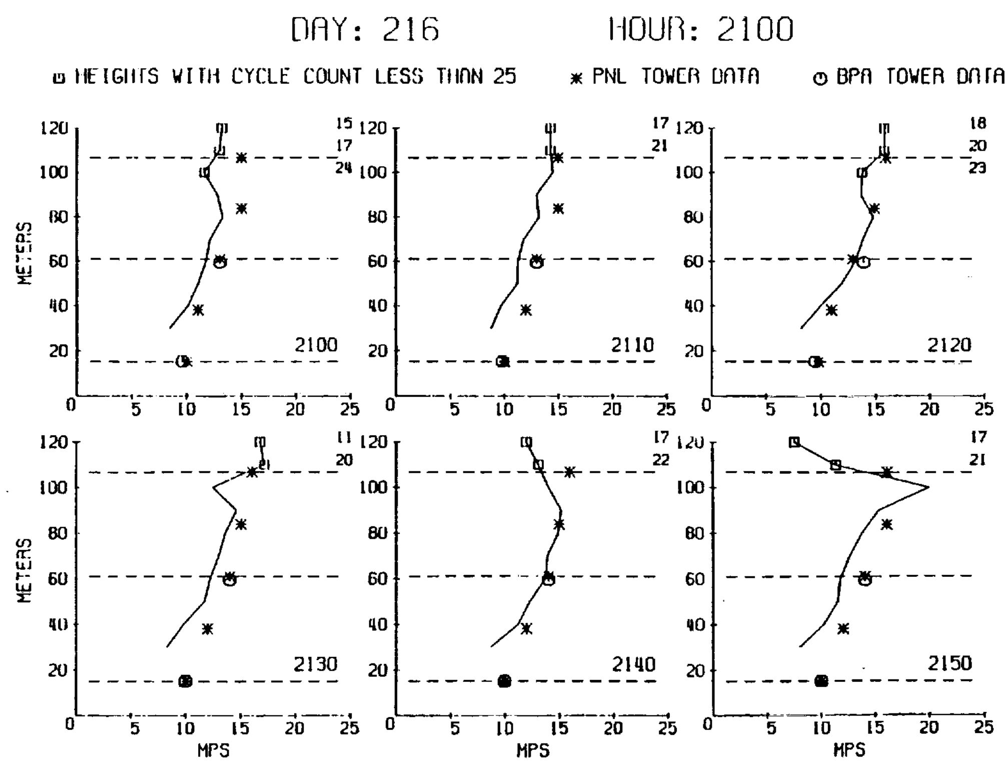

Figure 20--Examples of 10-minute average vertical profiles of wind speed measured at three different locations (PNL, BPA and Acoustic) in the topography of Goodnoe Hills, Washington

