Gust-Rise Exceedance Statistics for Wind Turbine Design

C. H. Huang
G. H. Fichtl

July 1979

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SUMMARY

When designing a wind machine, the number of large amplitude gusts for the design-life exposure of a wind machine should be estimated, because velocity change controls the acceleration rate of a rotor. Since the record length of data is insufficient, the theoretical study of gust rise may shed some light on the empirical formulation in which some important parameters may have been ignored.

Fichtl^(a) developed an equation based on Rice's theory (1944, 1945), which estimates the total number of crossings with positive slope per unit of time that exceeds a prescribed level of velocity change. This paper discusses the analytical representation of Fichtl's formulation and presents useful results of the velocity change for the design life of a wind energy conversion system (WECS).

With a lag time of 10 sec and an hourly mean longitudinal wind velocity of 10 m/sec, the magnitude of velocity change for 1-hr recurrence is 6.5 m/sec for a large wind machine; the magnitude of velocity change for 30-yr recurrence is larger than 1-hr recurrence by a factor of about six. The magnitude of velocity change is substantially reduced, when the cut-out velocity is incorporated into the calculation. For a given level of velocity change, the number of gust rises per unit of time also varies with the nondimensional parameter.

(a) G. H. Fichtl, "Technique for Calculating Wind-Speed Changes in the Atmospheric Boundary Layer for WECS Design." (Draft)

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INTRODUCTION

In designing a wind machine as in conducting strength-and-fatigue analyses, the velocity changes over a certain lag time should be known, because the magnitude of velocity changes controls the acceleration rate of a rotor in a wind machine. The theoretical study of gust rise may shed some light on the formulation for general sites and may indicate some important parameters that have been ignored in the empirical formulation. Generally, field data are inadequate and the period for data collection is insufficient to make a definite conclusion on gust rise.

Fichtl^(a) developed an equation, based on Rice's theory (1944, 1945), for estimating the total number of crossings with positive slope per unit of time that exceeds a prescribed level of velocity change. This paper is concerned with the analytical representation of Fichtl's formulation and presents a method for obtaining useful results of the velocity change for the design life of a wind energy conversion system (WECS). The characteristics of turbulence spectra and the variability of length scale, turbulence intensity, and surface roughness that are needed for computing the total number of gust rises from the formula are also described briefly in this paper.

(a) G. H. Fichtl, "Technique for Calculating Wind-Speed Changes in the Atmospheric Boundary Layer for WECS Design." (Draft)

A TEMPORAL WIND-CHANGE PROCESS EQUATION

Fichtl^(a) derived an equation for the temporal wind-change process, based on Rice's theory (1944, 1945). In Fichtl's formulation, if the total number of crossings with positive slope per unit of time over the expected life of a wind machine is assumed known, then the magnitude of the velocity change over lag time (τ) can be determined. According to Rice's theory, the average number of temporal wind changes with positive slope per unit of time, which exceeds a prescribed value of velocity change (Δu), may be expressed as:

$$N(\Delta u) = N_0 e^{-\frac{(\Delta u)^2}{2\sigma_{\Delta u}^2}} \quad (1)$$

where

- $\sigma_{\Delta u}$ = the standard deviation of velocity change (Δu) because of turbulence gusts
- N_0 = the expected number of zero crossings with positive slope per unit of time because of wind change
- N_0 is given by:

$$N_0^2 = \frac{1}{(2\pi)^2} \frac{\int_{-\infty}^{\infty} \omega^2 \phi_{\Delta u}(\omega) d\omega}{\int_{-\infty}^{\infty} \phi_{\Delta u}(\omega) d\omega} \quad (2)$$

(a) G. H. Fichtl, "Technique for Calculating Wind-Speed Changes in the Atmospheric Boundary Layer for WECS Design." (Draft)

where

- ω = the angular frequency in units of radian per unit of time
- $\phi_{\Delta u}$ = the spectra of Δu in frequency domain as given by:

$$\begin{aligned}\phi_{\Delta u}(\omega, z, \tau) &= 2 \phi_u(\omega) (1 - \cos \omega \tau) \\ &= \frac{2}{\bar{u}} \frac{\sigma_u^2 \cdot L_u}{\pi} \cdot \frac{1 - \cos \omega \tau}{1 + \left(\frac{L_u \omega}{\bar{u}(z)} \right)^2}\end{aligned}\quad (3)$$

where

- z = the height above the ground
- $\bar{u}$ = hourly longitudinal wind velocity
- σ_u = the standard deviation of longitudinal velocity
- L_u = the integral scale length.

