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W. C. Cliff
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Prepared for the U.S. Department of Energy
under Contract No. EY-76-C-06-1830

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WIND VELOCITY-CHANGE (GUST RISE) CRITERIA FOR WIND TURBINE DESIGN

W. C. Cliff
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SUMMARY

This paper derives a closed-form equation for root mean square (rms) value of velocity change (gust rise) that occurs over the swept area of wind turbine rotor systems and an equation for rms value of velocity change that occurs at a single point in space. These formulas confirm the intuitive assumption that a large system will encounter a less severe environment than a small system when both are placed at the same location. That is, because of a spatial-averaging effect the wind characteristics that engulf a large system are less severe than those for a small system. Assuming a normal probability density function for the velocity differences, an equation is given for calculating the expected number of velocity differences that will occur in 1 hr and will be larger than an arbitrary value. A formula is presented that gives the expected number of velocity differences larger than an arbitrary value that will be encountered during the design life of a wind turbine. In addition, a method for calculating the largest velocity difference expected during the life of a turbine and a formula for estimating the risk of exceeding a given velocity difference during the life of the structure are given. The equations presented are based upon general atmospheric boundary-layer conditions and do not include information regarding events such as tornados, hurricanes, etc.

CONTENTS

INTRODUCTION

In many cases, the wind-turbine design engineer, needs to know wind characteristics that engulf all or part of the turbine rotor system because a spatial-filtering effect caused by the size of the wind turbine rotor system must be accounted for in order to provide wind characteristic design inputs. One such input is the wind's velocity change, $[u(t+\tau) - u(t)]$, which occurs over time (τ). Velocity change, which is averaged over the swept area of a rotor system, is less severe than the maximum velocity change occurring at a single point. That is, within the swept area of the rotor, areas of velocity change greater than the average velocity change as well as areas of lesser velocity change occur simultaneously. This paper presents formulas for estimating the velocity change encountered over the swept area of the rotor system. The formulas are generic and may be used for any size of wind turbine system operating in the neutral atmospheric boundary layer. A meter-kilogram-second (mks) system of units is used in this report.

CONCLUSIONS

A closed-form solution for the rms value of velocity difference, $\Delta u(\tau) = [u(t+\tau) - u(t)]$, encountered over the disk of rotation of a wind turbine is derived in equation (13) of this report. Assuming that the probability density function for the velocity difference is normal, equation (14) estimates the expected hourly number of velocity changes that exceed a given value. To compute the expected number of velocity changes that exceed a given level during the life of a machine, equation (15), which includes the hourly mean longitudinal wind velocity climatology for the turbine site, is given. If the designer wishes to estimate the once-in-10, 30, 100 yr etc., velocity change, equation (15) should be evaluated according to a set number of years for various values of X until $N_T \simeq 1$, where N_T equals the total number of expected positive velocity changes, greater than X, which occur in a given number of years. The value of X that yields $N_T \simeq 1$ would be the value of Δu that can be expected to be exceeded once in a given number of years (Y). To evaluate the risk of exceeding a particular value of Δu during the lifetime of a turbine, a Poisson model, as seen in equation (16), is used.

EVALUATING RMS OF VELOCITY DIFFERENCE

This section derives an expression for the root mean square (rms) value of the longitudinal velocity change encountered over the disk of rotation of a wind turbine.

The rms of change in longitudinal velocity component is defined by the following equation:

$$\sigma_{\Delta u}(\tau) = \left[\frac{1}{T} \int_0^T [u(t+\tau) - u(t)]^2 \, dt \right]^{\frac{1}{2}} = \overline{\left[u(t+\tau) - u(t)\right]^2}^{\;\frac{1}{2}} \qquad (1)$$

where

u = longitudinal wind component fluctuation (fluctuation of wind component parallel to the mean wind direction)

$\sigma_{\Delta u}(\tau)$ = rms of velocity change of longitudinal velocity component

