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# Wind Direction Change Criteria for Wind Turbine Design

W. C. Cliff

January 1979

Prepared for the U.S. Department of Energy
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## SUMMARY

This paper presents a method for estimating the root mean square (rms) value of the wind direction change, $\Delta\theta(\tau) = \theta(\tau + \tau) - \theta(\tau)$, that occurs over the swept area of wind turbine rotor systems. An equation is also given for the rms value of the wind direction change that occurs at a single point in space, i.e., a direction change that a wind vane would measure. Assuming a normal probability density function for the lateral wind velocity change and relating this to angular changes, equations are given for calculating the expected number of wind direction changes, larger than an arbitrary value, that will occur in 1 hr as well as the expected number that will occur during the design life of a wind turbine. The equations presented are developed using a small angle approximation and are, therefore, considered appropriate for wind direction changes of less than 30°. The equations presented are based upon neutral atmospheric boundary-layer conditions and do not include information regarding events such as tornados, hurricanes, etc.

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## 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, depending on 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 direction change, $[\theta(t + \tau) - \theta(t)]$, which occurs over time ($\tau$). The direction change, which is also averaged over the swept area of a rotor system, is less severe than the maximum direction change occurring at a point within the swept area. That is, within the swept area of the rotor, areas of direction change greater than the average direction change as well as areas of lesser change occur simultaneously.

This paper presents formulas for estimating the direction 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 strong wind conditions. A meter-kilogram-second (mks) system of units is used in this report.

## CONCLUSIONS

A solution for the rms value of direction change, $\Delta\theta(\tau) = [\theta(t + \tau) - \theta(t)]$, encountered over the disk of rotation of a wind turbine is derived in Equation (6) of this report. Assuming that the probability density function for the lateral velocity difference is normal, Equation (9) estimates the expected hourly number of direction changes that exceed a given value. To compute the expected number of direction changes that exceed a given level during the life of a machine, Equation (10), which includes the hourly mean longitudinal wind component climatology for the turbine site, is given. If the designer wishes to estimate the once in 10, 30, 100 yr, etc., direction change, Equation (10) should be evaluated according to a set number of years for increasing values of X (direction change) until $N_T \simeq 1$, where $N_T$ equals the total number of expected direction changes, greater than X, which occurs in a given number of years.

The value of X that yields $N_T \simeq 1$ would be the value of $\Delta\theta(\tau)$ that can be expected to be exceeded once in a given number of years (Y). These exceedance values must stay within the approximation constraints imposed on the deviations (i.e., less than 30°), and the values obtained for the long-term exceedance values are, at best, engineering guesses with little experimental validation.

## EVALUATING RMS OF WIND DIRECTION DIFFERENCE

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

The rms of change in the wind direction change is defined by the following equation:

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

where

$\theta(t)$ = wind direction angle at time (t). (0 reference angle generally taken parallel to the mean direction of flow.)

$\sigma_{\Delta\theta}(\tau)$ = rms of the wind direction change

$\tau$ = time over which the directional 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:

$$\sigma_{\Delta\theta}(\tau) = \overline{[\theta^2(t+\tau) + \theta^2(t) - 2\theta(t)\,\theta(t+\tau)]}^{\frac{1}{2}} \qquad (2)$$

For small angles (less than 30°) the following formula will be used to approximate the angle, $\theta$.

$$\theta(t) \simeq \frac{v(t)}{\overline{U}_h} \qquad (3)$$

where

$v(t)$ = lateral component of velocity at time (t)

$\overline{U}_h$ = hourly mean longitudinal component of wind speed at hub height

Using the approximation given by Equation (3) and noting that the assumed distribution shape for $v(t)$ is transferred to $\theta(t)$ and that $\overline{\theta^2(t + \tau)} = \overline{\theta^2(t)}$ when $\tau$ is short compared to T, Equation (2) becomes:

$$\sigma_{\Delta\theta}(\tau) = \frac{\sqrt{2}}{\overline{U}_h} \left[\overline{v^2(t)} - \overline{v(t)\, v(t + \tau)}\right]^{\frac{1}{2}} \tag{4}$$

Equation (4) may now be written in its spectral equivalent form as:

$$\begin{aligned} \sigma_{\Delta\theta}(\tau) &= \frac{\sqrt{2}}{\overline{U}_h} \sigma v \left[\int_0^\infty \phi_v(f)\, df - \int_0^\infty \phi_v(f) \cos 2\pi f\tau\, df\right]^{\frac{1}{2}} \\ &= \frac{\sqrt{2}}{\overline{U}_h} \sigma_v \left[\int_0^\infty \phi_v(f)\, [1 \quad \cos 2\pi f\tau]\, df\right]^{\frac{1}{2}} \end{aligned} \tag{5}$$

where

$f$ = frequency (Hz)

$\phi_v(f)$ = normalized power spectrum of the lateral wind component, v.

