18E

PNL-3426

UC-60

Turbulence Spectrum Observed by a Fast-Rotating Wind Turbine Blade

J. R. Connell

June 1980

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

PNL-3426

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

The views, opinions and conclusions contained in this report are those of the contractor and do not necessarily represent those of the United States Government or the United States Department of Energy.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$_____ *: Microfiche \$3.00

*Pages	NTIS
	Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

3 3679 00054 4900

TURBULENCE SPECTRUM OBSERVED BY A
FAST-ROTATING WIND TURBINE BLADE

J. R. Connell

June 1980

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

ACKNOWLEDGMENTS

The help of J. C. Doran in the acquisition and assurance of quality data from the vertical plane array in May 1979 and in playing devil's advocate, and of David C. Powell in computing the spectral density curves of the time series of wind speed from that data, are gratefully acknowledged.

Discussions with Sten Frandsen and Carl Jørgen Christensen at Risø in Denmark were especially stimulating.

SUMMARY

The spectrum of turbulence encountered by a point on a fast-rotating wind turbine blade is shown to be possibly quite different from that measured by a stationary anemometer. The physically reasonable expectations are supported quantitatively by experiments using Pacific Northwest Laboratory's vertical-plane anemometer array. The measurements indicate that the blade encounters energy densities in two regions of the turbulence spectrum much different than those seen by stationary anemometers.

For typical turbine types and wind conditions, the spectral energy redistribution phenomenon may be significant only for turbine blade diameters larger than 10 m. The spectral shift should also affect gust statistics for rotating blades; the duration of gusts that are smaller than the diameter of the disk of blade rotation will decrease. Correspondingly, the rise rate will increase by a factor of about ten.

CONTENTS

	<u>Page</u>
ACKNOWLEDGMENTS	iii
SUMMARY	v
LIST OF FIGURES	ix
INTRODUCTION	1
CONCLUSIONS AND RECOMMENDATIONS	3
SPECTRAL REDISTRIBUTION DUE TO CIRCULAR SAMPLING OF WIND SPEED	4
ESTIMATING WHICH WIND TURBINES WILL EXPERIENCE SPECTRAL REDISTRIBUTION	9
EXPECTED MODIFICATION OF GUST CHARACTERISTICS DUE TO CIRCULAR SAMPLING OF WIND	12
REFERENCES	13
APPENDIX	A-1

LIST OF FIGURES

	<u>Page</u>
1 Graphic Representation of the Relation Between the Input Turbulence Spectrum and the Output Torque Spectrum of a WECS	1
2 A Schematic Illustration of the Type of Modified Spectrum That May be Observed at a Point on a Rotating Blade	4
3 The Effect of Frequency of Turbulence Energy on Increasing the Amount of High-Frequency Energy of Fluctuation in the Turbine Output Torque	6
4 Spectra for Rotationally Sampled Wind Speed Fluctuations	8
A-1 Location of 3-D Anemometers in the Vertical Plane Array	A-2
A-2 Spectra Calculated from Measured Winds at the Vertical Plane Array	A-3
A-3 Schematic Comparison of Eulerian Spectra at Single Points, an Average of Spectra Experienced for Equal Time at Each of the Points Around the Ring and a Spectrum of Ring-Average Turbulence	A-4
A-4 Frequency Shifting of a Spectrum From That Seen by a Stationary Observer to That Seen by an Observer Moving With a Fixed Velocity	A-10

INTRODUCTION

Fatigue, power output quality and control systems of wind energy conversion systems (WECS) each may be influenced quite strongly by atmospheric turbulence. For design purposes it is important to know how the turbulence energy is distributed among all frequencies of fluctuation. For example, suppose that the WECS input-output response for transforming turbulence energy to torque at the WECS shaft is represented by a transfer function, $H(n)$ where n is the frequency of fluctuation. The input turbulence energy to the WECS is represented by the spectral density function, $S(n)$. The output torque fluctuation will have a spectral distribution represented by

$$T(n) = H(n) S(n),$$

if the system responds linearly. This is shown schematically in Figure 1. (The graph scales are logarithmic.)