Equation (3) was obtained through the use of the Dryden spectral density function $[\phi_u(\kappa)]$ for the longitudinal component of turbulence:

$$\phi_u(\kappa) = \frac{\sigma_u^2 L_u}{\pi} \cdot \frac{1}{1 + (L_u \kappa)^2} \quad (4)$$

Substituting Equation (3) into Equation (2), the following equation is obtained.

$$N_0^2 = \frac{\bar{u}^2(z)}{L_u^2(z)} \frac{\int_0^\infty \frac{2}{\pi} \Omega^2 \left[\frac{1 - \cos \left(\Omega \frac{\tau \bar{u}(z)}{L_u(z)} \right)}{1 + \Omega^2} \right] d\Omega}{(2\pi)^2 \left[1 - e^{-\tau \bar{u}(z)/L_u(z)} \right]} \quad (5)$$

where

$$\Omega(z) = \frac{L_u(z)\omega}{\bar{u}(z)}$$

Introducing the log-law wind profile into Equation (5) results in:

$$N_0^2 = \frac{K_1^2 \bar{u}^2(z_r)}{L_u^2(z)} \frac{1}{(2\pi)^2} \frac{\int_0^\infty \frac{2}{\pi} \Omega^2 \left[\frac{1 - \cos\left(\frac{\Omega \tau \bar{u}(z_r) K_1}{L_u(z)}\right)}{1 + \Omega^2} \right] d\Omega}{1 - e^{-\tau \bar{u}(z_r) K_1 / L_u(z)}} \quad (6)$$

where

$$K_1 = \frac{\bar{u}(z)}{\bar{u}(z_r)} = \frac{\ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right)}{\ln\left(\frac{z_r}{z_0}\right) - \psi\left(\frac{z_r}{L}\right)}$$

and for neutral conditions, $\psi\left(\frac{z}{L}\right) = 0$

where

- $\bar{u}(z_r)$ = the wind speed at a reference height (z_r)
- ψ = the correction term for the wind speed as a result of thermally stratified flow.

In Equation (1), the standard deviation ($\sigma_{\Delta u}$), which depends on the standard deviation (σ_u), must be known. However, since σ_u is usually not known, it is expressed as a function of a known quantity. In the following, a relationship between σ_u and the hourly mean longitudinal wind velocity ($\bar{u}$) is derived.

According to the similarity theory, the ratio of σ_u/u_* is a universal function of the Monin-Obukhov stability parameter z/L and can be expressed as:

$$\frac{\sigma_u}{u_*} = F\left(\frac{z}{L}\right) \quad (7)$$

where

- $F\left(\frac{z}{L}\right)$ = a universal function
- u_* = the friction velocity.

Under neutral conditions, the function (F) is equal to 2.5; i.e., $F_u(0) = 2.5$.

The wind profile follows the log law as:

$$\bar{u} = \frac{u_*}{k} \left[\ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right) \right] \quad (8)$$

where

- z_0 = the surface roughness
- k = the von Karman constant, 0.4
- z = the hub height above the ground.

