Site Calibration for the Wind Turbine Performance Evaluation

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The accurate wind speed information at the hub height of a wind turbine is very essential to the exact estimation of the wind turbine power performance testing. Several methods on the site calibration, which is a technique to estimate the wind speed at the wind turbine's hub height based on the measured wind data using a reference meteorological mast, are introduced. A site calibration result and the wind resource assessment for the TaeKwanRyung test site are presented using three-month wind data from a reference meteorological mast and the other mast temporarily installed at the site of wind turbine. Besides, an analysis on the uncertainty allocation for the wind speed correction using site calibration is performed.

Key Words : Site Calibration, Wind Turbine, Flow Distortion Correction Factor, Wind Direction Sector

1. Introduction

The goal of this study is to analyze the wind data of the TaeKwanRyung test site, and perform a site calibration for the wind turbine performance evaluation. The performance of a wind turbine is evaluated based on the wind data which are picked up at a meteorological mast (Hau, 2000). Usually, this meteorological mast (MM) is located near to the wind turbine and at the place which is not aerodynamically disturbed by the presence of a wind turbine. Especially, if there are some obstacles such as mountains, buildings, etc., the wind data measured at the meteorological mast are not the same as those at the site of wind turbine. Therefore, a way of the site calibration which converts the measured wind data at the meteorological mast to the equivalent wind data at the wind turbine is to be considered for the exact testing of the wind turbine performance. Figure 1 shows the map of the TaeKwanRyung test site. A meteorological mast and the wind turbine to be tested are located at the point marked as 'Ref. MM' and 'Temp. MM'. As can be seen, a lot of obstacles, mainly mountains and buildings, influence the wind flow. Therefore, a site calibration is to be made.

In accordance with the IEC (International Electro-technical Commission) standard 61400-12, a site calibration is carried out (IEC, 1998). As shown in Fig. 1, two meteorological masts are constructed for a site calibration. One is the reference meteorological mast of measuring wind resources for the test site and the other is the temporal meteorological mast for the site calibration, which will be replaced by the wind turbine to be tested. The distance between two meteorological masts is 3.4 times of the wind turbine rotor diameter, which complies with the IEC standard. Figure 1 also shows the disturbed wind sector where sensors installed on the reference meteorological mast are influenced by the wake of the wind turbine. The measured data at the reference meteorological mast for winds from the disturbed sector shall not be used for the wind turbine site calibration (IEC, 1998). Two site

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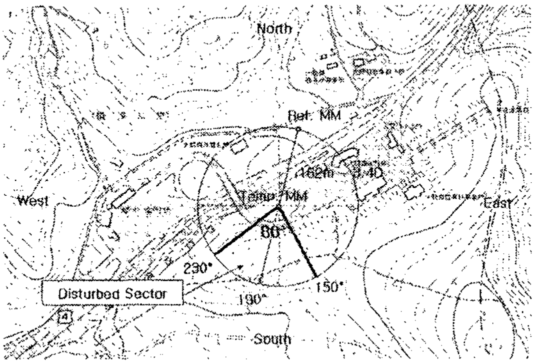


Fig. 1 Map of the TaeKwanRyung test site

calibration methods are introduced, which are the bin-averaging ratio method and the least square method. A site calibration is made based on these two methods and the usefulness of these methods is to be reviewed in this article. The three-month wind data at the TaeKwanRyung site are used in this study. Finally, the uncertainty issue in the site calibration is covered, in which the reliability analysis on the wind speed correction is conducted.