FIGURE 1. Graphic Representation of the Relation Between the Input Turbulence Spectrum and the Output Torque Spectrum of a WECS. The hatched region represents the portion of turbulence that will not affect the shaft torque for the threshold and transfer functions specified.

Figure 1 shows a machine transfer function, plotted as a solid line, and a spectral density function of wind speed fluctuations, plotted using a solid line with dots. The product of these two graphs results in the torque spectral density function, plotted using a dashed line. Since both the transfer function and the turbulent wind spectrum decrease rapidly at high frequency, their product decreases even more rapidly. The horizontal line indicates the designer-specified lowest magnitude of torque fluctuation that is significant to the WECS. Frequencies higher than that which correspond to the torque cutoff magnitude will not be important. Recent work at the Pacific Northwest Laboratory (PNL) has shown that a rotating blade may experience turbulence such that the spectrum increases rather than decreases in the frequency region where a typical design cutoff frequency exists, which implies that the higher frequency component of fluctuation perhaps should not be neglected or "cut off".

It appears that the use of stationary point, or Eulerian, spectra of turbulence for rotating blade analyses can result in large inaccuracies in design. This paper presents evidence that the distribution of energy in a spectrum of the turbulence experienced by a rotating wind turbine blade can differ significantly from the spectrum of turbulence of the same wind observed by fixed objects. Several criteria are given for estimating whether the turbulence spectrum observed by each specific rotating turbine blade may be altered by the rotation. Finally it is pointed out that gust characterizations of the turbulence that affect wind turbines will be quantitatively altered when the effect of rotating blades is taken into account.

CONCLUSIONS AND RECOMMENDATIONS

The graphs and equations in the paper are intended only as first estimates. Tests of their validity have begun, using the PNL vertical plane array data. A physical and mathematical theory is also being developed for comparison with observations.

The perhaps unusual procedure of publishing these early and tentative results may have merit in both stimulating further consideration by designers of the real processes occurring at a WECS blade and in providing us at PNL with more rapid feedback. The best measurements of the turbulence experienced by a rotor are to be made at or by the blades themselves. Such measurements should be the next step in our improving ability to provide useful wind characteristics.

SPECTRAL REDISTRIBUTION DUE TO CIRCULAR SAMPLING OF WIND SPEED

Rotational motion of a large blade causes a nonuniform upward shift in the frequency of the turbulence energy seen by the blade. In effect, energy is removed from the middle of the Eulerian spectrum and placed at frequencies up to a factor of ten greater. Figure 2 illustrates schematically a change in the turbulence spectrum that might occur when the observation point changes from a stationary point to a point fixed to a rotating WECS blade. The spectral densities are weighted by the frequency and both coordinates are plotted on a logarithmic scale, following atmospheric science convention.

FIGURE 2. A Schematic Illustration of the Type of Modified Spectrum That May be Observed at a Point on a Rotating Blade. It is compared with spectra for point and ring-average Eulerian turbulence.

A detailed theory is not derived in this paper, although an heuristic explanation is presented in the Appendix. The principal concept is that a rotating blade traverses small eddies in the wind much more rapidly than the rate at which the wind carries them past a stationary point.

The spectral transformation observed from or by the rotating blade may include several significant effects on a WECS.

1. In the mid-frequency range (say, 0.01 to 0.1 Hz), which contributes to power and to low-frequency components of stress as viewed in the Eulerian frame, less energy will be found by the rotating blade since the energy in Eulerian mid-frequencies will appear as higher frequency fluctuation.
2. In the 0.1-Hz to 10-Hz range, a rotor's filtering effect, represented by its transfer function operating on an Eulerian spectrum such as is shown in Figure 1, may reduce the fluctuation of force at the rotor shaft to insignificant levels. However, with mid-frequency Eulerian energy shifted to a higher frequency range (but with the same scale of spatial variation), as viewed by the rotating blade, much more energy may be observed in the higher range (see Figure 2 and 3a). A significant extra amount of energy may "leak through" the transfer function tail to appear as high-frequency fluctuations of output torque. For example, if the threshold of torque as a result of turbulence is at the level marked by 3 in Figure 3b, the rotating shaft would experience significant fluctuations of torque up to a frequency of about 0.62 Hz. The same analysis using

