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ADVANCES IN THE QUANTIFICATION OF TURBULENCE: A WIND RESOURCE CHARACTERISTIC

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ABSTRACT

Wind resource assessment is a critical parameter in a diverse range of considerations within the built environment. Engineers and scientists, engaging in building design, energy conservation/application and air-quality/air-pollution control measures, need to be cognisant of how the associated wind resource imposes increased complexities in their design and modelling processes. In this regard, the topographical heterogeneities within these environments, present significant challenges to quantifying the resource and its turbulent characteristics. Indeed, from the perspective of assessing the wind resource within the built environment, topographical heterogeneity is the primary proponent of turbulence and the main inhibitor to acquiring meaningful measurements.

This paper presents two aspects of turbulence assessment within the built environment. Firstly, an analysis of how turbulence is quantified is considered. The industry standard, turbulent intensity (TI) [1] is compared with a proposed alternative metric described as *Fourier Dimension* modelling (Df). Secondly, the application of the turbulence assessment is considered with respect to how it affects the productivity of small/micro wind turbines in complex environments. The TI metric is the only metric utilised in the consideration of wind turbine productivity though Gaussian distribution analysis [2]. The T_{Df} model has yet to be developed sufficiently to apply it in this regard.

Keywords: Turbulence, Wind Power, Urban Environment

1 INTRODUCTION

With increased emphasis on load centred electrical generation as a means to reduce transmission losses, the question now arises as to what implications this could have on wind generation technologies being installed closer to urban centres. Increased prevalence of blind bluff bodies encountered in urban topographies escalates the erratic nature of wind velocities. This erraticism, ultimately manifests an increased prevalence of turbulence, which has been shown to affect turbine performance both positively and negatively when measured using the Turbulence Intensity (TI) metric [3, 4].

$$T.I. = \frac{\sigma_u}{\overline{u}}$$

(1)

where σ_u (ms^{-1}) is the standard deviation of wind speed over the sampling period (10 minutes) and $\overline{u}$ is the mean wind speed (ms^{-1}) over the sampling period.

However there are known issues with the TI metric as a means to quantify turbulence in an urban environment. Firstly, the asymptotic nature of the metric - as mean wind speeds approach zero - derives associated TI values that are greater than 100%. Gusts are also more prevalent in an urban context and as a consequence, the standard deviation can be uncharacteristically high. Secondly the TI metric was originally developed as a means to classify site conditions on wind farms where wind characteristics are relatively laminar in nature (with an associated lower standard deviation). Another underlying principle on which the TI model is based is that wind speeds are considered to be normal (Gaussian) in nature within the industrial standard 10 minute sampling period [5]. Our measurements show that this is not the case in an urban context and this can very easily be demonstrated in consideration of a normal distribution with a mean wind speed of 2 m/s and a TI of 50%.
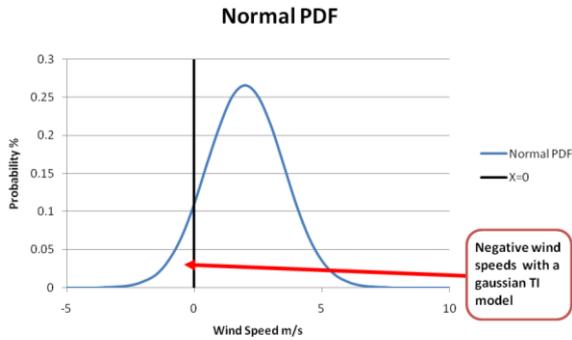
Figure 1 Normal PDF with mean of 2m/s and TI of 50%

developments at Marrowbone Lane, located in Dublin 8 (53°20'15.96''N, 6°17'10.27''W.

Site 2 (SUB 2) is characterised by low rise developments with increasing amounts of similar height vegetation. The anemometry is installed at St. Pius X National (Girls) School, located in Terenure, Dublin 6W (53°20'15.96''N, 6°18'19.02''W). Both the Marrowbone and St Pius sites will be hereafter referred to as *URB 1* and *SUB 2* respectively.