Therefore, the standard deviation (σ_u) is related to the hourly mean longitudinal wind velocity ($\bar{u}$) by:

$$\sigma_u = K_2 \bar{u}(z_r) \quad (9)$$

where

$$K_2 = \frac{F\left(\frac{z}{L}\right)k}{\ln \frac{z_r}{z_0} - \psi\left(\frac{z_r}{L_0}\right)}$$

From the definition of $\sigma_{\Delta u}$ and by using Equation (9), the standard deviation $\sigma_{\Delta u}$ is:

$$\sigma_{\Delta u}^2 = 2 K_2^2 \bar{u}^2(z_r) \left[1 - e^{-K_1 \bar{u}(z_r) \tau / L_u(z)} \right] \quad (10)$$

where

- $\bar{u}(z_r)$ is the hourly mean longitudinal wind velocity at the reference height.

To obtain the climatological exceedance rate of Δu , the total number of crossings of Δu must be found. This may be done by introducing the probability density function of hourly mean longitudinal wind velocity as follows:

$$N(\Delta u) = \int_0^\infty N_0 e^{-\frac{\Delta u^2}{2\sigma_{\Delta u}^2}} p[\bar{u}(z_r)] d\bar{u}(z_r) \quad (11)$$

The Weibull distribution and the Rayleigh distribution for hourly mean longitudinal wind velocity $[P(u)]$ are frequently used to fit the climatological mean wind distribution. Since the Rayleigh distribution of hourly mean longitudinal wind velocity is completely determined if the climatological hourly mean longitudinal wind velocity is known, the probability density function $p[\bar{u}(z_r)]$ as in Equation (11) will be used as the Rayleigh distribution.

$$p[\bar{u}(z_r)] = \frac{\bar{u}(z_r)}{\theta^2} e^{-\frac{\bar{u}^2(z_r)}{2\theta^2}} \quad (12)$$

$$\theta = \sqrt{\frac{2}{\pi}} <\bar{u}(z_r)>$$

where

- $\langle u(z_r) \rangle$ = the climatological ensemble average, i.e., the climatological mean longitudinal wind velocity such as the annual mean longitudinal wind velocity speed.

Substituting Equation (12) into Equation (11) results in:

$$N(\Delta u) = \int_0^{\infty} N_0 e^{-\frac{\Delta u^2}{2\sigma_{\Delta u}^2}} \frac{\bar{u}}{\theta^2} e^{-\frac{\bar{u}^2(z_r)}{2\theta^2}} d\bar{u}(z_r) \quad (13)$$

For convenience, Equation (13) is expressed in nondimensional form as:

$$H(y_u, T_u, \Lambda_u) = \int_0^{\infty} n(\chi T_u; \Lambda_u) e^{-\frac{y_u^2}{2\chi^2(1-e^{-\chi T_u})}} \chi^2 e^{-\frac{\chi^2}{2}} d\chi \quad (14)$$

where

$$\chi = \frac{\bar{u}(z_r)}{\theta}$$

$$\Lambda_u = \frac{\lambda_c}{L_u(z)}$$

τ = the lag time for the velocity change (Δu)

$$H(y_u, T_u, \Lambda_u) = N(\Delta u) \frac{L_u(z)}{K_1 \theta} = N(\Delta u) \frac{L_u(z) \ln\left(\frac{z_r}{z_0}\right)}{\theta \ln\left(\frac{z}{z_0}\right)} \quad (15)$$

$$y_u = \frac{\Delta u \ln \left(\frac{z_r}{z_0} \right)}{\sqrt{2} (2.5) k \theta} \quad (16)$$

$$T_u = \frac{\tau \theta \ln \left(\frac{z}{z_0} \right)}{L_u(z) \ln \left(\frac{z_r}{z_0} \right)} \quad (17)$$

$$n(xT_u) = \frac{1}{2\pi} \left\{ \int_0^\infty \frac{\left[\frac{2}{\pi} \Omega^2 \frac{1 - \cos(x T_u \Omega)}{1 + \Omega^2} \right] d\Omega}{1 - e^{-xT_u}} \right\}^{1/2} \quad (18)$$

where n as defined in Equation (18) relates to the expected number of zero crossings as a result of wind change (N_0).