2. Wind Data of the TaeKwanRyung Test Site

Two meteorological masts which are schematically shown in Fig. 2 are required for the site calibration. The wind resources at the test site are presented from Fig. 3 to Fig. 5. These show the wind data measured on the two meteorological masts at the TaeKwanRyung site for three months from the July 9, 2002 to October 8, 2002. All the sensor outputs on the two meteorological masts such as anemometer, wind vane, thermometer, and barometer are 10-minute averaged and recorded (NRG systems, 1996). Figure 3 shows the data acquired from four anemometers on the reference meteorological mast installed at the height of 46 m (#1), 45.6 m (#2), 23 m (#3), and 10 m (#4). Also, Fig. 4 shows the data obtained from three anemometers installed on the temporal meteorological mast at the height of 46 m (#1), 23 m (#2), and 10 m (#3). And, the wind vane sensor is located at the height of 46 m on each meteorological mast. The effect of the wind shear by the height difference can be noticed from

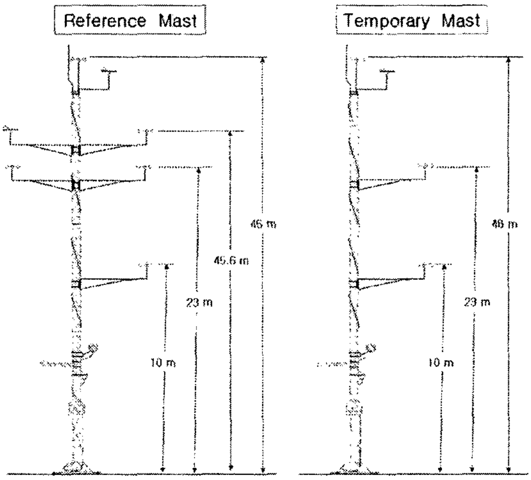


Fig. 2 Reference MM and temporal MM

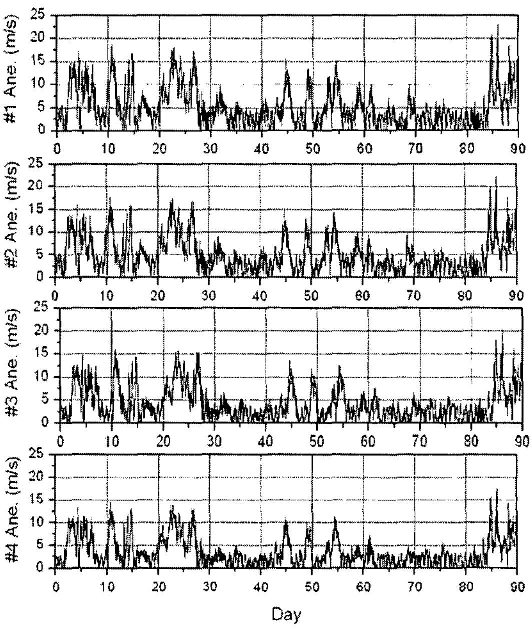


Fig. 3 Wind speed data at the reference MM

Figs. 3 and 4. Figure 5 plots the wind speed distribution according to the wind direction from the measured wind speed data on the two meteorological masts. The degree means the wind direction, and the 0 degree represents the north wind, and the degree is increased clockwise. It can be concluded from the measured wind data that the major wind of the TaeKwanRyung test site comes from the east and west, although there is a little dependency on the season. The circles

