The Influence of Atmospheric Turbulence on the Kinetic Energy Available During Small Wind Turbine Power Performance Testing

By

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1. Introduction

The influence of atmospheric turbulence on the total kinetic energy available in the wind has been discussed for many years. Putman (1948) discussed this concept in his synopsis of the experiments carried out on the 1250 kW Smith-Putman wind turbine at Grandpa's Knob, Vermont in the early 1940's. Putman demonstrated through the use of the cube factor, the ratio of $\overline{U^3}/\overline{U}^3$, that using an hourly average wind speed to calculate the total kinetic energy available to the turbine would underestimate the actual kinetic energy by up to 14%, at the Grandpa's knob site.

Engineers have often ignored the influence of atmospheric turbulence because of its dual influence on turbine power production. The presence of atmospheric turbulence not only increases the kinetic energy available to the wind turbine; it also tends to decrease the efficiency of the turbine at converting the kinetic energy into mechanical or electrical power. While each of these two characteristic effects of turbulence can be significant, they also have the potential to cancel each other out. This may lead one to inappropriately diminish the importance of turbulence when evaluating turbine performance.

Currently the only discussion of turbulence in the IEC 61400-12 (1998) international standard for wind turbine power performance testing is a requirement that the site characterization documentation should include a scatter plot of the turbulence intensity as a function of wind direction. No guidance or standards are included which either state an acceptable range for the approach turbulence or provide any indication of any corrections that may need to be applied to account for the local turbulence.

This paper will demonstrate that the presence of atmospheric turbulence at the test site is particularly important when evaluating small wind turbines. Unlike utility grade wind turbines, the smaller wind turbines are often placed on shorter towers, in a wide variety of landscapes, and often in less than optimal locations. These factors combine to create a wide range of turbulent environments in which the wind turbines are expected to perform. Therefore, it is important that the power performance testing standard for small wind turbines should adequately address the influence that the atmospheric turbulence has on expected power performance.

2. Turbulence in the Atmospheric Boundary Layer

The atmospheric boundary layer is created by aerodynamic friction resulting from the motion of the air relative to the earth's surface and thermal gradients between the upper atmosphere and the surface. The resultant is a vertical wind shear that varies not only in magnitude but also in structure. The variation in mean wind speeds with height above grade is often defined using a power law relationship where:

$$U_z = U_{ref} \times \left(\frac{z}{z_{ref}} \right)^n$$

where:

n = power law coefficient;
U_z = longitudinal mean velocity at height, z;
U_{ref} = longitudinal mean velocity at a reference height, z_{ref};
z = height above local grade; and
z_{ref} = reference height above local grade.

The magnitude of the power law coefficient may vary between 0.1 in exceptionally smooth terrain to approximately 0.35 in very rough terrain such as built-up urban areas (Snyder, 1981). An estimate for the value of the power law coefficient can be obtained from the surface roughness length, z_o, using the following relationship from Counihan (1975):

$$n = 0.24 + 0.096\log_{10} z_0 + 0.016(\log_{10} z_0)^2$$

There are several references which site values for the surface roughness length based on descriptive characterizations of the local terrain. Three of the more common references are Davenport (1965), Simiu and Scanlan (1978), and Weiringa (1992). While there is some disagreement about specific values of z_0 for a particular terrain, in general, values range from less than 1 cm for smooth surfaces up to several meters for the middle of urban areas. Figure 1 shows typical values for n and z_0 for various terrains ranging from seas to highly built-up urban areas, along with plots of the associated vertical velocity profiles.

In addition to producing a velocity deficit near the surface, the presence of aerodynamic friction and thermal gradients are also responsible for the creation of atmospheric turbulence. The variation in the longitudinal turbulence intensity, T.I., within the lower portion of the atmospheric boundary layer, from 0 to 100m above grade, can be defined from the following relationship from Snyder (1985):

$$\left(\frac{U_{rms}}{\overline{U}}\right) = T.I. = n\ln\left(\frac{30}{z_0}\right) \div \ln\left(\frac{z}{z_0}\right)$$

where:

U_{rms} = root mean squared longitudinal velocity; and
$\overline{U}$ = mean longitudinal velocity.