τ = time over which the velocity difference takes place

T = time period for defining turbulence (generally considered between 10 min to 1 hr)

t = time

$\overline{(\;)} = \frac{1}{T}\int_0^T (\;)\, dt.$

Equation (1) may be expanded and written as:

$$\sigma_{\Delta u}(\tau) = \overline{\left[u(t+\tau)^2 + u(t)^2 - 2\, u(t)\, u(t+\tau)\right]}^{\;\frac{1}{2}} \; . \qquad (2)$$

In equation (2), the first and second term on the right are each equal to the variance of the u component. The last term is equal to the autocorrelation of the u component. Equation (2) may now be written in its spectral equivalent form as:

$$\sigma_{\Delta u}(\tau) = \left[2 \int_0^\infty \phi_u(f)df - 2 \int_0^\infty \phi_u(f) \cos 2\pi f\tau \ df \right]^{\frac{1}{2}}$$

$$= \sqrt{2} \left[\int_0^\infty \phi_u(f) \ (1 - \cos 2\pi f\tau) \ df \right]^{\frac{1}{2}} \tag{3}$$

where

f = frequency (Hz)

$\phi_u(f)$ = power spectrum of the u component.

Any standard atmospheric spectra model can be used in equation (3) to solve for $\sigma_{\Delta u}(\tau)$. However, the results would only be applicable for a system, sensing a small volume (e.g., anemometer systems). When systems sample larger volumes of space, equation (3) must be modified to adjust for the spatial-filtering effect of averaging over a larger volume of space.

One approach for adjusting equation (3) is to assume that systems will respond to a frequency with a value equal to $\overline{U}_h/D$, where $\overline{U}_h$ equals mean longitudinal wind velocity at hub height and D equals characteristic diameter of the machine. A second approach is to assume that sampling of the larger system acts as a filter with the 3-db (half-power) point set at a frequency commensurate with machine size. A closed-form solution may be obtained in the latter technique whereas the first technique leaves an integral that must be numerically integrated. Therefore, the second technique was selected for this report.

The Dryden spectra[1] given by the following equation was used to obtain the closed-form solution.

$$\phi_u(f) = \sigma_u^2 \frac{\overline{U}_h}{L_u \pi^2} \frac{1}{\left[\frac{\overline{U}_h}{2\pi L_u}\right]^2 + f^2} \tag{4}$$

where

σ_u^2 = variance of longitudinal wind component, $m^2\ sec^{-2}$

$\overline{U}_h$ = mean wind speed at hub height, $m\ sec^{-1}$

L_u[a] = turbulent length scale, m, as given by the following equation:

$$L_u = \frac{25\ z_h^{\ C}}{z_o^{\ 0.4}} \tag{5}$$

C = EXP $[-0.025\ (\ell n\ z_o)^2 + 0.17\ \ell n\ z_o - 0.8]$

z_o = surface roughness, e.g.,

$z_o = 0.005$ m (smooth terrain)

$z_o = 0.05$ m (moderate terrain)

$z_o = 0.34$ m (rough terrain)

z_h = height of measurement, m (hub height of wind turbine for the wind turbine case).

The filter function used to account for the physical size of the system is given by:

$$G(f) = \frac{\left(\frac{\overline{U}_h}{D}\right)^2}{\left(\frac{\overline{U}_h}{D}\right)^2 + f^2} \quad . \tag{6}$$

The 3-db (half-power) point for G(f) occurs when $f = \overline{U}_h/D$.

(a) The value given for L_u is the authors' empirical curve fit to curves given for L_u by Counihan[2].

Equation (3) as modified by equation (6) to account for the size of the sensing system, becomes:

$$\sigma_{\Delta u}(\tau) = \sqrt{2}\left[\int_0^\infty \frac{\phi_u(f)\left(\frac{\overline{U}_h}{D}\right)^2}{\left(\frac{\overline{U}_h}{D}\right)^2 + f^2} (1 - \cos 2\pi f\tau)df\right]^{1/2} \quad . \tag{7}$$