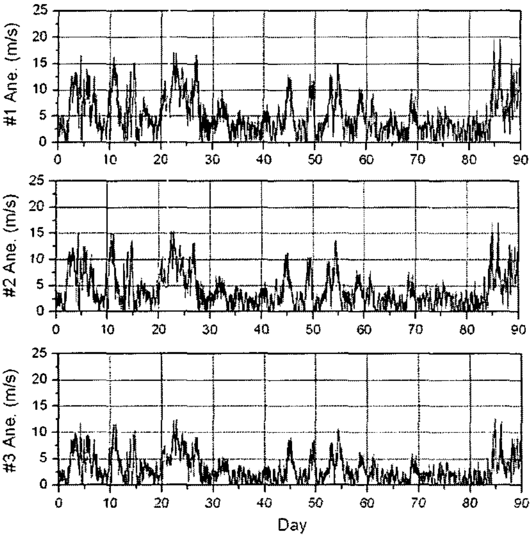
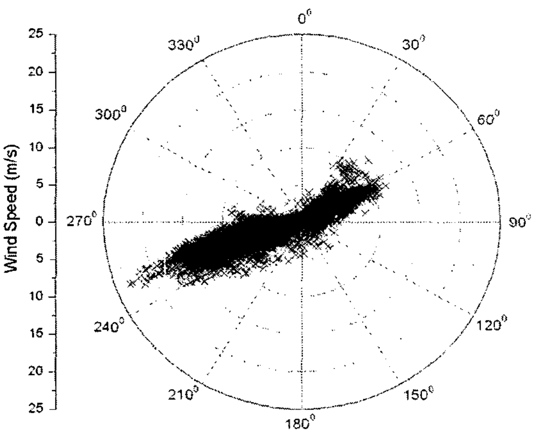
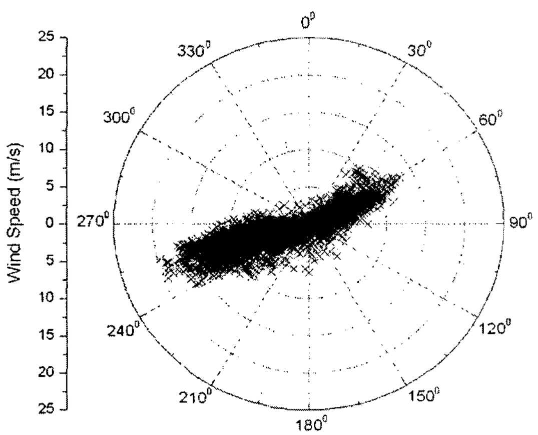


Fig. 4 Wind speed data on the temporal MM



(a) Wind rose for the reference meteorological mast



(b) Wind rose for the temporal meteorological mast

Fig. 5 Wind rose of the TaeKwanRyung test site

on the wind rose plot stand for the wind speed of 25 m/s, 20 m/s, 10 m/s, and 5 m/s. All the data in Fig. 5 are coming from the anemometer and the wind directional vane positioned on the two meteorological masts at the height of 46 m. Because of the difficulty in setting the north of the wind vane as the true north, a special calibration method using a vision image correction is applied (Lee et al., 2003). By using this method, the amount of error in reading a vane can be limited within 2 degrees from the true direction.

3. Site Calibration Methodology

As mentioned before, a site calibration at the TaeKwanRyung test site is the very necessary step for the successful performance evaluation of the wind turbine, because of its large topological variations (IEC, 1998). However, the IEC 61400-12 specifies only minimal requirements on the wind data collection and selection for a site calibration. There is no mentioning about the site calibration methodology in the IEC standard. Therefore, the site calibration researchers should devise their own ways of a site calibration. The requirements on the wind data handling for a successful site calibration are summarized as follows based on the IEC 61400-12 standard. As described in Fig. 6, the measurement sector which means the set of wind direction not disturbed by the wake of the wind turbine should be divided as wind direction sectors of a maximum of 30° width. Then, all the measured wind data are to be sorted in wind direction sectors. For each wind direction sector, a minimum of 24 hours of data at wind speeds ranging from 5 m/s to 10 m/s should be acquired. All the wind data processed in a site calibration should be 10 minute averaged data (IEC, 1998). Therefore, at least 144 wind speed data are required for a reliable site calibration. If enough data are acquired for each wind direction sector, the flow distortion correction factor, K_{CF} in Eq. (1) should be determined using an appropriate method.

$$V_{WT} = K_{CF} V_{REF} \quad (1)$$

The above relation predicts the wind speed (V_{WT})

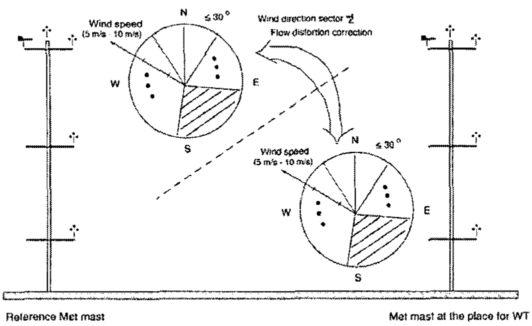


Fig. 6 Schematics of a site calibration procedure

at the hub of the wind turbine by using the measured wind speed (V_{REF}) at the reference meteorological mast.