As a result of the PDF illustrated in Figure 1 there are obvious issues as all wind models are based on speeds rather than velocities. Consider a cup type anemometer designed to rotate in one direction only. The TI model when applied to a Gaussian PDF of wind speed implies that the anemometer should rotate in two directions. Note also, if these negative wind speeds are truncated the standard deviation and TI values will change.

That said, this currently does not present an issue for the following reasons. Firstly wind turbines have cut in wind speeds that are predominantly greater than 3 ms^{-1}. Therefore any power that is generated below a 10 minute average wind speed of 3ms^{-1} is negligible in respect to the yearly output for most sites. Secondly where these wind speeds are lower and more erratic, such as within the urban context, there are only a limited number of installations currently installed. The consequences therefore result in an inability to predict power performance accurately therein.

This has led to the development of a new mathematical model for measuring turbulence called the Turbulent Fourier Dimension T_{Df} [6, 7].

2 TURBULENCE QUANTIFICATION

2.1 Field Measurements

Observations are made at two sites (URB 1 and SUB 2) in the Dublin city area using a CSAT3 three-dimensional sonic anemometer [8]. Measurements were taken consistently from 4/4/2012 to 15/5/2012 at both locations at a frequency of 10Hz with an associated resolution-between $0.5 – 1.0$mms^{-1}, with data including date and timestamp and wind-speed using Cartesian coordinates (u_x, u_y, u_z). These can then be resolved to provide wind speed, wind direction and standard deviation for any given sample size.

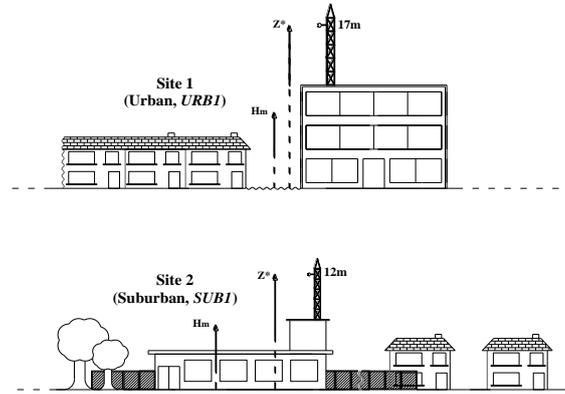Site 1 (URB 1) is characterised by mixed building morphologies containing low and high rise

Figure. 2: Relative context of wind observation locations.

2.2 Turbulence Intensity (TI)

The longitudinal turbulence intensity considered here is slightly modified compared to the traditional TI method where the horizontal component (u_x,u_y) wind speeds over a 10 minute sequential window are cosine corrected. This correction was calculated in accordance with IEC 61400-2[1] which is the generally accepted industrial standard and therefore suitable as a benchmark for T_{Df} .

2.3 Turbulent Fourier Dimension (T_{Df})

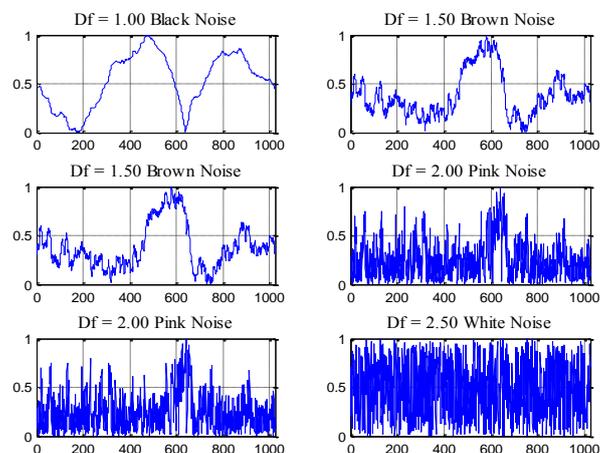This model has been developed from fractal models and is closely related to noise theory.