Incorporating equation (4) for $\phi_u(f)$ into equation (7) yields:

$$\sigma_{\Delta u}(\tau) = \sqrt{2}\left[\int_0^\infty \frac{\sigma_u^2\ \overline{U}_h^3}{\pi^2\ L_u\ D^2}\ \frac{(1 - \cos 2\pi f\tau)}{\left[\left(\frac{\overline{U}_h}{2\pi L_u}\right)^2 + f^2\right]\left[\left(\frac{\overline{U}_h}{D}\right)^2 + f^2\right]} df\right]^{1/2} \quad . \tag{8}$$

The solution to equation (8) is:

$$\sigma_{\Delta u}(\tau) = \sqrt{2}\ \sigma_u\left[\frac{\left(1 - e^{-\frac{\overline{U}_h\tau}{L_u}}\right) - \frac{D}{2\pi L_u}\left(1 - e^{-\frac{2\pi\overline{U}_h\tau}{D}}\right)}{1 - \frac{D^2}{(2\pi L_u)^2}}\right]^{1/2} \quad . \tag{9}$$

When the diameter (D) of the system goes to zero, the following classical result is obtained.

$$\sigma_{\Delta u}(\tau) = \sqrt{2}\ \sigma_u\left(1 - e^{-\frac{\overline{U}_h\tau}{L_u}}\right)^{1/2} \quad \text{for } D = 0 \quad . \tag{10}$$

A useful engineering variation of equation (9) is obtained using the neutral-boundary-layer log profile given by

$$\overline{U}_h = \frac{u_*}{k} \ln z_h/z_o \tag{11}$$

and the approximation that $\sigma_u \simeq 2.5\, u_*$[3], where

$u_* = \sqrt{\tau_w/\rho}$

τ_w = surface shear stress

ρ = density of air

k = Von Karmans constant, 0.4.

Thus, σ_u is now expressed as:

$$\sigma_u \simeq \frac{\overline{U}_h}{\ln z_h/z_o} \tag{12}$$

and equation (9) becomes:

$$\sigma_{\Delta u}(\tau) = \frac{\sqrt{2}\,\overline{U}_h}{\ln z_h/z_o} \left[\frac{\left(1 - e^{-\frac{\overline{U}_h \tau}{L_u}}\right) - \frac{D}{2\pi L_u}\left(1 - e^{-\frac{2\pi \overline{U}_h \tau}{D}}\right)}{1 - \frac{D^2}{\left(2\pi L_u\right)^2}} \right]^{\frac{1}{2}} . \tag{13}$$

(NOTE: $\sigma_{\Delta u}$ is a function of z_o, $\overline{U}_h$ and τ).

CALCULATING DISTRIBUTION OF VELOCITY DIFFERENCES

Assuming that velocity differences are Gaussian distributed, the following formula (14) gives the approximate number (N) of velocity changes, $u(t+\tau) - u(t) = \Delta u(\tau)$, per hour that exceed a given value, X. The number (N) represents the positive $\Delta u(\tau)$'s; this number should be doubled if negative $\Delta u(\tau)$'s are included.

$$N(\Delta u(\tau) > X) = \frac{1800}{\tau}\left(1 + d_1 z + d_2 z^2 + d_3 z^3 + d_4 z^4 + d_5 z^5 + d_6 z^6\right)^{-16} \qquad (14)$$

(NOTE: N is a function of $\sigma_{\Delta u}(\tau)$, τ and X)
where

τ is in seconds

$$z = \frac{X}{\sigma_{\Delta u}(\tau)}$$

d_1 = 0.0498673470

d_2 = 0.0211410061

d_3 = 0.0032776263

d_4 = 0.0000380036

d_5 = 0.0000488906

d_6 = 0.0000053830

and $\sigma_{\Delta u}(\tau)$ is calculated using equation (13).

The first term on the right side of the equation is the total number of positive $\Delta u(\tau)$'s that occur per hour, that is, $3600/\tau$ events per hour spaced τ seconds apart, half being positive and half being negative.