At heights above 100m, Snyder (1981) suggests that the turbulence intensity can be estimated by assuming a T.I. value of 0.01 at 600m and assuming a linear relationship between 100m and 600m.

Figure 2 shows the corresponding variation in longitudinal turbulence as a function of height above grade for the same terrain features shown in vertical velocity profiles indicated in Figure 1.

The current site characterization requirements included in the IEC 61400-12 (1998) standard only include limitations on the presence of topographical variations near the site, the presence of nearby operating wind turbines, and the location of significant obstacles in the direct vicinity of the test site. All of these criteria could potentially be met for site descriptions ranging from a sea environment to a suburban environment. Assuming that hub heights may also vary between 10m (the minimum hub height referenced in the proposed small wind turbine annex) to 50m above grade, Figure 2 indicates that the T.I. values may range from less than 10 percent up to values over 30 percent. The influence that this wide range of hub height T.I. values may have on the level of kinetic energy approaching a test unit is discussed in the following section.

3. Increase in Kinetic Energy Associated with Turbulent Flow

The first step in calculating the increase in kinetic energy associated with various levels of turbulent intensity is to define the distribution of wind speeds within the sample period used for evaluating small wind turbine power performance curves.

Three characteristic forces define the airflow within the atmospheric boundary layer: macro, meso, and microscale motions. Macroscale motion features scales in excess of 2000 km created by synoptic troughs, ridges, highs, lows and frontal boundaries. Mesoscale features range from near macroscales down to individual cloud cells with dimensions of 1–20 km. Microscale motions are those that are influenced by smaller obstacles and terrain features and are considered to be the turbulent portion of the approach flow. One defining characteristics of the microscale flow is that the magnitude of the velocity fluctuations within each of the three Cartesian cordinates are of the same magnitude, whereas in both the macro and meso scales the longitudal components of the flow dominate the lateral or vertical fluctuations.

The distribution of mean wind speeds is often assumed to follow a Rayleigh (or Weibull) distribution. Such a distribution is used in the IEC 61400-12 standard for calculating the estimated annual energy production (AEP) for a site based on an annual average wind speed. As such, the Rayleigh distribution includes the influence of macro, meso, and microscale motion, as discussed above. When evaluating the distribution of wind speeds over a shorter averaging time period, such as the 10 minute average identified in the IEC61400-12 standard, or the 1 minute average proposed for the small wind turbine annex to this standard, a different wind speed distribution may be warranted. At the 1 to 10 minute time intervals, the influence of macro and mesoscale motion is limited. Rather, the motion is dominated by the microscale or turbulent motion. Panofsky and Dutton (1984) indicate that the Gaussian distribution can be used to approximate the probability density function for turbulent motion despite the fact that turbulence is not specifically a Gaussian process.

Figure 3 shows the distribution of 1-second wind speeds within various averaging times ranging from 10 seconds to 1 hour. The data was collected at CPP's test site at 10m above grade. The site can be characterized as "open-country" and has the classical $1/7^{th}$ power law velocity profile. The plot clearly indicates that, at least up to the 10 minute averaging time, the distribution of wind speeds is indeed Gaussian in nature. At the 1 hour averaging time the distribution comes less symmetric and begins to approach the Rayleigh distribution. However, even at the 1 hour averaging time period the Gaussian distribution still more closely defines the wind speed distribution.

