A new view of turbulence: Quantifying chaotic effects and their impact on wind turbines

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The SALE Project

The Simulation for Asset Lifetime Extension (SALE) project is a collaborative R&D programme between Octue (formerly Ocean Array Systems) and the Offshore Renewable Energy Catapult (OREC). Broadly, the SALE project objectives are to:

- Develop a more powerful analysis for characterising turbulence and simulating its effect on turbines, including evolution of wake turbulence.
- Validate the analysis by cross-check between LiDAR and met. mast measurements.
- Validate predicted load spectra and wake dispersion properties for a 7MW offshore turbine.
- Investigate further applications of the new simulation technique.

This poster addresses the first stage of the SALE project above.

Abstract

Alongside the growth of the wind energy sector has come an increased interest in the Atmospheric Boundary Layer (ABL), within which wind turbines and arrays are situated. The ABL is turbulent, which affects yield of individual turbines and arrays as well as peak and fatigue loading of devices caused by the unsteady flow.

However, the most popular metric of turbulence (Intensity I, expressed at hub height) is insufficient for expressing the enormous complexity of the flow - especially for increasingly large turbines. Even state of the art moment quantities like spectral tensors) are unwieldy and difficult to establish using existing met. masts or LiDARs [1, 2] - as well as failing to represent the chaotic nature of the flow (intermittency, organised and self-similar structure).

Various more easily measured phenomena (thermal gradients, shear, veer) are tightly coupled with turbulence but rarely used to help quantify it, which wastes useful information.

Objectives

Our motivation here is to combine models for individual effects (shear, veer, thermal gradient, coherent turbulent structure, skin friction) into a single analytical framework that:

- Expresses the state of the turbulent atmosphere in the height range where wind turbines operate; includes (or has the ability to include) atmospheric stability, coherent structure, surface roughness effects, extreme topography, intermittency, veer, and shear;
- covers the range of length scales required by the onshore engineering purpose (e.g., site assessment or turbine simulation);
- incorporates variation of quantities with height;
- is expressible in a compact parameter set;
- can be robustly determined from available measurement data;
- can be used to generate an artificial wind field (for site-specific simulation purposes) and
- can generate metrics commonly used in existing site assessment.

An Anisotropic Turbulent ABL Model

Almost all turbulent flows exhibit coherency, and are often analysed in terms of their ‘structural’ content. As discussed by Kelley [3], coherency in the flow leads to the highest stresses in wind turbines, so preserving coherency is helpful – even essential – in characterisation of turbulence for the ultimate purpose of determining unsteady loading on turbines.

The ABL contains two key regions, ‘inner’ and ‘outer’. The inner region behaves logarithmically and is well described by models presently in use in the wind industry. In the outer region, a different scaling relation applies to the size of turbulent eddies, affecting the behaviour of the Reynolds Stress profile as well as the (coupled) shear and veer profiles.

Shear profile (U(z)) models such as those of Grynig et al. [6] or Peña et al. [7] have begun to account for this. For convenience we use a modified Coles ‘waltz’ model [8, 9], since we can obtain a parametric expression of cross-spectrum S13(k,z) from an extended analysis of the same:

\[
U_\infty = \frac{1}{\lambda} \left( \frac{z+b}{b} \right) + Dv \left( \frac{b}{\lambda} \right) \exp \left( -\frac{z}{\lambda} \right)
\]

\[
S_{13}(k,z) = \frac{4}{k} \left( 1 - 2 \cdot \frac{k^2}{\lambda^2} \right) \left( \frac{\lambda}{k} \right)^2 \eta
\]

\[
\eta = \frac{z}{\lambda} + \frac{b}{\lambda}
\]

Representing and forming of distribution of Coherent Structure, we adopt the ‘Attached Detached Eddy Model’ of Perry and Marusic [10], which uses structural analysis to account for turbulent anisotropy.

Key Steps:

- Knowing that the hairpin is the predominant eddy structure in the ABL, assume a simplified shape of eddy, which exists at a range of scales and strengths
- Relate a single eddy to its influence on shear U(z) and Reynolds Stress R13(z) = f(S13(k,z))
- Formulate convolition equations that relate U(z) and R13(z) to eddy scale and strength distributions (w, T):

\[
\frac{d^2}{dz^2} F(z) + \frac{2}{z} \frac{d}{dz} F(z) = \int_0^\infty \left( e^{-\frac{(z-z')}{\lambda}} - e^{-\frac{(z+z')}{\lambda}} \right) \frac{d^2}{dz'^2} F(z') dz'
\]

- Solve by deconvolution for the scale and strength distributions
- Repeat the above steps in a single, simultaneous non-linear optimisation, such that:

- U(z) best fits the robustly measurable shear profile
- S13(k,z) best fits the valid portion of the measurable spectrum (instrument dependent)
- dT(z)/dt (derivable from R13 using Monin-Obukhov [11]) best fits any available temperature gradient measurements

Conclusions

An analytical framework has been derived (and is presently in publication) that:

- Incorporates physically meaningful turbulent characterisation using coherent structure
- Expresses all properties of the ABL (shear, veer, turbulent spectral tensor, coherency, temperature gradient) in a compact and tightly-coupled six parameter set
- Can be used with band-limited LiDAR measurements to characterise the ABL

Next Steps

Inclusion of low-level jets and spatial intermittency (where coherent structures cluster together) are both presently possible to include in this model, although may require measurements beyond standard LiDAR / Met. Mast campaigns to fully constrain the equation system.

References


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