J. Wind Eng. Ind. Aerodyn. 156 (2016) 146–158

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Reconstructing long-term wind data at an offshore met-mast location using cyclostationary empirical orthogonal functions

Ji-Young Kim [a,*], Kwang-Yul Kim [b]

[a] Korea Electric Power Research Institute, Daejeon, Republic of Korea
[b] School of Earth and Environmental Science, Seoul National University, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form
28 July 2016
Accepted 28 July 2016

Keywords:
Offshore met-mast
Wind data
Reconstructing long-term data
CSEOF

ABSTRACT

For the development of a wind power plant, plant design and its project feasibility analysis are implemented with wind data observed by a met-mast at a target location. Since observation period/time of a met-mast is normally about one year before the plant design, correlation with long-term data existing in the neighborhood of the target location is used for hindcasting past met-mast data to reduce uncertainty in the feasibility analysis, which is called the Measure-Correlate-Predict (MCP) method. In this study, cyclostationary empirical orthogonal function (CSEOF) analysis as a new approach is employed to extend the 1.5-year offshore met-mast HeMOSU-1 data into 34-year long-term data based on the MERRA reanalysis dataset. Both the one- and two-dimensional CSEOF results are compared with that of the widely-used MCP method. The CSEOF method shows a similar level of accuracy to the existing method for mean wind speed, while the former exhibits a slightly better accuracy for the frequency distribution of wind speed and the capacity factor as an index related to the estimation of wind power generation. In additional hypothetical test based on reanalysis datasets, the 1D-CSEOF method shows, in general, a better performance than the conventional MCP method in terms of the accuracy of statistical properties of wind.

1. Introduction

Wind power is an energy source that is in the spotlight, spurring the development of new and renewable energy all around the world. Korea is also experiencing a shortage of electricity, but it is not easy to construct thermal or nuclear power plants anymore because of its small land area. Considering the geographic characteristics of the Korean Peninsula surrounded by the seas on the three sides, there is a rising interest in the development of the offshore areas with relatively rich resources. The Korean government has recently established a development plan for a 2.5 GW offshore wind power plant in the West (Yellow) Sea as an effort to leap as a leading country in offshore wind power. The project and research now has been proceeding with the phase 1 of the test site construction on a scale of 100 MW. An optimal location that is economically feasible and available for a large-scale development has been chosen considering wind resource distribution according to a numerical wind resource map, topographic characteristics such as sea floor depth, and distance from the coastline (Kim et al., 2013). Korea's first offshore met-mast, HeMOSU-1, has been set up and operated near Buan-gun, Jeollabuk-do, and Yeonggwang-gun, Jeollanam-do, where the selected target site was placed in 2010 as shown in Fig. 1. Various meteorological data including wind direction and speed observed at HeMOSU-1 are used in assessing the project feasibility, wind farm layout design, and turbine structure design (Oh et al., 2012). When evaluating the feasibility of wind power project or estimating design load for structure, it is important to characterize the long-term trends and year-to-year variability of observational data.

Since met-mast data generally has a short observation period, around one to two years, past data are reconstructed by extrapolation through regression, known as the measure-correlate-predict (MCP) technique, using neighborhood long-term observation data. Several MCP algorithms have been suggested based on the linear regression method proposed by Derrick (1992), which estimates the relationship between the wind speeds at target and reference sites. Rogers et al. (2005) compared four MCP algorithms in terms of the accuracy of the estimated wind speed and the effect of the length of employed data on the accuracy of estimation. Thøgersen et al. (2007) implemented general-purpose software for four of the MCP methods including a linear regression model; this model is universally accepted so far. Various methods were developed to overcome limitations of the linear regression method, but they do not consistently show improved results in the context

* Corresponding author.
E-mail address: jy_kim@kepco.co.kr (J.-Y. Kim).

http://dx.doi.org/10.1016/j.jweia.2016.07.017
0167-6105/

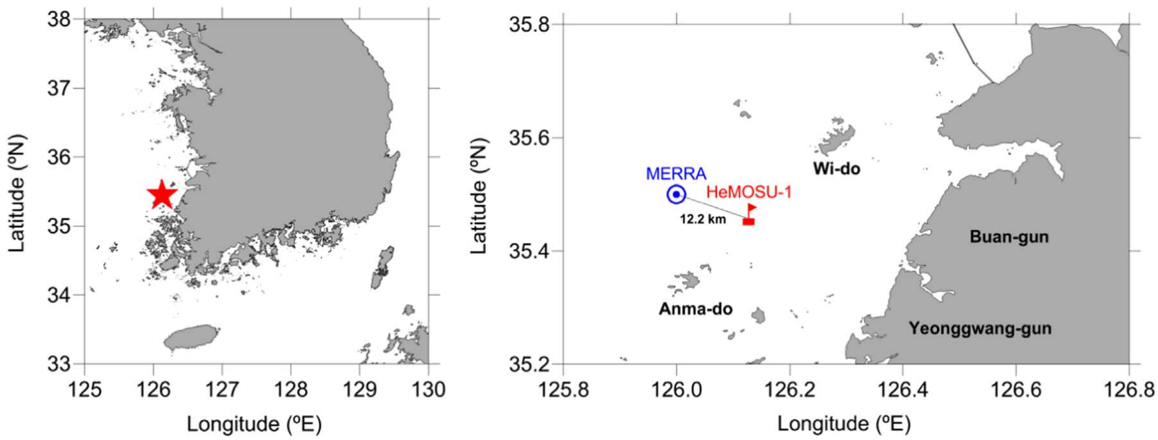

Fig. 1. Locations of the measurements (HeMOSU-1) and one-point reference (MERRA).

