2014-06-12

The Development of Synthetic Wind Series Based on Gaussian and Non Gaussian Statistics

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“The Development of Synthetic Wind Series Based on Gaussian and Non Gaussian Statistics”.

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12th June 2014
Overview

- Introduction to Wind Energy
- Data Acquisition and Statistical Summarisation
- Artificial Wind Speeds
- Results
- Future Applications
- Acknowledgements
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Kinetic wind energy is harnessed by converting to mechanical energy via the turbine rotor and then into electrical energy through the generator:

Wind Energy is fundamentally derived from an extension of kinetic energy formula!

$$P = \frac{C_p \cdot \rho \cdot A \cdot u^3}{2}$$

where the mechanical output power ($P$) is a function of the performance coefficient of the turbine ($C_p$), the density of air ($\rho$), the area swept by the turbine projected in the direction of the wind ($A$) and wind-speed ($u$).
It is worth considering that Cp is limited by Betz limit of 59.3% efficiency however an important fact that is often missed is that this is strictly speaking only applicable in laminar kinetic mass flow systems.

(N.B. Turbulence and Pressure drop over the blades are not considered!)

As wholly laminar environments are rarely present in real world scenarios it is evident that further investigation is required when trying to bound the likely coefficient of performance in a turbulent environment.

This model also assumes instantaneous response i.e. zero inertia model! This has a tendency to make large power prediction errors. +/- 30% error is not uncommon for microturbines in turbulent urban environments.
Known power prediction issues;

- Accuracy of power curves (standard dev and error is not published)
- Data recording issues (averaging of scalars expressed as vectors)
- Cup anemometers (values under range recorded as 0)
- Statistical Distortion due to excess 0s.
- Quantification of turbulence (There are known issues with TI)
- Lack of transient response models
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Data Acquisition and Statistical Summarisation

- DUBLex (Dublin, Urban Boundary Layer Experiment) UCD, DIT and NUI Maynooth.
- High resolution data for multiple purposes e.g. \( \text{CO}_2 \) monitoring / temp / moisture / wind speed
- Has multiple applications air quality / litter dumping / temp. hot spots / urban wind generation.
- A mast installation is on top of DIT Kevin Street for approximately 1 year also
From this industrial standard 10 minute bins are drawn based on longitudinal values of mean TI and a proposed new metric $T_{Df}$. This metric essentially measures how noisy a signal is.

$$T_{Df} = \text{unbounded Fractal Dimension by Fourier means}$$

Industry Standard

$$\bar{u} = \frac{\text{mean wind speed}}{\text{standard deviation}} \times \text{mean wind speed}$$

$TI = \frac{\text{standard deviation}}{\text{mean wind speed}}$

Fractal Persistent

Fractal Anti-Persistent

Non Fractal

<table>
<thead>
<tr>
<th>Fractal Persistent</th>
<th>Fractal Anti-Persistent</th>
<th>Non Fractal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Values of $D_f$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>
Fractal Noise is scale invariant and needs to be normalised (max value). i.e. Df is a measure of erratic nature but gives no indication to the amplitude!
Data Acquisition and Statistical Summarisation

- Df = 1 is effectively 0% turbulence by the $T_{Df}$ metric

- However the current TI metric would classify this sample as having 31% turbulence

- The current TI metric does not allow for trends within the wind speed sample

- N.B. the $T_{Df}$ metric does not cater for the spread of the erratic signal

- Therefore there is a need for both metrics when describing a wind speed signal
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Generation of Artificial wind speed signals based on TI, $T_{Df}$ and mean speed

If we consider a 10 minute bin of 10Hz data summarised to mean, TI and $T_{Df}$

Question:
What can we do with it?
It is pointless in proposing a new metric ($T_{Df}$) unless it has some practical application!

So lets consider mixing Gaussian statistics with non Gaussian statistics!
Consider a series of 600 random numbers \( (n_x) \) between 0-1 subjected to the following convolution \( (\otimes) \) in the frequency domain.

\[
[u_x(t)] = \frac{1}{t^{1-q/2}} \otimes t \ [n_x(t)]
\]

Where: \( T_{Df} \) (Turbulent Fourier Dimension) = \( (5-q)/2 \)

Frequency domain equivalent with \( i \) indexing filter

\[
[U_x(\omega)] = \frac{1}{(i\omega)^{q/2}} \ [n_x(\omega)]
\]

For this example lets take a \( T_{Df} \) of 1.8, a TI of 0.45 (45%), and a \( u \) mean of 7.5 m/s
Generating a fractal curve of known $T_{Df}$ gives the following graph.