FIGURE 3. The Effect of Frequency of Turbulence Energy on Increasing the Amount of High-Frequency Energy of Fluctuation in the Turbine Output Torque.
 (a) Input spectra and transfer function
 (b) Output spectra

the spectrum at a fixed point would indicate a cut-off of fluctuating torque to the shaft at a lower frequency, 0.25 Hz.

The evidence for significant frequency shifting comes from two measurements of entirely different kinds. The primary evidence is from PNL vertical plane arrays. The secondary evidence is from windmill spectra described later in this paper. The original PNL array consisted of 8 wind velocity anemometers placed uniformly around a 24-m diameter circle in a vertical plane and one anemometer at the center of the circle (Verholek 1978). The present array, at the same field site, contains a similar set of anemometers on a 49-m diameter circle and four anemometers equally spaced on a concentric 34-m diameter inner circle. Time series of wind speed are composited for a hypothetical rotating blade by sampling the anemometers on the outer circle at equal time intervals in rotational sequence. For the 24-m the time increment used for sampling successive anemometers was 0.1 s, equivalent to a blade rotation period of 0.8 s. The analysis for the 49-m array is for an 0.2 s time increment, corresponding to a rotation period of 1.6 s. The linear speed of the blade at array radius is the same for both arrays, 94 m s^{-1} .

Spectra for both of the rotationally sampled time series of wind speed are shown in Figure 4. (The spikes at high frequency are due to wind shear and are not our direct concern here.) These spectral density curves dip in the middle-frequency range and rise in the high-frequency range. A comparison of the rotating-blade spectrum with a single-point Eulerian spectrum is shown in Figure 4b for the new large array. There are local changes in spectral

FIGURE 4. Spectra for Rotationally Sampled Wind Speed Fluctuations:
 (a) 24-m diameter array at 1 rev. per 0.8 s;
 (b) 49-m diameter array at 1 rev. per 1.6 s, May 1979.
 The turbulence data used were block averaged over 0.1 s and 0.2 s time averaged for the 24-m and 49-m array cases respectively.

energy, as the observation point changes from Eulerian to blade, of one or two orders of magnitude in two frequency ranges.

Since this modification of the spectrum could be quite important for WECS design and also for performance evaluation, this preliminary information should be made available for consideration to a wide readership. A personal communication with Dr. Sten Frandsen and Dr. Carl Jørgen Christensen of the Danish National Laboratory, Risø, indicates that measurements of the shaft torque of the Gedser mill have shown a similar spectral distribution. (See Lundsager, Christensen and Frandsen 1979, Figure A.5.2).

ESTIMATING WHICH WIND TURBINES WILL EXPERIENCE SPECTRAL REDISTRIBUTION

The spectrum alterations measured for 12-m and 24-m radius blades rotating at a speed of 1.25 and 0.62 rps, respectively, are large. It is important to know whether there is a significant effect for other blade diameters and rotation speeds. An approximate method for predicting the existence of spectral redistribution for a rotating blade is explained in the next several paragraphs. This is followed by a brief discussion of the changes in gust characteristics that correspond to the changes in spectra of turbulence seen by a rotating wind turbine blade.

A crude physical analysis of the process of frequency shifting has led to development of the several criteria given below for determining the conditions under which wind turbines would experience significantly altered wind spectra. The criterion represented by the next equation must be satisfied approximately

if frequency shifting of spectrum content is to result from a rotor blade rapidly chopping across spatial variations in wind speed associated with turbulence. (If turbulent eddies are significantly larger than the rotor diameter, D , the rotor simply spins around inside them, experiencing only their normal Eulerian fluctuation, rather than chops across them. A discussion and derivation is given in Part 2 the Appendix).

$$\frac{D}{\lambda_h} \equiv \frac{D n_h}{\bar{u}} > \alpha$$

where D = rotor diameter,

λ_h = smallest eddy size that will affect WECS performance,

$n_h = \bar{u}/\lambda_h$ = inverse time scale of smallest significant eddy in the Eulerian frame,

$\bar{u}$ = mean wind speed and

α = a dimensionless positive number whose magnitude is of the order of one.

