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Subcontractor Report

Development of a Low-Dimensional Wind Turbine Inflow Turbulence Model

Second Quarterly Report: December 15, 2002 – March 15, 2003

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During this quarterly research period (15 Dec. 2002-15 Mar. 2003), we have made progress in the first two Tasks listed under PHASE I of our research effort:

Task 1: Data Set Identification, Selection, and Characterization

Individual Cases99 data sets have been chosen for the initial data analysis. A more objective approach is being undertaken to characterize the entire data set (particularly with an eye toward those times when aircraft data are also available). To that end, software has been written to determine gradient and bulk Richardson numbers and total turbulent kinetic energy (TKE) at selected heights for the entire project. This addition to the data record will enable us to focus on the more critical events.

Conversion code has been developed for the 20- and 1-Hz Cases99 data sets (ASCII) to NetCDF that is compatible with the format of the associated aircraft data sets. A networked high-storage PC has been identified for common data storage and acquisition by individual researchers on this project.

Task 2: Turbulence Model Development

Investigations are underway to assess the ability of the Penn State/National Center for Atmospheric Research Mesoscale Modeling System Version 5 (MM5) to simulate fluxes. Wind and temperature data from the 55-m instrumented tower have been imported into the MM5 planetary boundary layer (PBL) scheme. Values of the bulk Richardson number are then calculated for each of the various levels for which flux data have been directly measured. A comparison is then made between the model-derived turbulent flux information and direct measurements at the tower. For this analysis, the 5-minute tower averages are used. This time scale is appropriate for models such as MM5 that have grid spacing on the order of 10 km. Case studies from 6 October and 20 October 1999 have been explored in detail because concurrent aircraft high-rate data sets for portions of those days are available. For the representative cases that have been examined to date, the agreement is good.

Constructions of stochastic Fourier representations of wind fields have been made for simple homogeneous models. Selected realizations have then been analyzed by proper orthogonal decompositions (POD) algorithms. Such a process clearly illustrates the advantages of POD over stochastic methods, in which coherent, intermittent, embedded structures are not adequately simulated by Fourier spectral representations.

Task 3: Prognostic Testing

We have deferred the identification of additional data sets for prognostic testing until a later time.

Supporting documentation relative to the above Task 2 discussion is included in Appendix A.

We have identified an additional graduate student for active participation in this project: John Spitler, assistant lecturer, Department of Mathematics (PhD). Both Spitler and his academic advisor in the mathematics department, Frederico Furtado, have interests in the mathematics of orthogonal projection methods.

In January 2003, Lindberg and Naughton attended the ASME Wind Energy Symposium in Reno, Nevada.

Appendix A

Task 2: MM5 Parameterizations

High-resolution numerical models of the atmosphere have been widely used to predict and diagnose fields of state parameters such as wind, temperature, and pressure. Model skill levels continue to rise, and an increasing reliance is being placed on numerical modeling efforts for a variety of applications. Of interest in the deployment and maintenance of low wind speed turbines is the ability of high-resolution models to capture significant turbulent events within the PBL. Investigations are underway to assess the ability of MM5 to replicate the turbulent structures in the PBL. A comparison is made between fluxes that are computed from MM5 with observed fluxes measured from a 55-m instrumented tower as part of the CASES99 field experiment.

Seven PBL parameterization schemes are available within the MM5 framework. To begin, the high-resolution PBL model of Zhang and Anthes (1982) is used. This scheme explicitly resolves the PBL and determines flux characteristics in both the surface boundary layer (SBL) and PBL. The bulk Richardson number is computed for each layer bounded by grid points. Four stability classes are identified, and fluxes of heat and momentum are computed using universal similarity functions.

To test the ability of MM5 to simulate fluxes, wind and temperature data have been taken from the 55-m instrumented tower. The procedure is as follows. Actual wind and temperature profiles were imported into the MM5 PBL scheme. Values of the bulk Richardson number could then be calculated for each of the various levels for which flux data have been directly measured. A comparison is then made between the model-derived turbulent flux information and direct measurements at the tower. For this analysis, the 5-minute tower averages are used. This time scale is appropriate for models such as MM5 that have grid spacings on the order of 10 km. Case studies from 6 October and 20 October 1999 have been explored in detail because concurrent aircraft high-rate data sets for portions of those days are available.