The fact that a Gaussian distribution can be used to define the wind speed distribution is quite fortuitous since a Gaussian distribution can be fully defined by its mean and rms values. If the measured wind speeds, U, are normalized by its short term average, $\overline{U}$, as shown in Figure 3, the Gaussian distribution can defined by $U_{\text{rms}} / \overline{U}$, the definition of the turbulence intensity, and the normalized mean wind speed, which by definition equals unity. Therefore, the relationship between the mean wind speed cubed and the mean cubed wind speed, i.e., the cube factor can be empirically determined by integrating the area under cubed wind speed probability distribution such that:

$$\left(\frac{\overline{U^3}}{\overline{U}^3}\right)=\sum_{\left(U/\overline{U}\right)}^{\infty}\left(\frac{U}{\overline{U}}\right)^3\times P\left(\frac{U}{\overline{U}}\right)$$

where:

$P\left(\frac{U}{\overline{U}}\right)$ = probability of the normalized wind speed $U/\overline{U}$, assuming a Gaussian distribution.

The resulting relationship between the cube factor and the local T.I. is shown in Figure 4. As stated in the previous section, the T.I. values that might be present at the hub height for a small wind turbine test unit may vary between 10 and 30 percent. Figure 4 indicates that the cube factor at 10 percent turbulence is only approximately 1.03, however, at 30 percent turbulence the cube factor increases to approximately 1.27. Therefore, with the same mean wind speed the kinetic energy approaching a turbine set at 10m above grade in a suburban environment would be 23% greater than that approaching a turbine set at 50m above grade in a sea environment. Although both of these potential test locations would meet the IEC 61400-12 site characterization standards, it is obvious that significantly different power performance results would be obtained at the two sites.

4. Potential Mitigation

There are various potential methods for mitigating this noted discrepancy in the kinetic energy present at different test sites. The most obvious might be the use of a cubed average wind speed, $\overline{U^3}^{(1/3)}$. Rather than comparing the wind turbine output against the 1-minute or 10-minute mean wind speed, the measured power curve could relate power production as a function of the averaged cubed wind speed. With this method the measured power production would be directly compared to the total kinetic energy approaching the wind turbine. The problem with such a procedure is two fold. First, an averaged cubed wind speed would be meaningless to the consumer. Charts or statistics are not generally available that provide any indication of the averaged cubed wind speed. And, since the presence of turbulence is a local phenomenon, it is unlikely that site-specific values could be obtained without collecting actual hub height wind speed data at each potential site. Second, if the goal of the specification is to provide an accurate and repeatable result, this procedure will fail. Since this procedure would not address the potential reduction in efficiency associated with increased atmospheric turbulence, different test locations could still result in different measured power curves.

A second means for mitigating the potential discrepancy in kinetic energy at various test sites involves evaluating the averaging times used to produce the power curves. Referring back to Figure 3, one will note that the deviation in wind speed decreases with decreased averaging time. At the CPP test site the measured T.I. at 10m for a 30-minute averaging time is approximately 22%. The cube factor for a T.I. value of 22% is approximately 1.14. If the averaging time is shortened to 10 minutes the T.I. value decreases slightly to approximately 18%, where the cube factor is approximately 1.10. If the averaging time is further shorted to 1 minute the T.I. value decreases to approximately 12% and the corresponding cube factor is reduced to 1.04. Thus, at least at the CPP test site, using a one-minute average would reduce the discrepancy between the recorded kinetic energy and the actual kinetic energy from 10 percent down to approximately 4 percent. Similar reductions would be expected for other test bed locations; however, the reductions may be very site specific.

A third method for minimizing the variation in kinetic energy from site to site would be to include a specific requirement for the hub height T.I. value within the site characterization standard. For example, the variation in kinetic energy could be maintained within +/-3 percent by limiting the hub height T.I. values between 13 and 18 percent. For an open country environment this would mean that the hub heights should be between approximately 10m and 50m. In a suburban environment the hub heights would need to be raised to a minimum height of approximately 50m. Note: this standard would likely restrict testing at extremely smooth sites.

These results suggest that the repeatability of the power performance measurements may be greatly enhanced, strengthening the integrity of the power performance standard, by combining the 1-minute averaging time and specific hub height T.I. requirement. However, this still will not provide any specific information to the consumer related to how a particular turbine will behave at various levels of T.I. Ultimately the consumer needs this information to assess the which turbine will provide the best return on investment at their specific local. Therefore, it may be advantageous to eventually expand the testing procedures to include power performance curves at multiple levels of T.I.