Then for a small WECS we might assume the following values:

$$D = 4 \text{ m}, \bar{u} = 10 \text{ m s}^{-1} \text{ and } n_h = 1 \text{ Hz.}$$

These give the following result:

$$\frac{D}{\lambda_h} = \frac{D n_h}{\bar{u}} = 0.4 < 1.$$

No frequency shifting would be expected. However, for $D \geq 10 \text{ m}$ and the same value of $\bar{u}$ and n_h as above, an effect might be observed. Our vertical plane

array measurements and analyses indicate that the effect is quite strong for $D = 24$ and 48 m. The Gedser mill has a diameter of 24 m and would be expected to experience the effect.

As shown in the Appendix, the ratio of the blade speed in rotation to the mean wind speed is also a factor in the frequency shift process, as is the three-dimensional "shape" of turbulence eddies, so that a more complete set of criteria for onset of the frequency shift phenomenon would be of the form shown in Equations (2) and (3).

$$\frac{D}{\bar{\lambda}_{\theta}} > 1 \quad (2)$$

$$\frac{D\bar{\omega}}{2\bar{u}} \frac{\bar{\lambda}_x}{\bar{\lambda}_{\theta}} > 1 \quad (3)$$

where D = diameter of circle of rotation of observation point fixed to rotor,

$\bar{\lambda}_{\theta}$ = mean dimension of eddies in the directions which the rotating blade passes,

$\bar{\omega}$ = average rotation rate of the blade in radians/sec,

$\bar{u}$ = mean wind speed and

$\bar{\lambda}_x$ = mean dimension of the same eddies but in the direction of the mean wind, $\bar{u}$.

EXPECTED MODIFICATION OF GUST CHARACTERISTICS DUE TO CIRCULAR SAMPLING OF WIND

The implication for gust statistics is equally profound. The Eulerian-frame widths of middle, wide and narrow (in time) gusts will become replaced by some that are up to a factor of at least $(D/2) \bar{w}/\bar{u}$ smaller as seen by a rotating blade. Gust period statistics may be greatly different for the rotating blade. The gust speed amplitudes probably will be less different.

REFERENCES

Verholek, M. G. 1978. Preliminary Results of a Field Experiment to Characterize Wind Flow Through a Vertical Plane. PNL-2518, Pacific Northwest Laboratory, Richland, WA 99352.

Lundsager, P., C. J. Christensen and S. Frandsen. 1979. Interim Report on the Measurements on the Gedser Wind Mill. Risø National Laboratory, Denmark,

APPENDIX

AN HEURISTIC EXPLANATION OF THE HYPOTHESIZED FREQUENCY SHIFTING BY A ROTATING BLADE

The explanation of the frequency shifting seen by a rotating blade is made in two parts. Part 1 discusses frequency shifting and spectral density functions of wind speed seen by a rotating blade. Part 2 develops a formula for estimating whether frequency shifting will be significant for any specified wind turbine size and rotation rate and turbulence structure.

Part 1: FREQUENCY SHIFTING AND SPECTRAL DENSITY FUNCTIONS OF WIND SPEED SEEN BY A ROTATING BLADE

The vertical plane array of anemometers at PNL measures the total wind velocity at turbulence rates (10 samples per s) in the stationary frame of reference at each of 8 points around the 49-m diameter circle and other locations as shown in Figure A-1. The array is designed to provide data with which one may analyze turbulence as viewed from a hypothetical rotating blade of a WECS. A blade rotation rate is selected and the turbulence data are composited into time series by taking single data points from successive anemometers around the ring to simulate the blade passing those positions on the circle.

