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N.D. Kelley and B.J. Jonkman

Technical Report
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OVERVIEW OF THE TURBSIM STOCHASTIC INFLOW TURBULENCE SIMULATOR

(Revised May 26, 2005)

The *TurbSim* stochastic inflow turbulence code was developed to provide a numerical simulation of a full-field flow that contains coherent turbulence structures that reflect the proper spatiotemporal turbulent velocity field relationships seen in instabilities associated with nocturnal boundary layer flows that are not represented well by the IEC Normal Turbulence Models (NTM). Its purpose is to provide the wind turbine designer with the ability to drive design code (FAST, MSC.ADAMS®, or YawDyn) simulations of advanced turbine designs with simulated inflow turbulence environments that incorporate many of the important fluid dynamic features known to adversely affect turbine aeroelastic response and loading.

The *TurbSim* code supports all of the features found in the previous *SNLWIND-3D* [1] and *SNwind* inflow turbulence simulator codes that had their roots in Paul Veers' original stochastic wind simulator *SNLWIND* [2]. All of the spectral models available in *SNLWIND-3D* (SMOOTH, WF_UPW, WF_07D, and WF_14D) as well as the IEC Kaimal and von Karman Normal Turbulence Models that are provided in *SNwind* are included. Incorporated within the March 1, 2005 release of Version 1.00e of *TurbSim* a new spectral model was added and designated as **NWTCUP** (NWTC Upwind). This model generates a turbulent inflow that is characteristic of the highly turbulent conditions experienced when testing turbines at the NWTC; i.e., downwind of a major mountain range. It represents a test environment corresponding to those found in complex terrain situations that often present challenges for turbine operations. In the future, it will be joined by another model (GP_LLJ) that will simulate flow conditions associated with the large vertical shears and coherent turbulence encountered beneath Great Plains low-level jet streams.

The *TurbSim* code provides the ability to *efficiently* generate *randomized* coherent turbulent structures that are superimposed on the more random background turbulent field as produced by one of the diabatic (non-neutral) spectral models; i.e., SMOOTH, WF_UPW, WF_07D, WF_14D, or NWTCUP. Typically the size of the structures have a higher probability of being scaled to the dimensions of the requested rotor diameter but the user may request the placement of the coherent disturbance in either the upper or lower half of the specified rotor disk for rotor diameters of 30 m or larger. The NWTCUP model incorporates additional scaling features to better reflect conditions seen at the NWTC; i.e., high turbulence intensities and intense coherent turbulent structures encountered during nighttime (stable) flows. However, for the present, this model utilizes the low-frequency (long-period) turbulent spectral model derived from measurements in San Gorgonio Pass, California [1] that does not fully reflect conditions seen at the NWTC. Some of these differences have been minimized through local scaling, but future model updates are planned to achieve better agreement with observed conditions.

The process of generating coherent turbulent structures involves first generating a background turbulent field using one of the diabatic spectral models listed above. The SMOOTH spectral model is generally recommended for conditions seen in homogeneous terrain, and the NWTCUP spectral model is recommended for complex terrain applications. The wind farm spectral models (WF_xxx) were originally developed to mimic conditions seen upwind and at two row-to-row separations *within* a large, multi-row wind farm at San Gorgonio Pass in California. They have been validated up to a height of 50 m above ground level. The NWTCUP model was validated using measurements from the upwind planar sonic anemometer array and response of the ART Turbine employed as part of the NWTC LIST Experiment [4]. The code also allows the user to use available observed turbulence information to improve the agreement in specific locations.

If coherent turbulence is requested (this option should be included when using the NWTCUP model) and the specified gradient Richardson number (dynamic stability) is greater than **-0.05,** a series of coherent disturbances are generated with random properties. These properties include the number of disturbances, time of occurrence in the simulated record, and intensity. They are empirically scaled by the hub-height mean wind speed (or height of the center of the disturbance requested in the upper or lower half of the disk), the gradient Richardson number, and the hub-height standard deviation of the vertical wind component (σ_w) derived from the simulated background turbulence field.

Incorporated within the release of Version 1.00f is the ability to test the effects of intense coherent turbulent structures. Specifying "KHTEST" in the turbulence characteristic field generates one intense disturbance in the middle of a time series, without the random properties otherwise employed when coherent turbulence is requested. This test option overrides the Richardson number and wind shear of the background turbulence field and is available with only the NWTCUP spectral model.