Any standard atmospheric spectral model can be used in Equation (5) to solve for $\sigma_{\Delta\theta}(\tau)$. However, the results would only be applicable for a system that senses a small volume (e.g., anemometer systems). When systems sample larger volumes of space, Equation (5) must be modified to adjust for the spatial filtering effect of averaging over a larger volume of space.

One approach for adjusting Equation (5) to account for system size would be to introduce a filter function to act as a high frequency cutoff. This paper does not pursue this approach by which a potential exists for obtaining a closed-form solution using the Dryden[1] atmospheric spectra and a first-order filter

with the 3-db (half power) point set at a frequency equal to $\overline{U}_h/D$, where D is the diameter of the turbine rotor system. Such a closed-form solution would be advantageous, because the user would not have to contend with a numerical integration.

A second approach, which is used for this paper, is to use a truncated spectra with the truncation occurring at a frequency equal to $\overline{U}_h/D$. Using the engineering approximations that $\sigma_v \simeq 0.75\sigma_u$[2] ($\sigma_u$ = rms of longitudinal wind component) and $\sigma_u \simeq \overline{U}_h/\ln z_h/z_o$[3] and truncating the spectra, Equation (5) may be written as:

$$\sigma_{\Delta\theta}(\tau) \cong \frac{1.1}{\ln\left(z_h/z_o\right)}\left[\int_0^{\overline{U}_h/D} \phi_v(f)\ (1 - \cos 2\pi f\tau)\ df\right]^{\frac{1}{2}} \tag{6}$$

where

D = diameter of wind turbine, m

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

$z_o$ = 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)

$z_h$ = height of measurement, m (hub height of wind turbine).

The results obtained by filtering as in the first approach and the results obtained by spectral truncation as in the second approach are within 5% of one another. Also the results are not a strong function of D; that is, a small change in D will not significantly affect the results. The truncation of the spectra was selected to be at a value of frequency equal to $\overline{U}/D$ until better values can be determined experimentally.

It is recommended that the von Karman spectra be used for $\phi_v$ in Equation (6). The von Karman spectra, which is internationally accepted and allows for spectral change as a function of surface roughness, is as follows:

$$\phi_v(f) = \frac{2L_v}{\overline{U}_h} \frac{1 + \frac{8}{3}\left(1.339\ L_v\ \frac{2\pi f}{\overline{U}_h}\right)^2}{\left[1 + \left(1.339\ L_v\ \frac{2\pi f}{\overline{U}_h}\right)^2\right]^{11/6}} \tag{7}$$

where $L_v$ is given by the following equation:[4]

$$L_v = \frac{5.1\ z_h^{0.48}}{z_o^{0.086}} \tag{8}$$

(Note: $\sigma_{\Delta\theta}$ is a function of $z_o$, $\overline{U}_h$, $z_h$ and $\tau$.)

## CALCULATING DISTRIBUTION OF WIND DIRECTION-CHANGE

Assuming that wind direction changes are Gaussian distributed, the following formula (9) gives the approximate number, N, of direction changes, $\Delta\theta(\tau) = \theta(t + \tau) - \theta(t)$, per hour that exceed a given value, X. (The right-hand term is an approximation to the double-sided integral of the normal distribution[5].) The number N represents an absolute number of $\Delta\theta(\tau)$, which should occur. Equal numbers should occur clockwise as counterclockwise; thus, if only the clockwise or counterclockwise $\Delta\theta(\tau)$'s are desired the calculated number, N, should be divided by two.

$$N[\Delta\theta(\tau) > X] = \frac{3600}{\tau} (1 + d_1 z + d_2 z^2 + d_3 z^3 + d_4 z^4 + d_5 z^5 + d_6 z^6)^{-16} \qquad (9)$$

where:

$\tau$ is in seconds

$z = \dfrac{X}{\sigma_{\Delta\theta}(\tau)}$

$d_1 = 0.0498673470$

$d_2 = 0.0211410061$

$d_3 = 0.0032776263$

$d_4 = 0.0000380036$

$d_5 = 0.0000488906$

$d_6 = 0.0000053830$

and $\sigma_{\Delta\theta}(\tau)$ is calculated using Equation (6).