The integral in Equation (18), which corresponds to that of Equation (2), diverges; this implies that an infinite number of zero crossings occur for velocity change (Δu). The infinite number of crossings arises from high-frequency fluctuations. In reality, viscosity causes a sharper roll-off (at high frequencies) than normal atmospheric spectra would indicate; besides, any instrument's response to turbulence will filter out high-frequency fluctuations. As a result, the total number of zero crossings for Δu remains finite. Therefore, a cutoff wavelength with the quantity λ_c is introduced so that N_0 will remain bound. Based on the shortest gust wavelength to which an instrument responds, λ_c was selected so that for wavelengths shorter than λ_c negligible or no additional response is obtained. Because Equation (14) contains double integrals, it is time consuming to evaluate Equation (14); therefore, an analytical expression for Equation (18), which saves computational time, can be approximately written as:

$$n(\chi T_u; \Lambda_u) = \frac{1}{2\pi} \left\{ \frac{\frac{2}{\pi} \left[\int_0^{2\pi/\Lambda_u} \left[\frac{\Omega^2}{1 + \Omega^2} - \cos(\chi T_u \Omega) \right] d\Omega \right] + \int_0^\infty \frac{\cos(\chi T_u \Omega)}{1 + \Omega^2} d\Omega}{1 - e^{-\chi \cdot T_u}} \right\}^{1/2} \quad (19)$$

Because the first term on the right-hand side of Equation (19) diverges, a cutoff wavelength (λ_c) is introduced. Therefore, no cutoff wavelength is introduced into the second term on the right-hand side of Equation (19). Thus, Equation (19) can be analytically expressed as:

$$n(\chi \cdot T_u; \Lambda_u) = \frac{1}{2\pi} \left\{ -1 + \frac{\frac{2}{\pi} \left[\Omega - \tan^{-1} \Omega - \frac{1}{\chi \cdot T_u} \sin(\chi \cdot T_u \Omega) + 1 \right]}{1 - e^{-\chi \cdot T_u}} \right\}^{1/2} \quad (20)$$

The total number of crossings (N) for the velocity change that exceeds a prescribed value of velocity change (Δu) or vice versa can be calculated from Equation (14); once the climatological mean longitudinal wind velocity, the turbulence scale, and the dimension of the structure (λ_c) are known. However, if the expected life of a structure is known, N can be determined by using the Poisson equation. The velocity change (Δu) for a lag time (τ) in seconds can be estimated from Equation (14). For example, suppose the expected life of a structure is 30 yr and the risk is 63%. In such a situation, the velocity change that exceeds a value of Δu at least once in 30 yr can be calculated using Equation (14).

FIRST EXCURSION WIND-SPEED CHANGE

A realization of velocity change (Δu) is schematically shown in Figure 1. Time (t_1) is associated with the first excursion of Δu , which exceeds a prescribed value of (Δu) critical. The collection of the time of the first excursion is statistically distributed. A Poisson failure model can be used to describe this statistical distribution; it can also be used to relate risk (R) to the design life of a WECS, (t_0 for $t > t_0$). According to the Poisson failure model,

$$R = 1 - e^{-Nt_0} \quad (21)$$

or

$$N = \frac{\ln(1 - R)}{t_0} \quad (22)$$

where N is the average rate of crossings of the velocity change Δu , which exceeds a prescribed value of $(\Delta u)_{\text{CRITICAL}}$. N can be calculated once risk and WECS life (t_0) are known. By substituting N and the specified values of τ , z_0 , z , z_r , θ , $L(z)$, and Λ_u into Equation (14), the velocity change (Δu) can be calculated.

FIGURE 1. Realization of Velocity Change, Δu , with time, t

GUST BUILD-UP RATES

In the previous section, the rate of the total number of crossings (N) for the velocity change exceeding Δu , including the climatological mean wind distribution, was discussed. In this subsection, the climatological mean wind distribution will not be considered; instead, the gust build-up rates as expressed directly in Equation (1) will be considered.