The coherent turbulent structures exhibit the correct temporal and spatial phase relationships associated with the flow elements of the breakdown of a Kelvin-Helmholtz (KH) wave or billow that have been derived from both Large-Eddy and Direct Numerical Simulations (LES and DNS). KH instability (KHI) is known to be more or less ubiquitous in the stable, nocturnal boundary layer. A more complete discussion of KHI and its impact on wind turbines is available in Sections 1-3 of [3]. The coherent structures generated are then superimposed on the more random background similar to what occurs in natural flows.

Modeled as a combination of *non-homogenous Poisson* and *Lognormal Stochastic Processes*, the randomized scaling of the coherent structures in this version of *TurbSim* is based on measurements taken from the anemometer array upwind of the NWTC ART Turbine as part of the Long-Term Inflow and Structural Testing (LIST) Program [3,4]. A flow chart of the *TurbSim* code is shown in Figure 1. In the future the NWTC-based scaling will be compared with measurements derived from the 120-m tower used as part of the Lamar Low-Level Jet Project (LLLJP) in Southeast Colorado and any systematic differences based on location and height above the ground accounted for.

The presence of superimposed coherent structures can induce *transient* loading events on simulated turbine rotors and supporting structures. The simulation of such structures is not adequately provided for in the inflow simulators up to now because of basic limitations in the mathematical procedures used. This combination of techniques; i.e., Fourier inversion plus time-domain Poisson and Lognormal modeled events, produces the highly *non-Gaussian* flow behavior associated with the presence of coherent structures in actual flows.

Every effort has been made to randomize the occurrence and scaling of coherent event structures that occur in natural, nocturnal boundary layer flows. If a flow containing coherent turbulent elements is desired, it is highly recommended that an ensemble of simulations using the same boundary conditions with a varying random seed be generated and the resulting statistics evaluated. Ideally, each of these individual flow realizations should be employed to drive the target wind turbine simulation, and the resulting aeroelastic response statistics should be compared in order to obtain some feel of the expected variability. A PERL-script to compute an ensemble of inflow realizations for a given set of boundary conditions is included in the distribution.

The incorporation of the discrete coherent events requires the storage of about 270 MB in addition to the *TurbSim* executable and associated support files. Files containing these events are included in the distribution. The use of the coherent events does require a bit more execution time in the *AeroDyn* program (where they are superimposed on the background turbulence) with the exact amount of time dependent on the number of events and their lengths called for in each realization that are, in turn, a function of the specified boundary conditions. The Cholesky factorization algorithm has been rewritten in *TurbSim* to be more efficient in terms of both CPU and memory usage.

As opposed to the previous simulators in which only one random number generator (RNG) was provided, *TurbSim* allows the user a choice of one of three RNGs. A specification of "RNSNLW" in the input file invokes the original Sandia RNG that is used with *SNLWIND* and *SNLWIND-3D*. Adding a second seed value in place of the "RNSNLW" character string invokes an intrinsic Multiple Linear Congruential Generator (MLCG and used with *SNwind*), or substituting the character string "RANLUX" invokes level 3 of the Lüscher "Luxury Pseudorandom Numbers" RNG (see the *TurbSim* documentation for additional information). After an extensive testing of these three generators, we recommend the use of RANLUX.

With a limited comparison of simulated results with measurements between 50 and 120 m from the LLLJP tower, we believe the current version of *TurbSim* is applicable up to heights of 100-120 m. See below.

TurbSim is intended to generate a series of inflow simulations based on a given set of initial boundary conditions that are employed with the design codes (FAST, MSC.ADAMS®, or YawDyn) to produce response (load) solutions that can be analyzed using ensemble statistics. For example, at least nine stochastic degrees of freedom have been incorporated into the NWTCUP model in order to provide the range of variation seen in actual flows. A minimum of 31 realizations is recommended for a specific set of boundary conditions to allow the use of large sample statistics to be employed properly.

In the future, we expect to expand this version of *TurbSim* to include:

- Any modifications that are necessary to reflect turbulent conditions as measured between the heights of 50 and 120 m on the LLLJP Tower (modified turbulence spectral models and coherent event Poisson and Lognormal distributions)

- Realistic inflow simulations (largely based on available boundary layer turbulence theory) up to a height of 200 m to accommodate the largest and highest rotors envisioned as part of the DOE Low-Wind Speed Turbine Program (LWST)

- Simulations of the turbine turbulent inflow conditions associated with the region of high vertical speed and *direction* shear below a low-level jet stream (LLJ) velocity peak that resides above the maximum rotor elevation

- Improvements to the low-frequency spectral model used in conjunction with NWTCUP simulations. The code currently applies a model derived from conditions seen in the complex terrain of San Gorgonio Pass, California and is not fully representative of long-period turbulent variations seen at the NWTC.