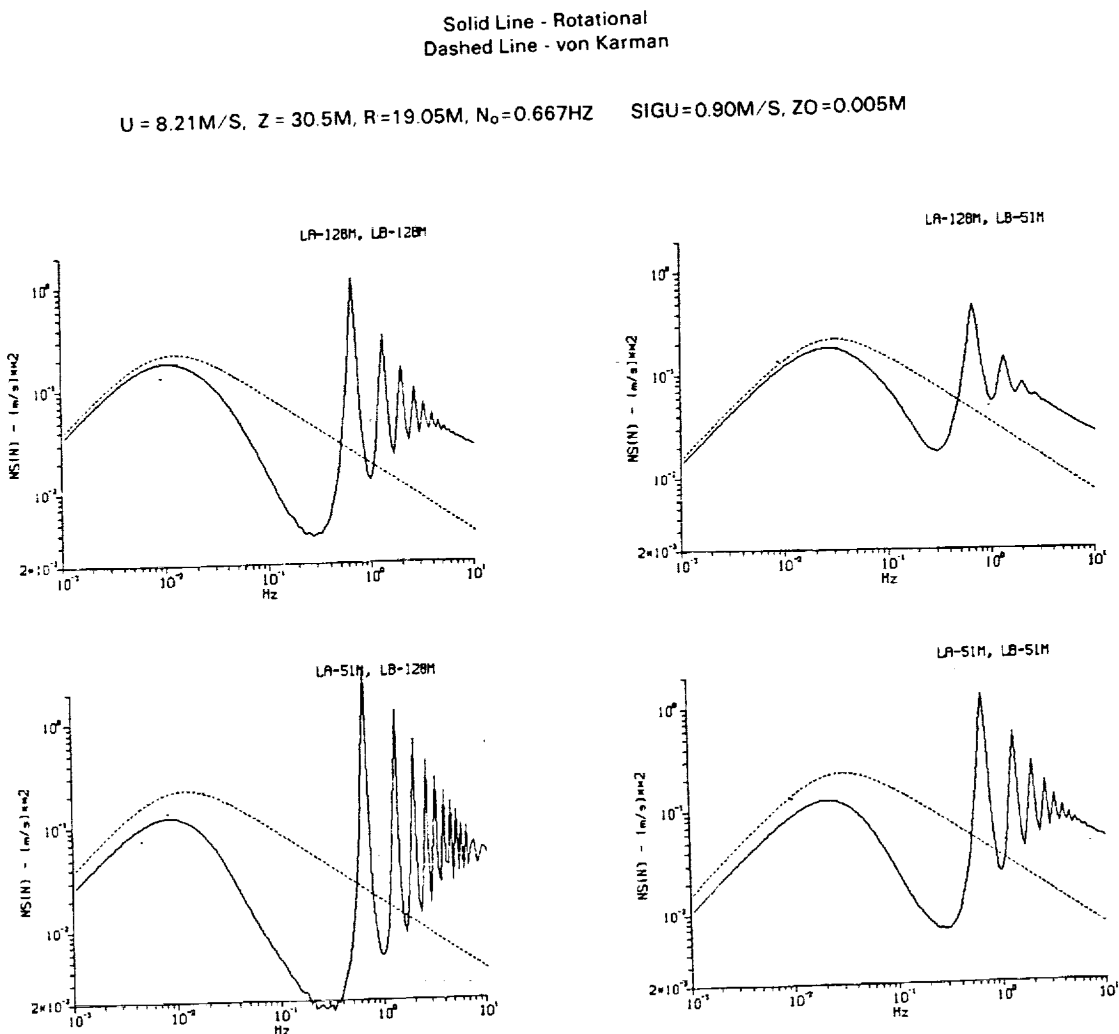

Figure 21--Effect on the theoretical spectrum of rotationally sampled wind speed at a MOD-OA wind turbine due solely to changes in length scales of turbulent wind, simulating one effect of topography

wind fluctuations as they are experienced by a point on a rotating wind turbine blade. The method used in the previous sections was to outline the historical development of an understanding of the rotationally sampled wind and its relation to wind turbine response. Over the years, we have taken a rather wide-ranging, though limited because of programmatic constraints, approach to research into rotationally sampled wind and corresponding response of wind turbines (1,2). Those efforts are briefly recapitulated here.

The research at the MOD-OA in Clayton, New Mexico using a vertical plane array conclusively demonstrates the importance of rotationally sampled wind velocity in explaining the response of a wind turbine to the wind. The pilot research at the MOD-2 in Goodnoe Hills, Washington, using hotfilm anemometers attached to the rotor blades shows that a relatively economical set of rotational measurements of the wind velocity at the rotor of a large wind turbine can be made. The tests of the hotfilm anemometers at the PNL rotating boom apparatus demonstrate that the accuracy of the hotfilm measurements of wind velocity required for design and testing of wind turbines can be achieved and maintained.

We conclude that the PNL theory is sufficiently accurate at all frequencies of wind fluctuation of importance that its extension into the time domain from the frequency domain is warranted. That effort is in progress.

A final conclusion is that the effects of vertical variation of temperature and of complex terrain airflow on the character of rotationally sampled wind velocity are substantial, but are not well known qualitatively and are nearly unknown at the quantitative level. Our understanding of the character of the wind in simple terrain is substantial, requiring significant improvement primarily in understanding of radial variation of the wind velocity along the blade at each instant. Thus, practical use of theory and empirical models of rotationally sampled wind can be made at the present time. On the other hand, radial distributions of wind along the blade, including phase relationships or complex airflow cases, can be handled at the present time only by direct measurements of rotationally sampled wind velocity using the method described in this paper.

REFERENCES

1. Connell, J. R. "Turbulence Spectrum Observed by a Fast-Rotating Wind Turbine Blade", PNL-3426, Pacific Northwest Laboratory, Richland, Washington, 1980.

2. Connell, J. R. "The Spectrum of Wind Speed Fluctuations Encountered by a Rotating Blade of a Wind Energy Conversion System: Observations and Theory", PNL-4083, Pacific Northwest Laboratory, Richland, Washington, 1981.

3. Rosenbrock, H. H. "Vibration and Stability Problems in Large Turbines Having Hinged Blades", C/T 113, ERA Technology, Ltd., Surrey, England, 1955.

ACKNOWLEDGEMENTS

A pioneering bit of theory has lain buried in a small section of a Doctoral Thesis and a report by H. H. Rosenbrock that were published in 1955 in England (3). Rosenbrock's work was brought to light after the first PNL measurement results were published and interpreted in terms of physical processes in the wind.

This project was sponsored by the U.S. Department of Energy. Pacific Northwest Laboratory is operated for the U.S. Department of Energy, under Contract DE-AC06-76RLO 1830, by Battelle Memorial Institute.