Figure 3: Simulated noise signals with results for 1024 random numbers

Effectively, the model quantifies a value of self symmetry within a signal, the more self symmetry that is present within a wind speed signal indicates a higher quantified noise content and in turn a higher turbulent content. The T_{Df} was calculated in accordance with the procedure laid out in [7]. In order to obtain a like for like comparison with the TI metric cosine corrected horizontal components (u_x, u_y) wind speeds over a 10 minute sequential window were also employed.

2.4 Comparative Results

As both metrics have a scaling factor that are dependent on mean wind speed, it is necessary to *bin* all calculated turbulence values based on mean wind speed over the 10 minute interval. For this reason averaging TI and T_{Df} values are avoided as they can be misleading and problematic when comparing similar sites.

It is evident in Figure 4 that the TI metric is inconclusive as to which site is more turbulent over the turbine operating wind speed spectrum.
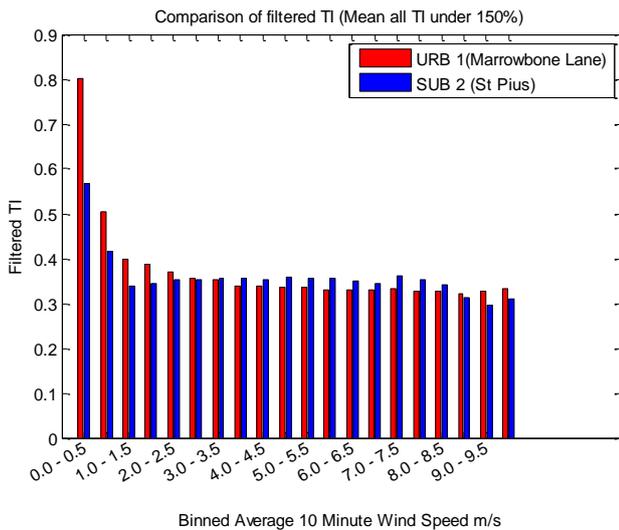
Comparison of filtered TI (Mean all TI under 150%)

Figure 4 Mean Filtered TI over a binned wind speed range for both sites.

With regard to the TI metric the URB 1 site is more turbulent at low wind speeds. It should be noted however, that such extreme low wind speeds with wind speeds less than 2.5ms^{-1} account for a sizable portion of the entire data set (*circa* 25% of the entire sample). Figure 4 also implies that SUB 2 is more turbulent from 3-8.5 ms^{-1}. (*Note:* these are typical operational wind speeds for micro turbines). Figure 5 depicts the T_{Df} for the same data set. The T_{Df} model gives a clear indication that URB 1 (Marrowbone) is more turbulent than the SUB 2 (St Pius).

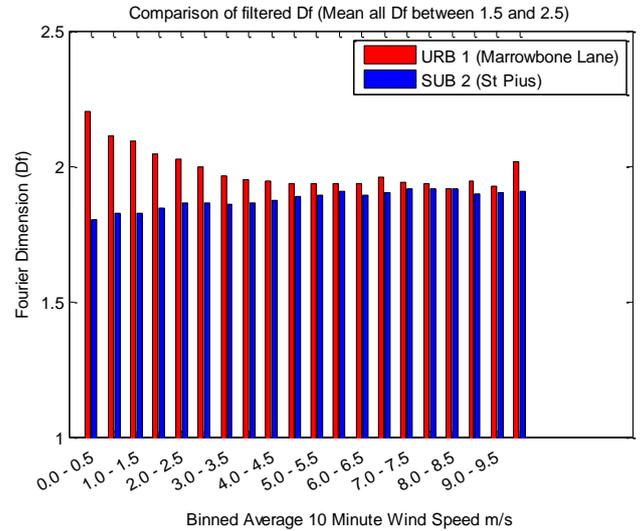Comparison of filtered Df (Mean all Df between 1.5 and 2.5)

Figure 5 Mean Filtered Df over a binned wind speed range for both sites.

As a result it is envisaged that the T_{Df} model could be used as a means for site classification based on generic turbulence bands.