COMPUTING THE TOTAL NUMBER OF EVENTS DURING THE LIFE OF THE TURBINE

The following equation may be used to compute the expected number (N_T) of longitudinal velocity changes (which exceed a given value) that occur over a given number of years (Y).

$$N_T(\Delta u(\tau) > X) = (8766)\ (Y) \int_0^{\infty} N\ p(\overline{U}_h) d\overline{U}_h \qquad (15)$$

where

N_T = total number of expected positive velocity changes, greater than X, which occur in Y

8766 = number of hr in 1 year

Y = number of years

$p(\overline{U}_h)$ = the probability density distribution of hourly mean longitudinal wind velocity that occurs at wind turbine hub height.

If only velocity changes that occur while the turbine is operating are of interest the limits of integration for equation (15) should be from the turbine cut-in velocity to the turbine cutout velocity rather than from 0 to ∞. The total number of velocity changes of a given magnitude that may occur during a turbine's life can be used in fatigue and control analyses.

EXPECTED MAXIMUM VELOCITY DIFFERENCE

To estimate a velocity change, $\Delta u(\tau)$ that has a reoccurrence interval of Y, equation (15) is solved using increasingly larger values of X until the X value selected results in a value for $N_T \simeq 1$. In this way, estimates of the expected reoccurrence intervals of maximum $\Delta u(\tau)$ can be calculated. That is, estimates of the once-in-10, 30, 100 yr etc., $\Delta u(\tau)$ may be computed.

RISK OF EXCEEDANCE ANALYSIS

To assess the risk of exceeding a large $\Delta u(\tau)$, a Poisson exceedance model is recommended as follows:[1]

$$F_p = 1 - e^{-T_L/M} \qquad (16)$$

where

F_p = probability that a value of $\Delta u(\tau)$ will be exceeded within a given period of time

T_L = design life of turbine

M = expected reoccurrence interval of $\Delta u(\tau)$, i.e., 30 yr, etc.

If a particular $\Delta u(\tau)$ has a reoccurrence interval equal to the design life of the structure, equation (16) shows that a 63% chance of exceeding that value of $\Delta u(\tau)$ exists.

EXAMPLE PROBLEM

Suppose a designer wants to know how many times (N_T) his wind turbine will experience dynamic loading caused by a 1-sec rise in longitudinal wind velocity, over the disk of rotation, that exceeds 1, 2, 4, 6, 8, 10, 12, 14 and 16 m sec^{-1} for cutout longitudinal wind velocity of 20 m sec^{-1}, 30 m sec^{-1} and no cutout as well as which 1-sec rise in longitudinal wind velocity should be expected to be exceeded only once during the 30 yr, i.e., the 1-sec rise in wind speed with an expected 30-yr reoccurrence interval.

The wind-turbine characteristics and environment for the example problem are as follows:

hub height	=	40 m
blade diameter	=	60 m
U_A	=	annual mean wind, 10 m sec^{-1}
z_o	=	0.05 m
Expected life of turbine	=	30 yr
L_u (From equation 5)	=	184 m

The Rayleigh distribution for $p(\overline{U}_h)$ is as follows:

$$p(\overline{U}_h) = \frac{\overline{U}_h \pi}{2U_A^2} e^{-\frac{\pi}{4}\left(\frac{\overline{U}_h}{U_A}\right)^2} \quad (17)$$

Using the above distribution and N from equation (14) in equation (15), the following tabular results are obtained for $\tau = 1$ sec.

TABLE 1. Number of Expected Velocity Changes (N_T) (Gust Rise) for Example Problem

Δu, m sec^{-1}	N_T: No cutout	N_T: Cutout, 30 m sec^{-1} (a)	N_T: Cutout, 20 m sec^{-1}
0.0	4.7×10^8	4.7×10^8	4.6×10^8
1.0	2.4×10^7	2.4×10^7	1.6×10^7
2.0	3.3×10^6	3.1×10^6	9.6×10^5
4.0	1.1×10^5	8.2×10^4	7.0×10^2
6.0	5.3×10^3	2.0×10^3	2.9×10^{-2}
8.0	3.3×10^2	2.8×10^1	1.2×10^{-7}
10.0	2.3×10^1	2.1×10^{-1}	-
12.0	1.8×10^0	8.0×10^{-4}	-
14.0	1.5×10^{-1}	-	-
16.0	1.4×10^{-2}	-	-
Δu for 1 occurrence during life of turbine	~12.5 m sec^{-1}	~9.3 m sec^{-1}	~5.3 m sec^{-1}

(a) Dashes indicate values below those considered in this example.