By using the Poisson failure model, the following equation results:

$$N(\Delta u) = N_0 e^{-\frac{(\Delta u)^2}{2\sigma_{\Delta u}^2}} \quad (23)$$

Equation (23) yields the nondimensional velocity change as follows:

$$\Delta U = \sqrt{2} (1 - e^{-T})^{1/2} \left[\ln \left(-\frac{T_L n_0}{\ln(1-R)} \right) \right]^{1/2} \quad (24)$$

where

$$\Delta U = \frac{\Delta u}{\sqrt{2} K_2 \bar{u}_r}$$

$$T = \frac{K_1 \bar{u}_r \tau}{L_u}$$

$$T_L = \frac{\bar{u}_r K_1}{L_u 2\pi} t_L$$

$$n_0 = \frac{N_0 L_u 2\pi}{\bar{u}_r K_1} = \left\{ -1 + \frac{\frac{2}{\pi} \left[\Omega - \tan^{-1} \Omega - \frac{1}{T} \sin(T\Omega) \right] + 1}{1 - e^{-T}} \right\}^{1/2}$$

and t_L is the time of exposure in the design wind condition.

METHOD OF CALCULATION

For convenience, Equation (1) for velocity change (Δu) is rewritten as follows:

$$H(y_u, T_u, \Lambda_u) = \int_0^\infty n(x T_u; \Lambda_u) e^{-\frac{y_u^2}{2x^2(1-e^{-xT_u})}} x^2 e^{-\frac{x^2}{2}} dx \quad (25)$$

where

$$n_u(x \cdot T_u; \Lambda_u) = \frac{1}{2\pi} \left\{ -1 + \frac{\frac{2}{\pi} \left[\Omega - \tan^{-1} \Omega - \frac{1}{x \cdot T_u} \sin(x \cdot T_u \Omega) + 1 \right]}{1 - e^{-x \cdot T_u}} \right\}^{1/2} \quad (26)$$

With the specification of Δu , τ , z_0 , z , z_r , θ , $L(z)$ and Λ , the integral in Equation (25) can be calculated by using Simpson's rule; thus, the values of H or N can be calculated for various values of τ , Λ_u , and Δu . With the risk value for WECS and the diameter of a rotor specified, the relationship can be established between the velocity change (Δu) exceeding a prescribed value of Δu at least once in the design life of a WECS and the lag time (τ).

A plot of the total number of nondimensional gusts (H) with amplitude exceeding a prescribed level of nondimensional velocity change (y_u) for various lag times (τ) is shown in Figure 2. For a specified value of H that can also be determined from Equation (21) and τ , the nondimensional velocity change (y_u) can be estimated for the life exposure of a WECS design (see Figure 2).

Knowledge of longitudinal spectra is needed to calculate the total number of gusts with amplitude exceeding the velocity change (Δu). Therefore, the different turbulence spectra, the turbulence intensity and length scale that are needed to compute the turbulence spectra will be described briefly in the following sections.

FIGURE 2. Relationship Between the Temporary Velocity Changes and the Total Number of Crossings

TURBULENCE SPECTRA

Turbulence spectra such as Dryden's spectra and von Karman's spectra have been frequently applied to turbulence simulations and fatigue analyses in aerospace engineering. In order to understand the limitations of these spectra and to determine their range of applicability, these spectra and Kaimal's spectra were compared by plotting these spectra as shown in Figure 3. Kaimal's spectra was obtained from the wind measurements for the surface boundary layer below 30 m. The validity of Kaimal's spectra above 30 m is not yet known; however, the comparison of the stable case of Kaimal's spectra and von Karman's spectra indicates that these two spectra are similar. Since von Karman's spectra has been frequently applied to the layer above 30 m and since Kaimal's spectra is similar, Kaimal's spectra in

FIGURE 3. Spectral Comparisons

the stable case may also be a good representation of the turbulence characteristics above the surface boundary layer. For neutral conditions, Kaimal's spectra departs significantly from von Karman's; therefore, the validity of these spectra above 30 m should be validated by wind data. The information on length scale and turbulence intensity needed in computing the turbulence spectra is described in the following subsections.