Examples of MM5-derived turbulent fluxes and corresponding measured fluxes on the tower are illustrated in Figs. 1 and 2. Figure 1 illustrates the comparison between the turbulent fluxes of momentum in the x-direction for MM5 and the 55-m tower. Figure 2 depicts the time history of the x-component of the turbulent fluxes of momentum. In each case, it can be seen that MM5 can replicate, with considerable skill, the first-order turbulent characteristics of the mean atmospheric flows. Future research tasks will focus on the ability of the MM5 framework to address singular events of strong wind and turbulence conditions. In addition, the high-rate (20-Hz) turbulence data from the 55-m tower will be examined to determine the variance of the momentum fluxes with stability class. This will permit some determination as to how a numerical model such as MM5 may be able to infer the range of turbulent events from the mean structure of the atmosphere.

Reference

Zhang, D.; Anthes, R. A. (1982). "A high-resolution model of the planetary boundary layer – sensitivity tests and comparisons with the SESAME-79 data." *J. Appl. Meteor.* (21); pp. 1594-1609.

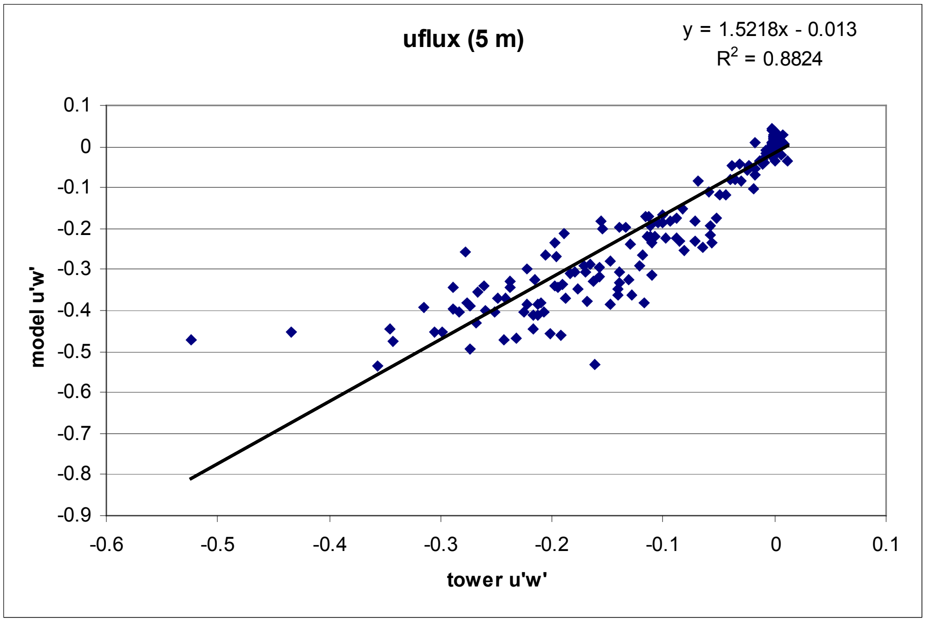

Figure 1. Comparison between x-momentum turbulent fluxes determined from MM5 with those measured at the 55-m tower at 5 m for 20 October 1999.