Therefore, the 1-sec rise in longitudinal wind velocity expected to be exceeded only once during the 30-yr period is ≃12.5 m sec^{-1}. The probability of exceeding this value during the life of the turbine is approximately 63%

as seen in equation (16). A larger value of Δu must be used if the designer wishes to lower the risk of exceeding the design value. For instance the probability of exceeding a Δu of 14 m sec^{-1} is only 14%, using equation (16). If the designer would consider only the Δu's occurring when the wind is between cut-in and cutout for the limits of integration of equation (15), extreme values of Δu would be somewhat less, depending on the cutout velocity.

Comparing columns two, three and four of Table 1 shows the major contribution to large values of Δu (gust rise) occurs when the mean longitudinal wind velocity is high. Therefore, this type of analysis should be useful not only for fatigue analysis but also for expected maximum dynamic loading because of gusts; that is, the analysis should be useful in determining the risk associated with encountering variously sized gusts during the life of the structure.

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APPENDIX A

PROCEDURE FOR CALCULATING VELOCITY DIFFERENCES

PROCEDURE FOR CALCULATING VELOCITY DIFFERENCES

The following criteria should be used for computing the longitudinal velocity variations encountered over the disk of rotation of a wind turbine. Velocity variation is defined as the difference in velocity at time $(t+\tau)$ and the velocity at an earlier time (t); therefore, velocity variation equals $u(t+\tau) - u(t)$.

The following formula gives the approximate number (N) of velocity changes $(u(t+\tau) - u(t) = u(\tau))$ per hour that exceed a given value, X. The number (N) represents the positive $\Delta u(\tau)$'s; this number should be doubled if negative $\Delta u(\tau)$'s are included.

$$N(\Delta u(\tau)>X) = \frac{1800}{\tau}\left(1 + d_1 z + d_2 z^2 + d_3 z^3 + d_4 z^4 + d_5 z^5 + d_6 z^6\right)^{-16}$$

where

τ is in seconds

$$z = \frac{X}{\sigma_{\Delta u}(\tau)}$$

$d_1 = 0.0498673470$

$d_2 = 0.0211410061$

$d_3 = 0.0032776263$

$d_4 = 0.0000380036$

$d_5 = 0.0000488906$

$d_6 = 0.0000053830$

$$\sigma_{\Delta u}(\tau) = \frac{\sqrt{2}\,\overline{U}_h}{\ell n\; z_h/z_o}\left[\frac{\left(1-e^{-\frac{\overline{U}_h\tau}{L_u}}\right) - \frac{D}{2\pi L_u}\left(1-e^{-\frac{2\pi\overline{U}_h\tau}{D}}\right)}{1 - \frac{D^2}{\left(2\pi L_u\right)^2}}\right]^{\frac{1}{2}}$$

where

D = diameter of wind turbine, m

$\overline{U}_h$ = hourly mean longitudinal wind velocity at hub height for which the computation is made, m sec^{-1}

z_h = hub height of wind turbine, m

z_o = surface roughness; e.g.,

z_o = 0.0005 m (smooth terrain)

z_o = 0.05 m (moderate terrain)

z_o = 0.34 m (rough terrain)

$$L_u = \frac{25 z_h^{\,c}}{z_o^{\,0.4}} \; ; \; L_u \text{ in meters}$$

$$c = \text{EXP}\left[- 0.025\,(\ell n\, z_o)^2 + 0.17\,\ell n\, z_o - 0.8\right] \; .$$

To calculate the total number of occurrences over the life of the wind turbine, equation (15) in the text should be used. The value of Δu, which causes equation (15) to equal 1.0, is the value of Δu with a reocurrence interval equal to the life of the turbine. The risk of encountering such a Δu during the life of the turbine may be calculated using equation (16) in the text.

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