1 Introduction

Of the atmospheric parameters which are generally input into (or required by) wind turbine loads calculation codes, several stand out, due to their prominence in load contributions: the 'mean' wind speed U, the standard deviation of streamwise turbulent velocity σ_u, the shear exponent α (calculated from wind speeds at multiple heights, e.g. Kelly et al., 2014a), and the characteristic turbulence length scale L corresponding to the most energetic turbulent motions (e.g. Wyngaard, 2010). Dimitrov et al. (2015) explored the importance of shear (α); Dimitrov et al. (2017) found that both fatigue and extreme turbine loads can be sensitive to, L in addition to the dominant influences of mean wind speed U and streamwise turbulence 'strength' σ_u. These are also consistent with the earlier finding of Sathe et al. (2013) that stability could affect fatigue loads through α and σ_u.

Within the context of obtaining site-dependent statistics of the most relevant load-driving parameters (U, σ_u, α, L) from conventional industrial wind measurements, this work focuses on the one parameter which has thus far been most difficult to measure: the turbulence length scale L. The turbulence length scale corresponds to the 'energy-containing sub-range' of turbulent velocity fluctuations associated with the peak of the streamwise velocity spectrum, which contribute most to turbulent kinetic energy (and σ_u)—and which can dominate the turbulence contribution to wind turbine loads. Measurements used in wind energy are usually stored as 10-minute statistics (average and standard deviation of wind speed and direction), so one cannot obtain turbulence spectra from them, nor can one calculate integral time or length scale from such observations.

Because of its widespread use in the wind industry and its inclusion in the IEC 61400–1, Edition 3 (2005) standard on design requirements for wind turbines, here we consider the spectral turbulence model of Mann (1994), and L as prescribed for this model. Within the 'Mann-model,' which uses rapid-distortion theory ('RDT') to account for shear-induced distortion of isotropic turbulence (see e.g. Savill, 1987; Pope, 2000), there is also a prescription for the scale-dependent time over which turbulent eddies of a given size are distorted. This time-scale is key to proper representation of atmospheric turbulence and reproduction of component spectra via RDT. However, the eddy-lifetime was not directly derived, but rather cleverly prescribed, by Mann (1994). Concurrent to and independent of the work herein, de Mare and Mann (2016) also derived some relations to create a model for time-varying eddy lifetime. The present article provides direct derivation of the eddy lifetime, which results in a relation between the three (spectral) parameters of the Mann model and measureable quantities. More importantly, the derivations here include connection of the turbulence length scale to routinely available quantities from typical 10-minute industrial wind records. The turbulence length scale is in fact that corresponding to the von Kármán (1948) spectral form, and thus the relation here is applicable to other turbulence models used in wind engineering, such as those relying on the Kaimal et al. (1972) spectrum.

After deriving the eddy lifetime and giving subsequent expressions for the turbulence length scale, this article proceeds to validation of the underlying assumptions. Constraints implied by fitting the Mann-model to measured spectra in non-neutral conditions, given eddy-lifetime and mixing-length relations, are also tested. This includes dependence of predicted velocity variance on model anisotropy parameter (Γ), as well as implications in the surface-layer and connection to previous findings in boundary-layer meteorology. Finally, the length-scale obtained from conventional 10-minute wind measurements via the new expression is compared to the length scale found from fits of Mann-model output to measured component spectra; this is done using data from multiple sites, representing several types of site conditions.

2 Theory

Relation of the turbulence length (spectral 'peak') scale to measureable statistics is possible through the eddy-lifetime form of Mann (1994), where the latter is defined in terms of the isotropic von Kármán spectrum that is distorted using RDT.

2.1 Eddy lifetime

A number of forms exist to estimate eddy lifetime τ_e, though these can be generally expressed as the ratio of a length scale (taken as the reciprocal of wavenumber, k^{-1}) to a velocity scale which follows from some integrated form of the (scalar) kinetic energy spectrum $E(k)$:

$$\tau_e \sim k^{-p-1}\left[\int_k^\infty \kappa^{-2p}E(\kappa)d\kappa\right]^{-1/2}, \qquad (1)$$

where the characteristic velocity scale can be generically described by

$$k^p\left[\int_k^\infty \kappa^{-2p}E(\kappa)d\kappa\right]^{1/2}.$$

Comparing to the 'coherence-destroying diffusion time' of Comte-Bellot and Corrsin (1971) and to the reciprocal of eddy-damping rates from Lesieur (1990), for use with rapid-distortion theory Mann (1994) chose an eddy lifetime that depends on eddy size (wavenumber) according to

$$\tau_M \propto k^{-1}\left[\int_k^\infty E(\kappa)d\kappa\right]^{-1/2}; \qquad (2)$$

i.e., equivalent to $p=0$ in terms of (1). The choice (2) for eddy lifetime was found to behave more reasonably than both the Comte-Bellot and Corrsin (1971) 'diffusion time' (where $p=1$)[1], as well as the timescale $[k^3E(k)]^{-1/2}$ (which in the inertial range is equivalent to $p=-1$)[2] implicit in eddy-damped quasi-normal Markovian [EDQNM] models (Andre and Lesieur, 1977; Lesieur, 1990); both of the latter lifetime models do not (reliably) integrate to give finite σ_u^2.

Mann (1994) re-writes τ_M as

$$\tau_M(k) = \frac{\Gamma}{dU/dz}\,\frac{(kL_{\mathrm{MM}})^{-2/3}}{\sqrt{{}_2F_1\left(\frac{1}{3},\frac{17}{6};\frac{4}{3};\frac{-1}{(kL_{\mathrm{MM}})^2}\right)}}, \qquad (3)$$

[1] The Mann (1994) expression is also equivalent (or at least proportional) to the 'convection time' of Comte-Bellot and Corrsin (1971).

[2] The reciprocal of eddy-damping rate, $[k^3E(k)]^{-1/2}$, is equal in the inertial range to (1) with $p=-1$ since $E(\kappa)\to\kappa^{-5/3}$ there. This expression is also similar to the 'rotation time' or 'strain time' given by Comte-Bellot and Corrsin (1971), but it should be noted that such expressions integrate from 0 to k, i.e. over eddies larger than $1/k$.