FIGURE A-1. Location of 3-D Anemometers in the Vertical Plane Array

Figure A-2 shows the spectrum for a point at 24 m radius on a hypothetical blade moving at a rate of one revolution per 1.6 s or about 0.6 Hz (dashed line). The large spike at about 0.6 Hz is the contribution at the fundamental frequency due to wind shear in the vertical direction. For the present discussion, we are not concerned about wind shear effects and will ignore the spike. The spectral distribution shown by the heavy line and bounding lines is for the wind at stationary locations at the eight points on the 48-m circle.

Several simple averages might be considered to approximate the results shown in Figure A-2. If a rotor on a horizontal axis machine were stationary for equal and long amounts of time, at all locations around the circle, then

FIGURE A-2. Spectra Calculated from Measured Winds at the Vertical Plane Array. The solid lines represent point Eulerian spectra. The dashed line represents the spectrum for rotationally sampled turbulence corresponding to that experienced by a moving turbine blade.

the average spectrum corresponding to the average torque transmitted to the shaft would be an average of the stationary point (Eulerian) spectra at all locations around the circle. This would produce a slight variation relative to a single point spectrum. (See Figure A-3, dashed line). A uniformly weighted average of instantaneous wind speeds around the circle would have a spectrum that has less middle- and high-frequency energy. This is what a stiff ring or annulus would transmit to the hub. (See Figure A-3, dot symbols).

FIGURE A-3. Schematic Comparison of Eulerian Spectra at Single Points, an Average of Spectra Experienced for Equal Time at Each of the Points Around the Ring and a Spectrum of Ring-Average Turbulence

Now consider that the blade rotates. If there are significant spatial variations of wind speed in the turbulence in the disc of rotation, the rotor will pass through them and experience fluctuations. The rapidity of fluctuation of wind speed, as seen by the blade, is proportional to the circumferential speed of the blade. Of course, the rate of wind fluctuation at the disc of rotation is proportional to the mean wind speed. However, for the size of eddy components that vary in the disc of wind speed and for a blade speed much greater than the wind speed, the blade will see the variation as occurring at a more rapid rate (a higher frequency) than would be seen by a non-moving point. This effect will not exist (appreciably) for the very wide eddies. In fact, for the large eddies, the rotating blade will observe the same spectral distribution of energy as for either ring averaging of fixed-point wind speeds or for a single point.

Keeping in mind that the rotating blade does not much alter the total amount of turbulence energy in the wind, we expect that the total energy (area under the spectral density functions in Figure A-1) must remain the same, although middle- and high-frequency portions will be shifted, in some non-uniform way, to higher frequency locations on the rotation spectrum. Thus, we would expect a depletion of energy density compared to that of the peak or middle-frequency region of the average Eulerian spectrum. The remaining part of the energy spectrum, at higher frequencies, should have locally greater energy density, compared to the fixed point Eulerian spectrum.^(a) The analysis

(a) The question of where the energy seen in point Eulerian spectra but not found in spectra for various averaged or sampled wind speeds has gone is not fully addressed here. The energy is variously ignored, aliased, transformed to heat or possibly observed as occurring at higher frequency because of movement of the observation point.

of the vertical plane array data shows that the combined effects for the rotating blade at the 48-m diameter produce a blade-referenced turbulence spectrum that has a minimum at 0.1 Hz and increases to quite large values between 0.6 Hz and 2.5 Hz (See Figure A-2).

The minimum in the rotation spectrum occurs at 0.1 Hz. The length of an eddy in the direction along the mean wind (normal to the disc of rotation) that produces a 0.1 Hz frequency at a stationary point for a 10 m s^{-1} mean wind speed is about 100 m. Its width in the disc will be somewhat less but still quite large. Let us say that it is 50 m wide. If the blade is rotating at 10 times the mean wind speed or 100 m s^{-1} , it crosses this eddy in a time of no longer than 0.5 s. It therefore sees this energy as fluctuating at a frequency of 2 Hz instead of 0.1 Hz. This is a frequency shift by a factor of 20. The energy which is seen at 0.1 Hz by the rotating blade must be associated with an even larger eddy.