5. Conclusions/Recommendations

The results presented in this paper indicate that the current site specification standards are not sufficient to ensure that accurate and repeatable power performance curves for small wind turbines. The results indicate that the kinetic energy present at the hub height can vary by as much as 20 percent depending upon the level of turbulence present at the test site.

The variation in kinetic energy can be somewhat mitigated by reducing the averaging time from 10 minutes to 1 minute and by setting specific standards for allowable hub height turbulence intensity levels. It is suggested by the author that the hub height turbulence intensity values should be required to be within the range of 13 to 18 percent. An empirical formula, which relates turbulence intensity to height above grade for various types of local terrain, indicates that this standard could be achieved for most potential test sites with hub heights between 10m and 50m above grade.

6. References

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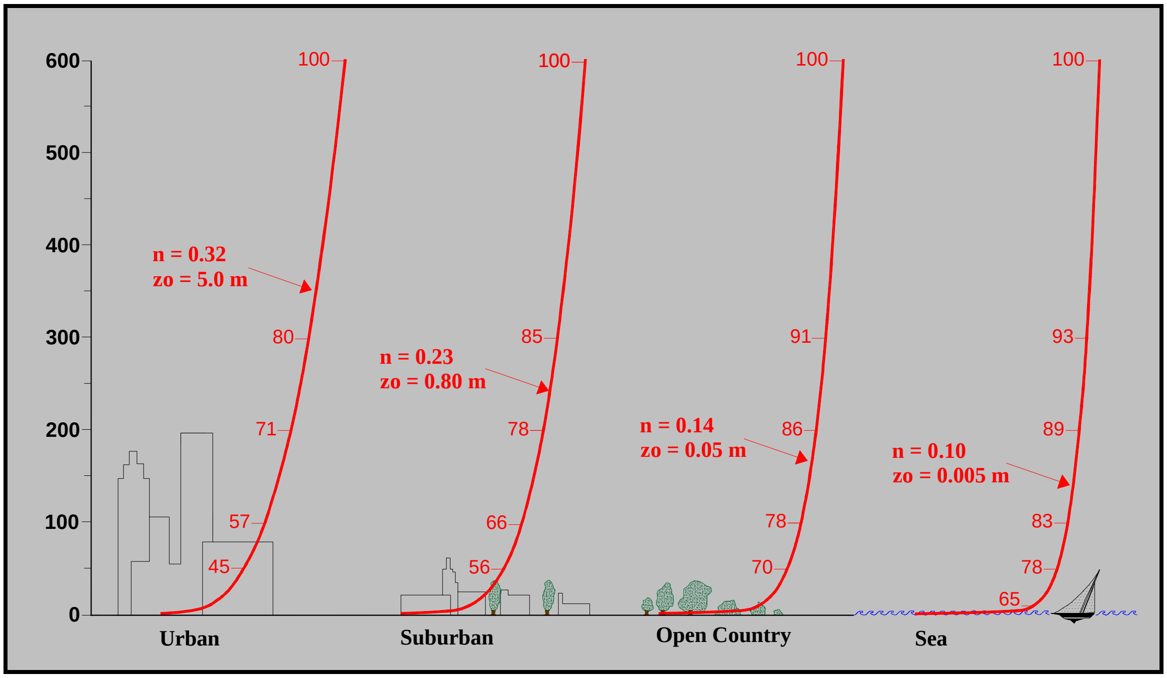