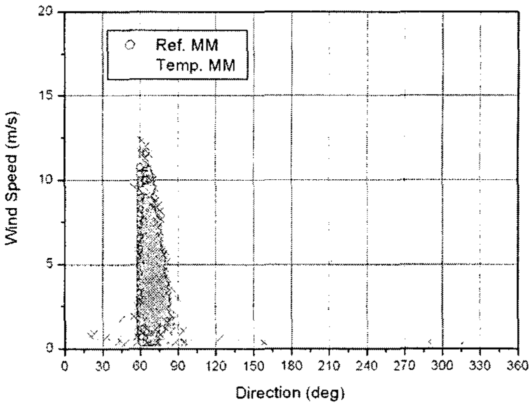
There are two methods in calculating a flow distortion correction factor, K_{CF}. The first one is the bin-averaging ratio method (Antoniou et al., 2001 ; Hunter et al., 2001). If there is enough wind speed data in the i-th wind direction sector, then the ratio of the average wind speed in the sector for the temporal meteorological mast over that for the reference meteorological mast can be calculated, which is the flow distortion correction factor, K_{CF} for the i-th wind direction sector. By applying the above procedure for all bins in the measurement sector, K_{CF} is to be determined as a function of the wind direction. The other method relies on the least square algorithm. The correlation between two wind speed data measured at each meteorological mast can be approximated as a linear equation of

$$V_{WT} = K_{CF} V_{REF} + V_{WT}|_0 \tag{2}$$

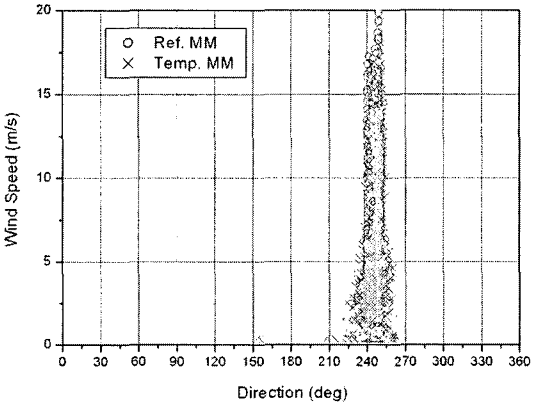
K_{CF} and $V_{WT}|_0$ are the slope and interception in the linear equation, and are determined using a least square algorithm (Curvers, 1999 ; Ferreira et al., 1999).

4. Site Calibration of the TaeKwanRyung Test Site

The wind resources collected for 3 months (from July 9, 2002 to October 8, 2002) at the TaeKwanRyung test site are used for the site calibration. All the wind speed data are sorted into each wind direction sector, which is obtained by



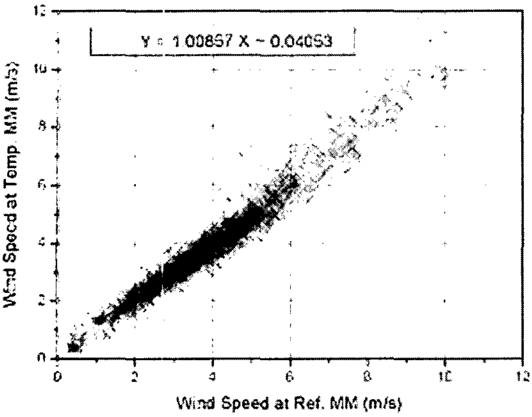
(a) East wind (60°~70°, sector #7)