This sort of crude estimation could be elaborated to attempt to derive a spectral density function to compare with the observations, but its main value is in showing that the effect can be significant. Clearly, an accurate theoretical and complete experimental description of the detailed result of the rotating blade frame of observation are the next tasks to be performed. These are being undertaken at PNL.

Part 2: A FORMULA FOR ESTIMATING WHETHER FREQUENCY SHIFTING WILL BE SIGNIFICANT
FOR ANY SPECIFIED WIND TURBINE SIZE AND ROTATION RATE AND TURBULENCE
STRUCTURE

The basic concept is that a rotor of diameter D , which is oriented with its axis of rotation parallel to the mean wind, chops across a wind field which fluctuates in both space and time. We wish to estimate whether these shifts in frequency will be significant to wind turbine performance. As an introduction to the phenomena, consider the simpler motion of a measuring aircraft flying parallel to the mean wind. The wind speed fluctuates both in space and time and has a wide range of wavelengths and frequencies. Less precisely, the wind field is comprised of eddies or lumps of wind speed variation that are continually changing, decaying and being joined by newer ones in a complex aggregate. Consider the spatial variation of the speed of the local wind to be fixed. Then the mean speed of movement of this wind field relative to some measuring point results in time variations of wind speed at the measuring point. If the speed of the observing aircraft is fast enough, then the time variation of wind speed will have the same statistical properties for any condition giving the same mean relative mean motion. For example, if $\vec{v}_w - \vec{v}_{\text{observer}}$ is a constant and in the direction of the mean wind, then the actual vector value of $\vec{v}_{\text{observer}}$ does not affect the observed time variations of wind speed.

If the direction of motion of the observer is constant, then for a "frozen turbulence" wind speed field, an increase in mean speed of the observer increases all frequencies of fluctuation observed by an amount that is inversely proportional to the spatial variation in the direction of mean relative motion.

For a fixed value of λ

$$\Delta f = \frac{\Delta c}{\lambda} , \quad (1)$$

where Δf is the increase in frequency of fluctuation

Δc is the increase in speed of the observer

λ is the wavelength of the wind speed variations.

In general, the frequency shift is derived as follows for an observer moving at a fixed velocity.

$$f = \frac{c}{\lambda} .$$

Thus,

$$\frac{df}{f} = \frac{dc}{c} \quad (2)$$

$$\int_{f_0}^{f_0 + \Delta f} \frac{df}{f} = \int_{c_0}^{c_0 + \Delta c} \frac{dc}{c} \quad (3)$$

$$\ln \frac{f_0 + \Delta f}{f_0} = \ln \frac{c_0 + \Delta c}{c_0} \quad (4)$$

$$1 + \frac{\Delta f}{f_0} = 1 + \frac{\Delta c}{c_0} \quad (5)$$

or,

$$\Delta f = \frac{f_0}{c_0} \Delta c = \frac{\Delta c}{\lambda_0} \quad (6)$$

If,

$$\Delta c = 10 c_0, \quad (7)$$

$$\frac{\Delta f}{f_0} = 10 \quad (8)$$

and

$$f = 11 f_0. \quad (9)$$

On a log-log plot of $nS(n)$ versus n , this appears as a uniform displacement in frequency of the $nS(n)$ spectrum by a factor of 11 as shown in Figure A-4.

A major modification of the form of frequency shifting of the turbulence is expected when the observer moves in a circular path orthogonal to the mean wind (as, e.g., a rotor) rather than a linear path. The very low frequency turbulence components have so little spatial variation over the diameter of the rotor that essentially no frequency shifting is observed. For middle-size eddies some frequency shifting will occur but not in the same way as for the smallest eddies. The frequencies of the smaller scale variations will shift as indicated by Equation (6).