3 POWER PREDICTION

Turbulence has been shown to have an effect on the turbine characteristic. Field trials by Lubitz [9] as well as correlation techniques by Langreder [3] (see Figure 6) have illustrated this point. The research undertaken by both Lubitz and Langreder concluded that turbulence has positive effects at low wind speeds and negative effects at higher wind speeds.
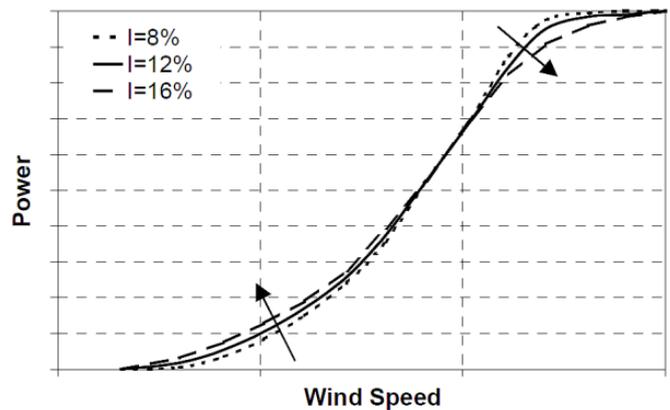
Figure 6 Typical Effects of Turbulence on Power Curves [3]

In recent years tentative steps have been made towards a generic means of predicting the effects of turbulence on a turbine characteristic with respect to modelling the power performance of micro turbines in turbulent environments. Albers [2] provides a means and justification of normalising the turbine characteristic for site specific measurements of TI.

This method if slightly amended has the ability to generate a power curve for a given turbine at any given TI value. The following steps can be made in order in order to generate power curves for a known turbine at various TI values.

1. Firstly take a manufacturer's power characteristic for any given turbine. (Note: This is an average turbine power taken from manufacturers test data)
2. Break up the wind speed into suitable sized datums (0.1m/s works well).
3. Generate a normal PDF for each of these datums using the datum as the average wind speed and the standard deviation as TI x the datum. (Note a large number of samples is required for an accurate result circa 6000 works well.)
4. For each of the 6000 generated wind speeds quantify the power based on the manufacturer's power curve. Note values outside of the working range need to be forced to 0 prior to averaging.

Figure 7 demonstrates how this approach can be used as a means to generate a power curves for all values of TI for a Skystream 2.5kW turbine.
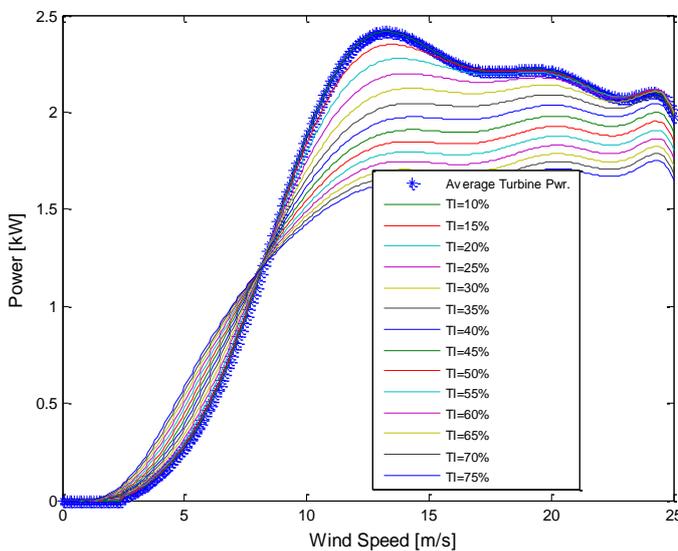

Figure 7 Alber's approximation of power curve based on varying TI

It should be noted that this mathematical approach is consistent with observations in the field studies by Lubitz and Langreder [3, 9]. Another interesting consideration concerns the manufacturer's data and how it is derived. Most manufacturers base their power curves on averaged field test data from generic site conditions in accordance with [1]. As these sites are subjected to some turbulence Albers

argues that this may need to be compensated for in the calculation. However as the TI data of the test conditions are rarely published, it is unlikely that an accurate answer can be formulated. If on the other hand we assume that the test sites are selected on the basis of being a low turbulence environment a compensating TI of between 10% and 20% would appear to be suitable for the vast majority of low turbulence test sites.