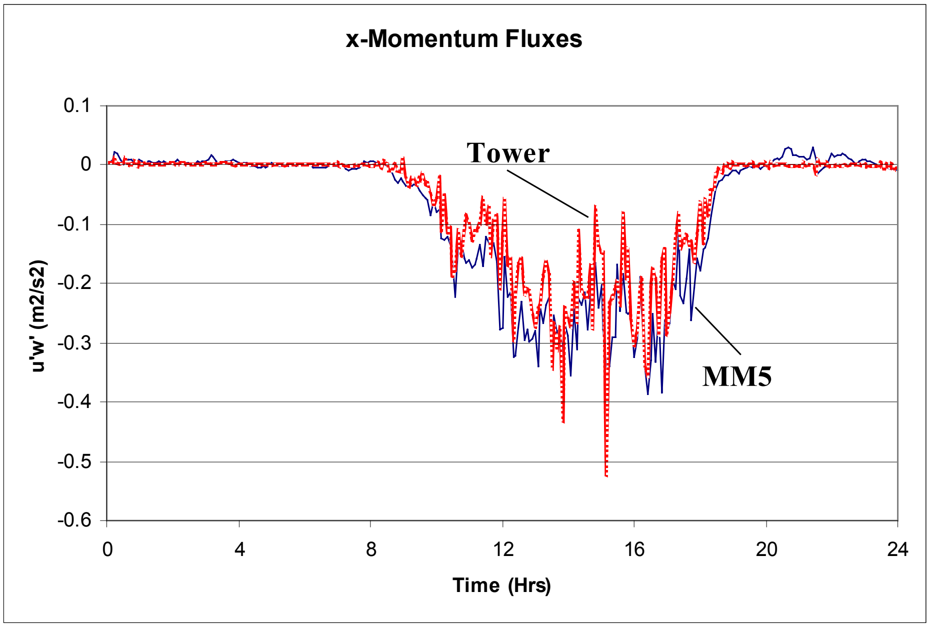

Figure 2. Comparison of the time history of x-momentum turbulent fluxes determined from MM5 with those measured at the 55-m tower at 5 m for 20 October 1999.

POD Modes for Stochastically Modeled Turbulence

A POD analysis of the modeled 1-D turbulence field shown in Fig. 3 has been performed. The eigenvalues, which correspond to the relative energy contained in each eigenvector, are shown in Fig. 4. It is clear from this figure that a significant amount of energy is contained in a large number of modes. This occurs because the original turbulence signal does not appear to contain highly coherent structures. Nonetheless, this case demonstrates that this turbulent field can be described effectively using POD modes derived from the data. The reason for the transition from a smooth decrease in the value of λ to the random low values seen for modes greater than ~63 is not known, but it is interesting to note that there are 127 modes in this analysis.

Ten mode shapes (eigenvectors) corresponding to the ten highest eigenvalues in Fig. 4 are shown in Fig. 5. It is clear that these modes are quite different from the original Fourier modes used to create this turbulence field. The modes do not appear to reveal any particular structure associated with the flow field because there are no dominant coherent structures in this flow.

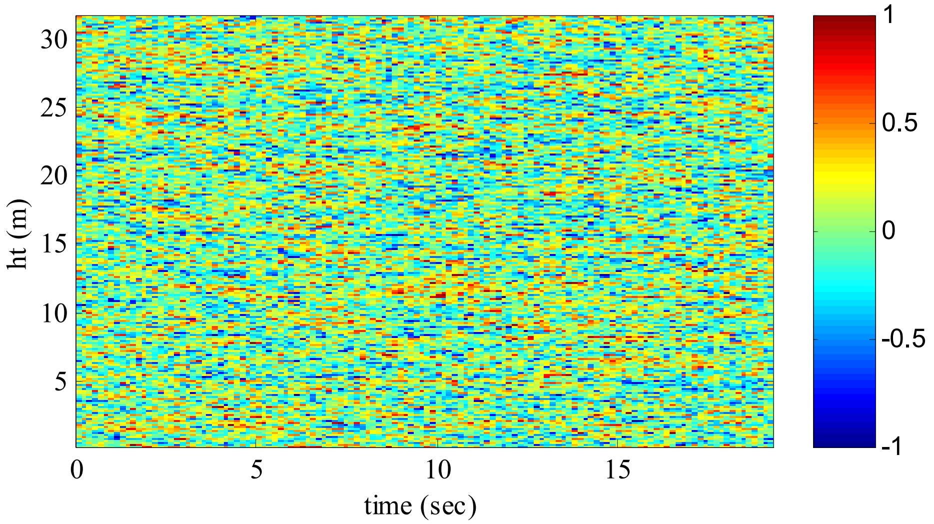

Figure 3: Stochastically modeled turbulence. The u-component of velocity is shown as a function of time and height.