FIGURE A-4. Frequency Shifting of a Spectrum from that Seen by a Stationary Observer to that Seen by an Observer Moving with a Fixed Velocity

An approximate criterion for determining the sizes and speeds of a blade of a rotor that will experience the effect of significant shifting of turbulence frequencies (or gust periods) can be readily derived. For simplicity assume that spatial variations of wind speed, neglecting mean wind shear, are characterized by wavelengths, λ_α . In a cylindrical coordinate system for which x is aligned with the mean wind and θ is aligned with the rotor linear velocity, the longitudinal and appropriate transverse wavelengths are, respectively, λ_x and λ_θ . The velocity of a point at radius R on the rotor is given by $R\bar{\omega}$ where $\bar{\omega}$ is the mean and nearly constant angular rotation rate of the rotor. The mean wind speed relative to an anemometer fixed to the earth is represented by $\bar{u}$.

If $R\bar{\omega} \leq \bar{u}$ and, for all spatial variations, $\lambda_\theta = \lambda_x = \lambda_y = \lambda_z$, then frequency shifting would be $\Delta f \leq 0.4 \bar{u}/\lambda_\theta$. The rate at which all but the smaller spatial variations of wind speed pass the blade would approach that with which they pass the stationary anemometer. The frequency observed will increase as $R\bar{\omega}/\bar{u}$ increases and as λ_x/λ_θ increases because the blade "chops" through the variations more rapidly than does the stationary point anemometer. This may become more clear if we write the ratio of average frequencies,

$$\frac{f_{\text{rot}}}{f_{\text{stat}}} \equiv \frac{R\bar{\omega}}{\bar{\lambda}_\theta} \left(\frac{\bar{u}}{\bar{\lambda}_x} \right)^{-1} \quad \text{for } R\bar{\omega} \geq \bar{u} \quad (10)$$

If $f_{\text{rot}}/f_{\text{stat}} > 1$ we expect to begin to see frequency shifting if the turbulence scales are small enough that the eddies are at least partly transversed by the point on the rotor at diameter D . As a first guess, $\bar{\lambda}_\theta$ should be smaller than D if spatial variation is to be significant. The approximate criteria for onset of frequency shifting of Eulerian spectral components follow.

$$\frac{D}{\bar{\lambda}_\theta} > \alpha_1 \sim 1 \quad (11)$$

$$\frac{R\bar{\omega}}{\bar{u}} \frac{\bar{\lambda}_x}{\bar{\lambda}_\theta} > \alpha \sim 1 \quad (12)$$

where

R is the radius of rotation of the observation point on the rotor,

$\bar{\omega}$ is mean angular velocity of the rotor,

$\bar{u}$ is the mean wind speed relative to the stationary anemometer (in the Eulerian frame of reference),

$\bar{\lambda}_x$ is the mean extent of spatial variations of wind speed in the direction of $\bar{u}$, and

$\bar{\lambda}_\theta$ is the mean extent of variation in the crosswind direction tangential to the circle of rotation.

As a first approximation we take α_1 and α_2 to have a magnitude of 1. Theoretical and empirical studies are under way to test and refine these rudimentary criteria. Several implications of the criteria are given in the text of this paper.