Figure 1. Longitudinal Velocity Profiles Over Uniform Terrain in Neutral Flow

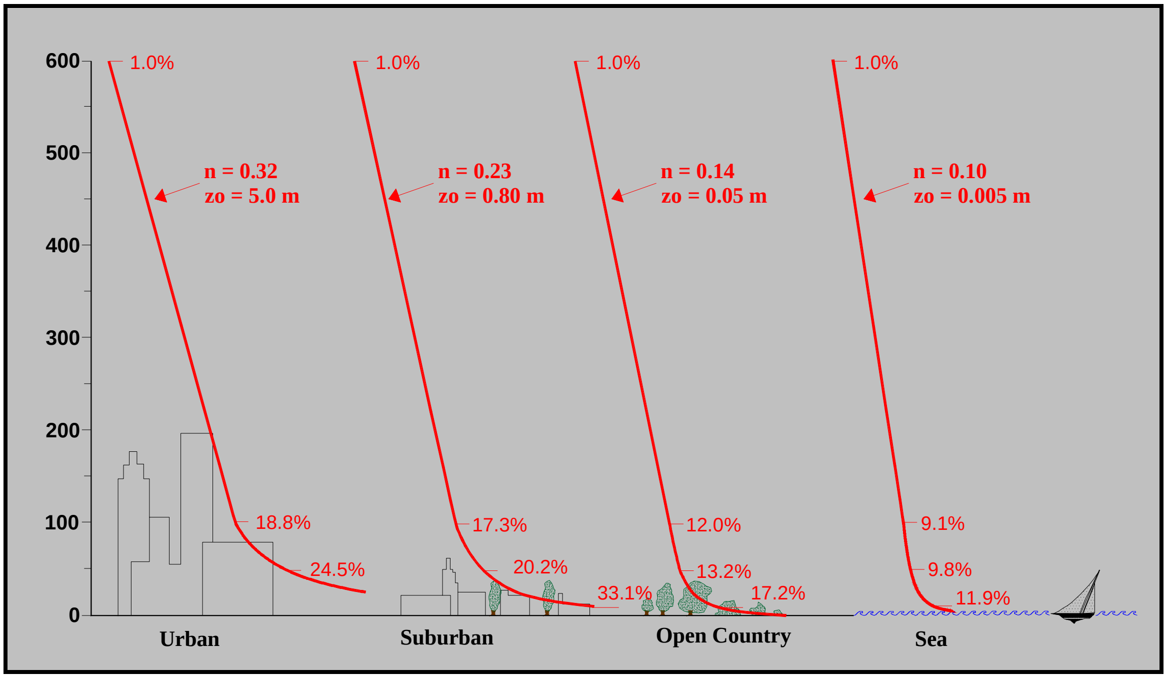

Figure 2. Turbulent Intensity Profiles Over Uniform Terrain in Neutral Flow

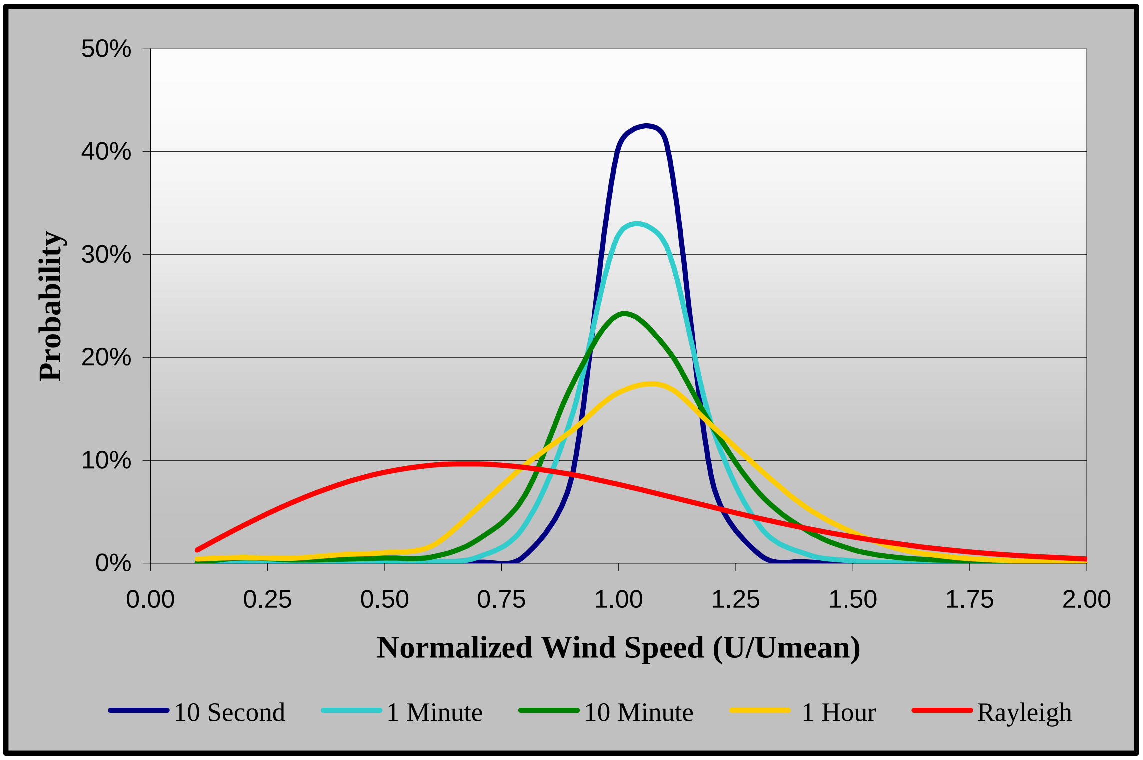