The first term on the right side of Equation (9) is the total number of $\Delta\theta(\tau)$'s that occur per hour, that is, $3600/\tau$ events per hour spaced $\tau$ seconds apart, half being clockwise and half being counterclockwise.

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

The total number of velocity changes of a given magnitude that may occur during a turbine's life should be useful in control analysis. The following equation may be used to compute the expected number ($N_T$) of direction changes (which exceed a given value) that occurs over a given number of years (Y).

$$N_T[\Delta\theta(\tau) > X] = 8766(Y)\int_0^\infty N\, p(\overline{U}_h)\, d\overline{U}_h \tag{10}$$

where

$N_T$ = total number of expected direction changes greater than X, which occur in Y

8766 = number of hr in 1 yr

Y = number of yr

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

If only direction changes that occur while the turbine is operating are of interest, the limits of integration for Equation (10) should be from the turbine cut-in velocity to the turbine cutout velocity rather than from 0 to ∞.

If a frequency distribution of the hourly mean values of the longitudinal wind component ($P(\overline{U}_h)$) is not known for a particular site being analyzed, the Rayleigh distribution for $P(\overline{U}_h)$ may be used as follows:

$$P(\overline{U}_h) = \frac{\overline{U}_h \pi}{2U_a^2}\, e^{\frac{-\pi}{4}\frac{\overline{U}_h^2}{U_a^2}} \tag{11}$$

where $U_a$ is the annual mean longitudinal wind component at hub height.

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# APPENDIX

## PROCEDURE FOR CALCULATING DIRECTION CHANGES

## PROCEDURE FOR CALCULATING DIRECTION CHANGES

The following criteria should be used for computing the angular changes in wind direction, which are encountered over the disk of rotation of a wind turbine. (Angular variation is defined as the difference in the wind angle $\theta(t + \tau)$ measured at time $(t + \tau)$ and the wind angle $(\theta(t))$ measured at an earlier time $(t)$; therefore, angular variation equals $\Delta\theta = \theta(t + \tau) - \theta(t)$.)

The following formula gives the approximate number (N) of angular changes, $\Delta\theta(\tau) = \theta(t + \tau) - \theta(t)$, per hour that exceeds a given value, X. The number (N) represents the absolute number of $\Delta\theta(\tau)$ that occurs. Equal numbers should occur clockwise as counterclockwise; thus, if only the clockwise or counterclockwise $\Delta\theta(\tau)$'s are desired the number (N) calculated is simply divided by two.

$$N[\Delta\theta(\tau) > X] = \frac{3600}{\tau} (1 + d_1 z + d_2 z^2 + d_3 z^3 + d_4 z^4 + d_5 z^5 + d_6 z^6)^{-16} \qquad \text{(A-1)}$$

where:

$\tau$ is in seconds

$z = \dfrac{X}{\sigma_{\Delta\theta}(\tau)}$

$d_1 = 0.0498673470$

$d_2 = 0.0211410061$

$d_3 = 0.0032776263$

$d_4 = 0.0000380036$

$d_5 = 0.0000488906$

$d_6 = 0.0000053830$

$$\sigma_{\Delta\theta}(\tau) = \frac{1.1}{\ln\left(z_h/z_o\right)}\left[\int_0^{\overline{U}_h/D} \phi_v(f)\ (1 - \cos\pi 2\tau f\ )\ df\right]^{\frac{1}{2}} \qquad \text{(A-2)}$$

D = diameter of wind turbine, m

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

$z_o$ = 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)

$z_h$ = height of measurement, m, (hub height of wind turbine).

$$\phi_v(f) = \frac{2L_v}{\overline{U}_h}\ \frac{1 + \frac{8}{3}\left(1.339\ L_v\ \frac{2\pi f}{\overline{U}_h}\right)^2}{\left[1 + \left(1.339\ L_v\ \frac{2\pi f}{\overline{U}_h}\right)^2\right]^{11/6}} \qquad \text{(A-3)}$$

$$L_v = \frac{5.1\ Z_h^{0.48}}{Z_o^{0.086}}$$

To calculate the total number of occurences over the life of the wind turbine, Equation (10) in the text should be used.

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