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List of Abbreviations

DNS	Direct Numerical Simulations
KH	Kelvin-Helmholtz
KHI	Kelvin-Helmholtz Instability
LIST	Long-term Inflow and Structural Testing
LLJ	low-level jet stream
LLLJP	Lamar Low-Level Jet Project
LES	Large-Eddy Simulation
LWST	Low-wind Speed Turbine
NTM	Normal Turbulence Models
NWTC	National Wind Technology Center
NWTCUP	NWTC Upwind
RNG	random number generator
MLGC	multiple linear congruential generator

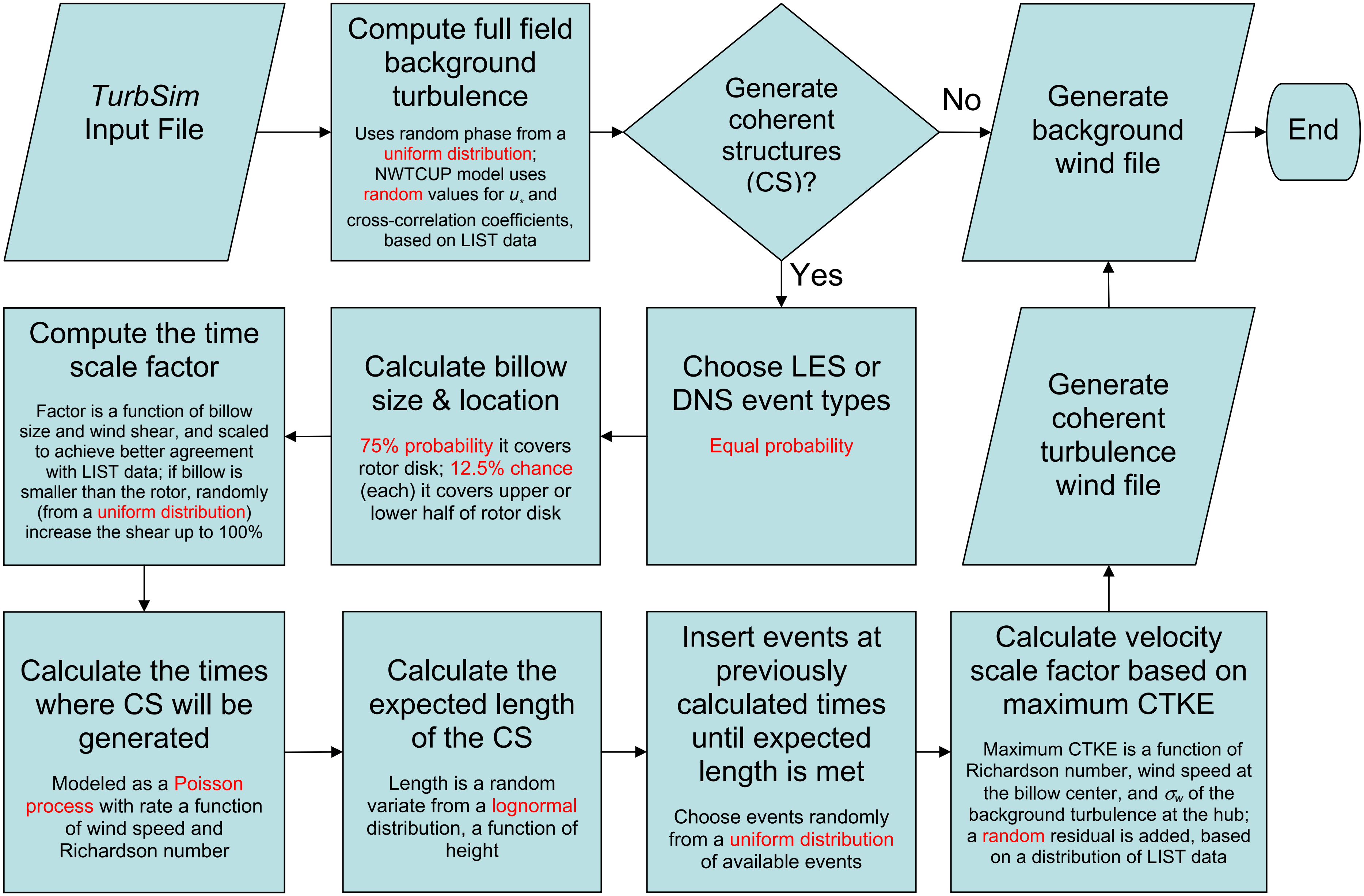

Figure 1. *TurbSim* Flowchart

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