Figure 3. Distribution of 1 Second Wind Speeds Within Various Averaging Times

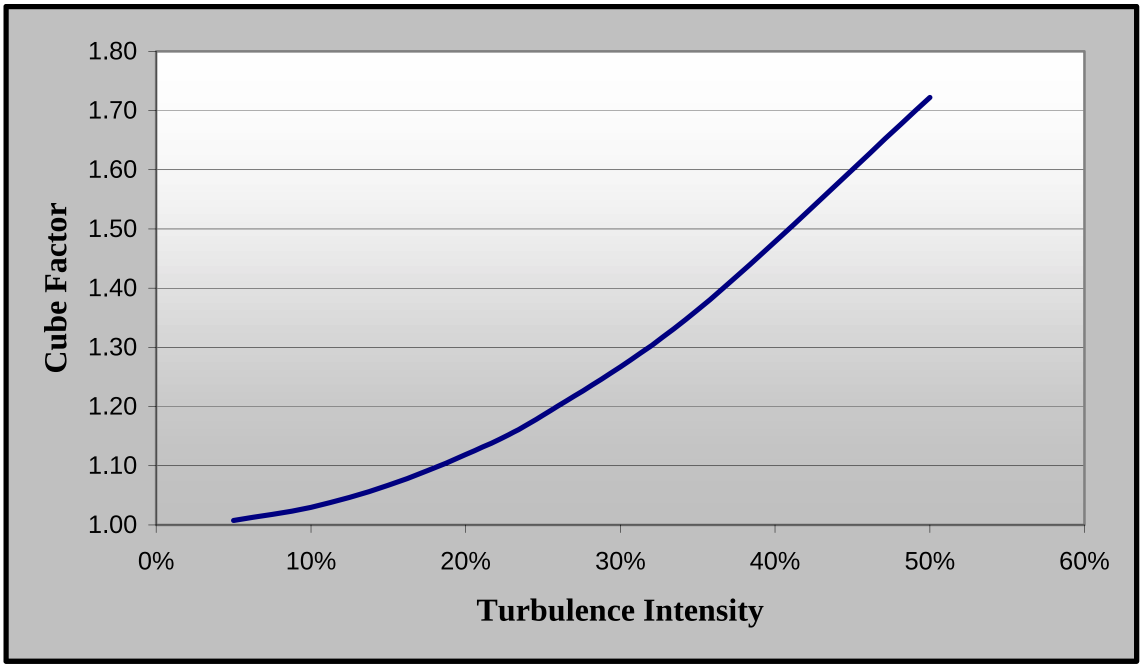

Figure 4. The Cube Factor as a Function of the Local Turbulence Intensity Assuming a Gaussian Distribution of Wind Speeds