We will continue analyzing such data sets. This effort will provide us with experience modeling flows using both stochastic Fourier modes and POD modes. We now believe that a combination of POD modes and Fourier modes may be used in the eventual modeling of the wind fields. The one spatial dimension analysis presented here will also be extended to two dimensions.

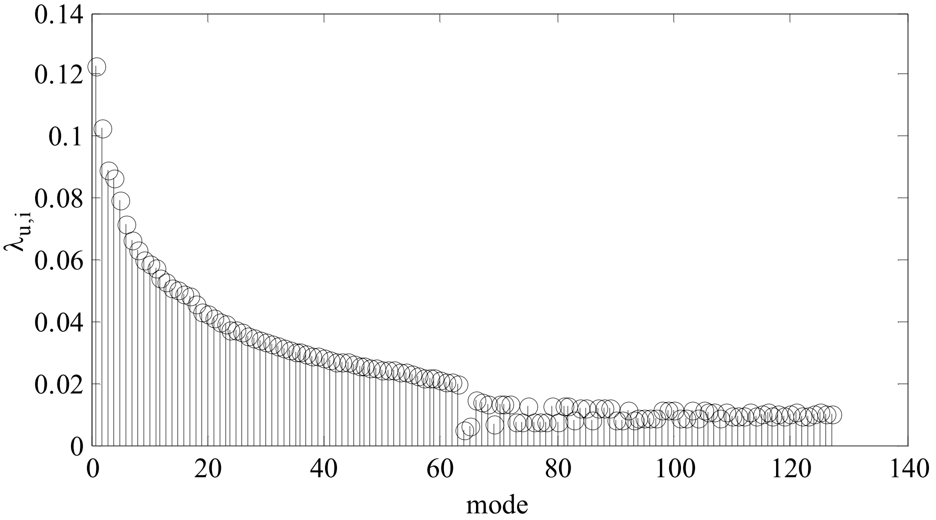

Figure 4. Eigenvalues determined for the stochastically modeled turbulence. The data used for this analysis contained 128 spatial locations (heights) and 4096 time locations.

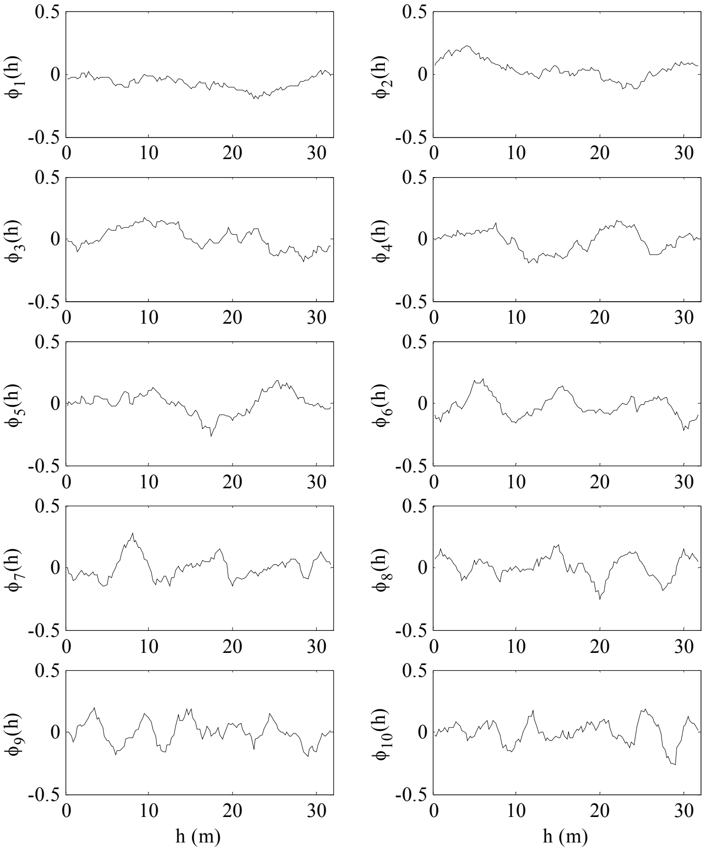

Figure 5. Eigenfunctions or modes corresponding to the highest ten eigenvalues shown in Figure 4.

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13. ABSTRACT *(Maximum 200 words)*

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