Fractal noise is scale invariant and as such has the same fractal properties at any scale.

Note the amplitude is not defined!

If we zoom in the concept becomes clearer!
Zooming in shows the fractal self symmetry within the curve.

However, this is not scaled and as such is of no use on its own.

If we normalise to unit standard deviation (divide by standard deviation) uniform scaling is maintained giving:

\[ \text{TDf} = 1.80 \]

0 mean fractal curve
Now that the curve is normalised around zero a known spread can be applied.

Standard dev is = mean x TI

So multiply across to give the next slide
Now that the curve has a spread indicative of the standard deviation it is now time to add in an average.
This artificial wind speed has the same statistical properties as an original recording of $T_{Df}$, TI and $u_{mean}$.

Early comparisons have shown this model to have a 97% statistical accuracy compared to a frequency bin equivalent.

However this is not over the full data set.

Fractal curve with $T_{Df} = 1.80$, TI = 0.45, $U_{mean} = 7.5$
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Statistical Sample Results TOA5_3515-2012-04-05 20

Measured Data

- Mean $u = 3.7392$ m/s
- Turb. Inten. $= 0.3102$
- TDi $= 2.0796$
- Fractal R2 Corr. $= 0.9719$
- Fractal RMS err $= 1.2681$

Simulated Data

- Mean $u = 4.3580$ m/s
- Turb. Inten. $= 0.3102$
- TDi $= 2.0800$
- Fractal R2 Corr. $= 0.9745$
- Fractal RMS err $= 1.3064$

Histogram (u m/s)

Time series wind signal 10Hz 10minutes

Difference Histogram (difference of u m/s)
Q: So just how good a model is it?

A: That is dependant on what you are using the wind speeds for but in general the following can be said based on the 2 urban data sets.

<table>
<thead>
<tr>
<th>Statistical Marker</th>
<th>Generalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Perfect</td>
</tr>
<tr>
<td>TI</td>
<td>Perfect</td>
</tr>
<tr>
<td>$T_{Df}$</td>
<td>Near Perfect</td>
</tr>
<tr>
<td>Histogram Shape</td>
<td>Near perfect</td>
</tr>
<tr>
<td>Differential Histogram</td>
<td>Some issues in the mid range / insignificant for power prediction</td>
</tr>
<tr>
<td>Time series</td>
<td>Seriality is met reasonably well. Generic Shape can be different</td>
</tr>
<tr>
<td>Skewness</td>
<td>Near Perfect</td>
</tr>
</tbody>
</table>

N.B. Minimal Data storage as well minimal computation time!
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Statistical accuracy of the system response model.

Future Applications

- Observed (10Hz) wind speed/direction
- Measure statistical wind markers (mean, T1, T2)
  - Artificial time series modelling/development
    - Generate noise signal (T_{DF})
      - Normalise noise signal to be representative of observed wind SD
      - Incorporate mean 'observed' wind speed
  - Time series model incorporating system inertia
  - Time series model incorporating system inertia
  - Compare
\[ u_{res} = u_{start} + \Delta u \left( 1 - e^{-\frac{t}{\tau}} \right) \]

Where:

- \( U_{res} = u \) resultant
- \( U_{start} = \) initial \( u \) at start of transient window
- \( \Delta u = \) change in \( u \) over transient window

As \( \tau \) increases e.g. larger turbines have greater inertia

Figure 13 Various system response capabilities based on varying \( \tau \).
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The author(s) would like to acknowledge Dr. Rowan Fealy, of the National University of Ireland, Maynooth (NUIM) and Dr. Gerald Mills, University College Dublin, (UCD) for providing the wind data employed in this analysis.
Thank you for your time.

Any Questions?

**Collaboration**
The Author’s of this research would be delighted to share and collaborate on similar projects.

**Other Works**
For further details on the ongoing work in this area please refer to the author’s research repository stored at;

[www.arrow.dit.ie](http://www.arrow.dit.ie)