3.1 Self Validation Procedure

As a form of self validation of the power predictability approach three powers were calculated and compared based on the following procedures.

Firstly the absolute power was calculated using the raw data (10 Hz) and a bounded polynomial similar to that in Figure 8. This was used as a benchmark as this is the only power that is calculated on the basis of the raw data.
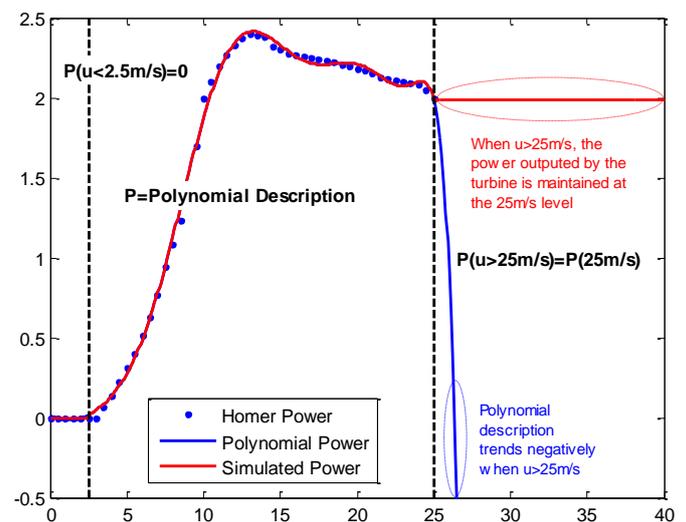

Figure 8 Bounded Polynomial

Secondly the mean power (Pmean) was calculated using the industry standard 10 minute mean (i.e. mean wind speed considered but no allowance for TI). Once again power is calculated using the polynomial method illustrated above.

Lastly the TI normalised power (Pnorm) is calculated based on the TI values influencing the power curve and as a resultant the power output is appropriately altered.

3.2 Comparative Results

The two simulated turbine output powers (Pmean and Pnorm) were benchmarked against the raw data power (Pabs).

The cumulative error for both sites (URB1 and SUB 2) indicates that virtually all (>99%) of all simulated Pnorm results are within +/- 50W of the Pabs value. To put this into context the Skystream is a 2.5kW turbine so >99% of all simulated Pnorm values lie within a 2% error.
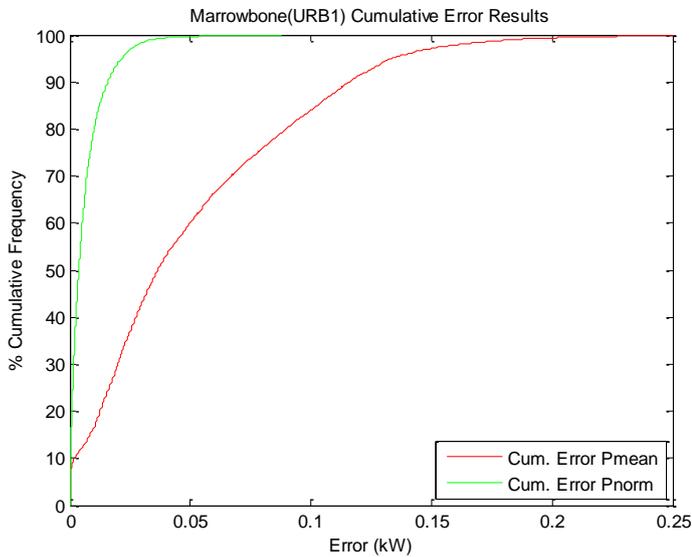