VARIATION OF THE LONGITUDINAL LENGTH SCALE

Variation of the longitudinal length scale has been investigated and many longitudinal-length-scale models have been proposed. Most researchers suggest that the longitudinal length scale increases with height as shown in Figure 4 (Barr, Gangsaas and Schaeffer 1974; Luers 1973; Teunissen 1970; Counihan 1975). Counihan (1975) suggested that the longitudinal length scale depends on the surface roughness and proposed a formula for the longitudinal length scale (L_u) at $z = 30$ m:

$$L_u = 108 \left(\frac{1}{z_0} \right)^{1/6} \quad (27)$$

which indicates that longitudinal length scale decreases with increasing surface roughness. In order to take into account the influence of surface roughness in the longitudinal length scale, Counihan (1975) suggested that the longitudinal length scale be expressed as:

$$L_u = cz^{\frac{1}{n}} \quad (28)$$

where the parameters c and n vary with the surface roughness length (z_0). Variations of these parameters with different terrain types are shown in Figure 5. Figure 5 also shows that the longitudinal length scale decreases with increasing surface roughness. For computational convenience, a regression fit for parameters, c and n , based on the curves given by Counihan (1975) was obtained:

$$c = \frac{25}{z_0^{0.4}}$$

$$\frac{1}{n} = -0.25 (\ln z_0)^2 + 0.17 \ln z_0 - 0.8$$

FIGURE 4. Longitudinal-Length-Scale Comparisons

TURBULENT INTENSITY

If Monin-Obukhov similarity for the longitudinal turbulent fluctuations and the log-law wind profile are used, the turbulence intensity (see Equation 9) can be expressed as:

$$\frac{\sigma_u}{u} = K_2 \quad (29)$$

FIGURE 5. Variation of C and $1/n$ with Roughness Length

where for neutral conditions,

$$K_2 = \frac{F\left(\frac{z}{L}\right)k}{\ln \frac{z}{z_0} - \psi\left(\frac{z}{L}\right)} = \frac{1}{\ln \frac{z}{z_0}}$$

Equation (29) shows that the turbulent intensity depends on the atmospheric stability, surface-roughness length, and height. The data of turbulent intensity collected by Counihan (1975) and Shelland (1968) are plotted in Figure 6. Figure 6 shows the variation of turbulent intensity with surface-roughness length z_0 . The turbulent intensity expressed in Equation (29) for various surface roughness and for the heights 10, 30, and 50 m under neutral conditions is also plotted in Figure 6. Curve A in Figure 6 is the regression fit of the experimental data proposed by Counihan (1975). For smaller surface-roughness lengths up to $z_0 = 0.1$, the curves B and C obtained from the similarity theory at heights of $z = 10$ m and $z = 30$ m, respectively, fit the experimental data well; however, for greater surface roughness, curve D, based on the similarity theory, is a good fit of experimental data up to the surface-roughness length of $z_0 = 1.0$ m. Beyond $z_0 = 1.0$, very little experimental data are available.

Further work on the measurements of turbulence intensity over high mountains or very rough urban areas is needed. In this rougher type of terrain, the value of turbulent intensity is suggested to be 0.3 to 0.4. The theoretical results and the experimental data, as shown in Figure 6, indicate that the turbulence intensity increases with increasing surface roughness and decreases with height. The relationship between various types of terrain features and surface-roughness length is shown in Table 1 (Counihan 1975).

FIGURE 6. Roughness Variation of Turbulence Intensity with Height and Surface

TABLE 1. Main Terrain Types and Surface Roughness Length

Quantity	Terrain Types				
	SMOOTH Ice-Mud-Snow-Sea	MODERATELY ROUGH Grass-Crops-Rural	ROUGH Woods-Woods-Suburbs	VERY ROUGH Urban	
z_0 cm	0.001-0.04-0.1-0.2	0.1 - 3 ~ 7 - 20	100	- 150	100-300-400
$\overline{u'w'}/u_0^2$	0.0004-0.006-0.001	0.0014-0.0020-0.0040		-	-
$1/\alpha$	0.08 - 0.11 - 0.12	0.13 - 0.143 - 0.16	0.20	- 0.23	0.25 - 0.40
$(\sqrt{\overline{u'^2}}/\overline{u})_{0 \leq z(m) \leq 30}$	0.10 - 0.12	0.13 - 0.20	-	0.20 -	0.30 - 0.48