of the target data characteristics (García-Rojo, 2004; Sreevalsan et al., 2007; Clive, 2008; Carta and Velázquez, 2011; Saavedra-Moreno et al., 2013).

Since most existing methods consider correlation of the wind speed for each bin of wind directions, it is difficult to understand how the principal physical components, such as the diurnal cycle of wind, in the data are calibrated by the regression method. In the present study, a new approach is developed by using cyclostationary empirical orthogonal functions (CSEOFs) in order to carry out regression analysis with respect to individual processes instead of individual wind direction bins. Kim et al. (1996); Kim and North (1997); Kim and Wu (1999), and Kim and Chung (2001) introduced the concept of CSEOF analysis to identify and extract individual spatio-temporal modes from a given dataset.

By carrying out CSEOF analysis, data are decomposed into cyclostationary loading vectors (CSLVs), each of which is modulated by corresponding amplitude or principal component (PC) time series following the naming convention of Kim et al. (1996). Each CSLV reflects a distinct process in the data and is rendered as temporally-varying spatial patterns together with their amplitude fluctuations on longer time scales. This provides a unique means of matching common processes between the target and reference data in terms of their evolution patterns and amplitudes.

Hamlington et al. (2011) used the CSEOF technique to extend significantly the period of sea level reconstructions based on tide gauge data. In a similar manner, the CSEOF technique is applied in this study for the purpose of extending the short-term measurements at HeMOSU-1 in conjunction with long-term reference data. By carrying out regression analysis in CSEOF space and comparing the regressed CSLVs against those derived from the target data, the accuracy of the reference data can be addressed more clearly in the context of major physical modes in the data.

Long-term hindcasting or forecasting of wind data is very difficult due to its irregular variation and various attempts are needed to improve the accuracy of estimation. As mentioned above, a new approach is introduced in the present study as an alternative to the existing MCP methods and to improve the estimation accuracy. This new concept will be addressed in detail in the Method section.

2. Data

HeMOSU-1, which is an offshore met-mast to promote the west coast offshore wind power project, is located on the West Sea about 30 km offshore as shown in Fig. 1. It performs various meteorological observations including wind direction and speed at several altitudes as shown in Fig. 2. HeMOSU-1 has accumulated approximately 2.5 years of observational data starting from February 2011. Since there are few offshore meteorological observatories operating for an appreciable length of time, it is unavoidable to use reanalysis reference data to estimate the long-term wind characteristics at the test site.

In this study, Modern Era-Retrospective analysis for Research and Application (MERRA) data are used as a reference dataset, which is of relatively high spatial and temporal resolutions among the long-term reanalysis datasets (GMAO, 2014). MERRA is a reprocessed dataset, into which various satellite-era datasets were blended by using the GEOS-5 atmospheric data assimilation system at Global Modeling and Assimilation Office (GMAO) of NASA. In this study, reference data are used in two different manners – only single-point data near HeMOSU-1 and 2-dimensional spatial array to consider the spatial distribution around the Korean Peninsula. A MERRA grid point at approximately 12.2 km west outbound from HeMOSU-1 is used for a one-dimensional (1D) analysis (see Fig. 1b and Table 1). For a 2-dimensional (2D) analysis, the domain includes offshore area around the Korean Peninsula (32°–39°N × 120°–135.33°E; see Table 1). Data at 50 m above the sea level, which is closest to the hub height of the wind turbine, are used. The details of the MERRA reference data are shown in Table 1. Meanwhile, the observational data at 46.3 m height from the sea level are taken from HeMOSU-1; this level is closest to the elevation of the MERRA data used in the present study. Since there are missing data due to data logger defect for about one month from June 5 to July 14, 2011, only the data after the missing period are used for training, leaving the earlier data before the missing period for verification. We also used the 1.5° × 1.5° European Center for Medium-Range Weather Forecasts Reanalysis (ERA) Interim product (Dee et al., 2011) in a hypothetical test.

3. Method

3.1. CSEOF analysis

It is useful to decompose complex physical system into simpler basis functions in order to understand the basic physical processes in the physical system. The CSEOF technique is introduced to separate individual physical processes from the datasets. This technique has been used in many previous studies and the details can be found in Kim et al. (1996, 2015); Kim and North (1997); Kim and Wu (1999), and Kim and Chung (2001). In CSEOF analysis, space-time data, $T(r, t)$, are expressed as a unique linear superposition