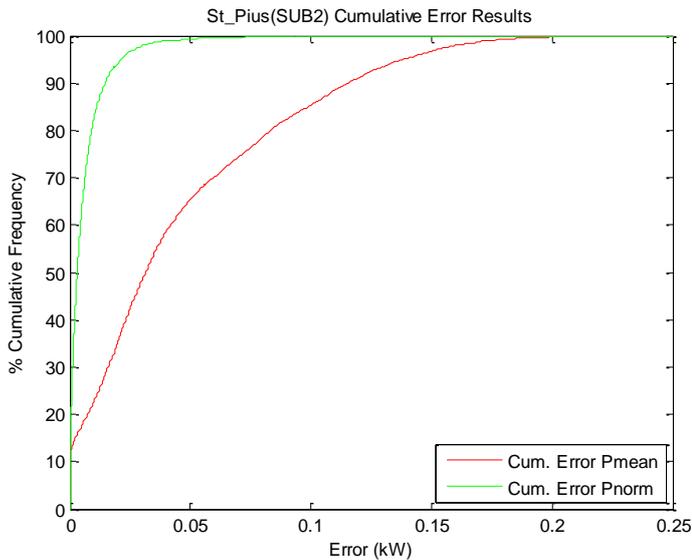Figure 9 Cumulative error for Marrowbone (URB1)

Figure 10 Cumulative Error for St Pius (SUB2)

This is in sharp contrast with the current industrial standard which is the Pmean based on the manufacturers power curve and the average wind speed over a 10 minute period.

4 CONCLUSION AND DISCUSSION

It is evident that the current uncertainty associated with the classification in an urban context poses many challenges to micro wind installation designers. These challenges pose significant difficulties to our limited understanding as to what turbulence is and more importantly how it affects micro wind energy systems. While it can be argued that the T_{Df} model is mathematically less intensive to compute due to its inherent reliance on the Fast Fourier Transform, it must also be remembered that it is not designed to measure turbulence in a similar manner to TI. That said, the T_{Df} methodology appears to present a more coherent means of classifying a site's turbulence level as suggested in Figure 5. There is however, limited correlation between the two metrics across a range of turbulent environments. A simple scenario below explains the reasoning why this is the case.

Consider a gradually increasing wind speed over a 10 minute period shown in Figure 11.
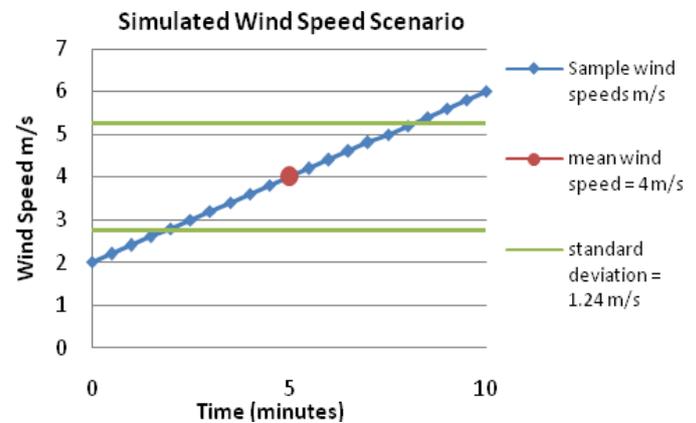

Figure 11 Wind speed scenario TI=31% T_{Df} =1

The trend is totally persistent in nature i.e. $T_{Df}=1$ and therefore having no turbulence by the T_{Df} metric. If we consider the same scenario from a TI perspective it has a value of 31%. So is the scenario turbulent or not?

It is also noted that there is currently no means of classifying how much turbulence is dependent upon directionality and therefore the concept of a *Turbulence Rose* may need to be investigated as a tool for adequate site selection and classification.

The real question is not what we can mathematically measure but how this measurement affects the power performance of a micro turbine scenario. To this end the TI metric is still the optimal metric for ascertaining power performance mathematically. It also has the ability to compress 10 minutes of data to just 2 datums (average wind speed and standard deviation) with the ability to simulate the 10 minute period based on these 2 datums.

Future work will involve the development of T_{Df} model to accurately predict power conditions with the aim of tying the T_{Df} model to Weibull analysis.

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