THEORETICAL RESULTS

The magnitude of velocity change of 1-hr recurrence computed from Equation (24) for three different types of WECS and various lag times are shown in Table 2. In obtaining the results in Table 2, the hub height of a WECS was at 50 m and the value of risk at 0.63. For one-dimensional turbulence, the effect of windmill size on the velocity change is relatively small as shown in Table 2. With a lag time of 10 sec and mean wind speed of 10 m/sec, the magnitude of velocity change is 6.46 m/sec for a large wind machine.

TABLE 2. Velocity Change for 1-hr Recurrence, m/sec

τ , sec	Diameter of Wind Turbine, m		
	Small, 1 m	Medium, 10 m	Large, 60 m
0.05	0.8879(a)	0.6776	0.5785
0.1	1.2257	0.9925	0.777
0.3	2.0324	1.7930	1.3072
0.5	2.5621	0.3252	1.7238
1.0	3.4861	3.1453	2.5288
3.0	5.5156	4.9251	4.4069
5.0	6.6701	5.9260	5.3234
10.0	8.2693	7.30	6.4595

(a) condition: $\bar{u} = 10$ m/sec

The magnitude of velocity change for 30-yr recurrence computed from Equation (25), including climatological data, is shown in Table 3. The conditions for obtaining these results are the same as in Table 2, except in those cases where the distribution of climatological mean wind speed was included. Comparing the results in Table 3 to the results in Table 2 indicates that the magnitude of velocity change with regard to the cases including the climatological data is significantly larger by a factor of more than five than those cases excluding the climatological wind data.

TABLE 3. Velocity Change for 30-yr Recurrence, m/sec

τ , sec	Diameter of Wind Turbine, m		
	Small, 1 m	Medium, 10 m	Large, 60 m
0.05	6.464	5.868	3.920
0.1	8.925	8.357	7.196
0.3	14.717	13.779	12.583
0.5	18.379	17.241	16.126
1.0	24.34	22.846	21.791
3.0	34.603	31.773	30.916
5.0	38.274	35.405	34.289
10.0	40.762	38.536	36.631

The magnitude of velocity change for a 30-yr recurrence with cutout speed of 25 m/sec is shown in Table 4. The results indicate that the magnitude of velocity change is substantially reduced.

TABLE 4. Velocity Change for 30-yr Recurrence with Cutout Speed of 25 m/sec

τ , sec	Diameter of Wind Turbine, $\bar{u}$ at 10 m/sec		
	Small, 1 m	Medium, 10 m	Large, 60 m
0.05	3.54	3.25	2.99
0.1	4.91	4.65	4.26
0.3	8.33	8.87	7.49
0.5	10.58	10.17	9.64
1.0	14.42	13.36	13.38
3.0	22.04	21.20	20.47
5.0	25.59	24.62	23.82
10.0	29.08	27.97	27.02

VARIATION OF GUST RISES WITH A NONDIMENSIONAL PARAMETER

If Dryden's spectra are used for obtaining the standard deviation of velocity change ($\sigma_{\Delta u}$), then, following Rice's theory and Equation (1), the number of crossings with gust amplitude difference exceeding a given level of Δu per unit of time becomes:

$$N = N_0 e^{-ax^2} \quad (30)$$

where

$$x = \frac{\Delta u}{\sigma_u}$$
$$a = \frac{1}{4 (1 - e^{-T})} \quad (31)$$

$$T = \frac{\bar{u} \tau}{L_u(z)}$$

The theoretical results as shown in Equation (30) indicate that the exceedance parameter (a) is dependent on the mean wind speed ($\bar{u}$), the turbulence scale $L_u(z)$ and the lag time (τ).

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