DISTRIBUTIONNo. of
CopiesNo. of
CopiesOFFSITE

	A. A. Churm DOE Chicago Patent Group 9800 S. Cass Avenue Argonne, IL 60439	S. J. Hightower Bureau of Reclamation Denver Federal Center Building 67, Code 254 Denver, CO 80225
5	W. C. Reddick/C. I. Aspliden Department of Energy 600 E. Street, N.W. Washington, DC 20545	M. Ginosar/J. Lerner California Solar Energy Commission Energy Resources, Conservation and Development Commission 1111 Howe Avenue, Mail Stop 15 Sacramento, CA 95825
5	G. P. Tennyson Department of Energy Albuquerque Operations Office 4501 Indian School Road N.E. Suite 151 Albuquerque, NM 87110	E. H. Gilmore Department of Agriculture Agriculture Research Service Bushland, TX 79012
27	DOE Technical Information Center Peter Smeallie AWEA Windletter 1609 Connecticut Avenue N.W. Washington, DC 20008 Clarissa Quinlan Alaska State Energy Office 338 Denali Street Anchorage, AK 99501 Ben Wolff American Wind Energy Association 1621 Connecticut Avenue, N.W. Fifth Floor Washington, DC 20009 Richard Katzenberg American Wind Energy Association Natural Power, Inc. New Boston, NH 03070 E. J. Warchol Bonneville Power Administration P.O. Box 3621 Portland, OR 97208	L. A. Liljedahl Department of Agriculture Agriculture Wind Energy Program Building 001, Room 126 BARC-West Beltsville, MD 20705 Jay Tappan Department of Energy State of Oregon Labor and Industries Building Room 111 Salem, OR 98310 Dr. Edgar Demeo Electric Power Research Institute 3412 Hillview Avenue Palo Alto, CA 94303 Dr. Olle Ljungstrom FFA, The Aeronautical Research Institute Forskningsstationen i Stockholm Drottning Kristinas Vag 47 S-114 29 Stockholm, Sweden

No. of
Copies

No. of
Copies

Ms. Abbey Page
Maine Office of Energy Resources
55 Capital
Augusta, ME 04330

J. Konigsberg
Montana Energy Office
Capital Station
Helena, MT 59601

Phillip French
NASA Scientific and Technical
Information Facility
P.O. Box 8757
Baltimore/Washington International
Airport
Baltimore, MD 21240

M. J. Changery
National Oceanic and Atmospheric
Administration
National Climatic Center
Federal Building
Asheville, NC 28801

2 E. W. Hewson/J. E. Wade
Oregon State University
Corvallis, OR 97331

Earl Davis
Pacific Gas and Electric Co.
215 Market St.
San Francisco, CA 94106

E. L. Luther
PRC Eng. Analysis Co.
Old Springhouse Road
McLean, VA 22102

Terry J. Healy/C. Hansen
Rockwell International
Rocky Flats Plant
P.O. Box 464
Golden, CO 80401

E. Kadlec
Sandia Laboratories
Division 5443
P.O. Box 5800
Albuquerque, NM 87115

I. Vas/Roger Taylor
Solar Energy Research Institute
1536 Cole Blvd.
Golden, CO 80401

D. Lindley
Taylor Woodrow Construction,
Limited
Taywood House
345 Ruislip Road
Southhall
Middlesex UBI 2QX
England

Thomas A. Schroeder
University of Hawaii at Monoa
2525 Correa Road
Honolulu, HI 96822

Ms. Susan Hosch
Washington State Energy Office
400 E. Union Avenue, 1st Floor
Olympia, WA 98504

John Young
Washington Public Power Supply
System
P.O. Box 968
Richland, WA 99352

G. D. Thomann
Wichita State University
P.O. Box 44
Wichita, KS 67208

Farrell Smith Seiler
Wind Energy Report
Box 14 - 104 X. Village Avenue
Rockville Centre, NY 11571

No. of
Copies

Dr. V. Barros
28 De Julio 28
9120 Puerto Madryn
Chulret
R. Argentina

ONSITE

- 2 DOE Richland Operations Office
P.O. Box 550
Richland, WA 99352

H. E. Ransom
R. K. Stewart

- 53 Pacific Northwest Laboratory
Battelle Boulevard
Richland, WA 99352

W. R. Barchet
J. C. Barnard
R. L. Conley
J. R. Connell (10)
J. C. Doran
K. Drumheller
C. E. Elderkin
D. L. Elliott
R. L. George
P. C. Hays
T. R. Hiester
T. C. Jameson
A. H. Miller
W. T. Pennell
E. H. Phinney
D. C. Powell
J. M. Proud (15)
J. W. Ramsdell
D. S. Renne
D. N. Reyes
H. L. Wegley
L. L. Wendell
R. K. Woodruff
Technical Information - Library (5)
Publishing Coordination (2)