From standard wind measurements to spectral characterization: turbulence length scale and distribution

In wind energy, the effect of turbulence upon turbines is typically simulated using wind input time series based on turbulence spectra. The velocity components’ spectra are characterized by the amplitude of turbulent fluctuations, as well as the length scale corresponding to the dominant eddies. Following the IEC standard, turbine load calculations commonly involve use of the Mann spectral-tensor model to generate time series of the turbulent three-dimensional velocity field. In practice, this spectral-tensor model is employed by adjusting its three parameters: the dominant turbulence length scale $L_{MM}$ (peak length scale of an undistorted isotropic velocity spectrum), the rate of dissipation of turbulent kinetic energy $\epsilon$, and the turbulent eddy-lifetime (anisotropy) parameter $\Gamma$. Deviation from ideal neutral sheared turbulence – i.e., for non-zero heat flux and/or heights above the surface layer – is, in effect, captured by setting these parameters according to observations.

Previously, site-specific $\{L_{MM}, \epsilon, \Gamma\}$ values were obtainable through fits to measured three-dimensional velocity component spectra recorded with sample rates resolving the inertial range of turbulence ($\gtrsim 1$ Hz); however, this is not feasible in most industrial wind energy projects, which lack multi-dimensional sonic anemometers and employ loggers that record measurements averaged over intervals of minutes. Here a form is derived for the shear dependence implied by the eddy-lifetime prescription within the Mann spectral-tensor model, which leads to derivation of useful forms of the turbulence length scale. Subsequently it is shown how $L_{MM}$ can be calculated from commonly measured site-specific atmospheric parameters, namely mean wind shear ($dU/dz$) and standard deviation of streamwise fluctuations ($\sigma_u$). The derived $L_{MM}$ can be obtained from standard (10 min average) cup anemometer measurements, in contrast with an earlier form based on friction velocity.

The new form is tested across several different conditions and sites, and it is found to be more robust and accurate than estimates relying on friction velocity observations. Assumptions behind the derivations are also tested, giving new insight into rapid-distortion theory and eddy-lifetime modeling – and application – within the atmospheric boundary layer. The work herein further shows that distributions of turbulence length scale, obtained using the new form with typical measurements, compare well with distributions $P(L_{MM})$ obtained by fitting to spectra from research-grade sonic anemometer measurements for the various flow regimes and sites analyzed. The new form is thus motivated by and amenable to site-specific probabilistic loads characterization.