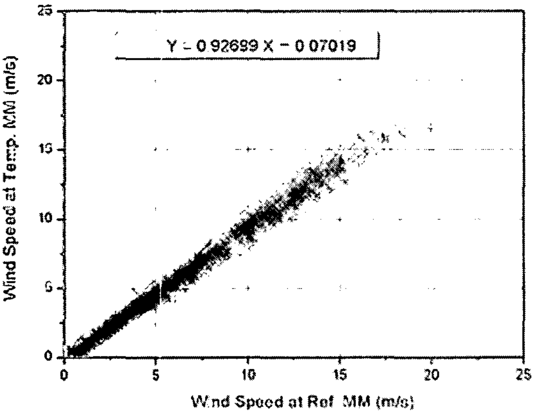
(b) West wind (240°~250°, sector #25)

Fig. 7 Wind data for the east and west wind direction sector

dividing the measurement sector of Fig. 1 into the unit of 10°. Fig. 7(a) and (b) represent the east wind components ranging from 60° to 70° (wind direction sector #7) and the west wind components ranging from 240° to 250℃ (wind direction sector #25). The points marked '○' and '×' indicate the measured wind data on the reference and temporal meteorological mast respectively. The wind data expressed as '×' in this figure are scattered because the wind direction sectors are classified based upon the data from the reference meteorological mast. The reason of wider scattering at the low wind speed is coming from the imperfection of the wind direction vane. The threshold of the wind vane sensor is 1 m/s, below which the vane is not responding (NRG, 1996). This scattering phenomenon, however, is

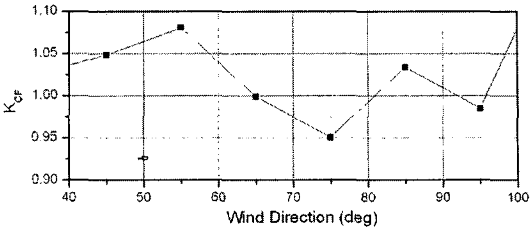


(a) East wind (60°~70°, sectr #7)

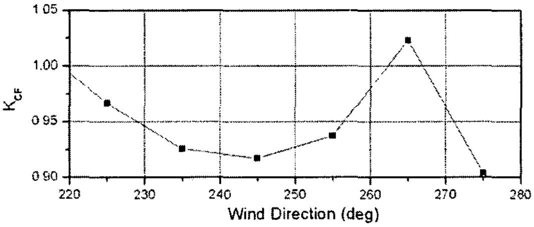


(b) West wind (240°~250°, sector #25)

Fig. 8 The correlation of the wind data measured at two meteorological masts

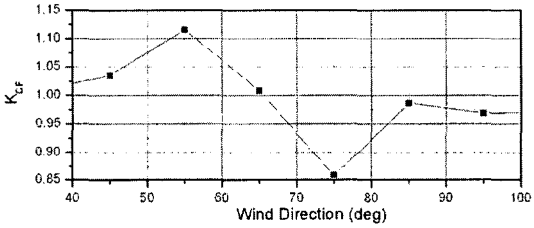


(a) East wind (40°~100°)

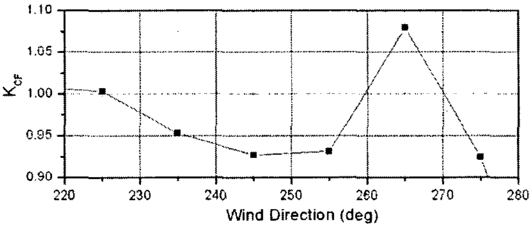


(b) West wind (220°~280°)

Fig. 9 Flow correction factor by bin-averaging ratio method



(a) East wind (40°~100°)



(b) West wind (220°~280°)

Fig. 10 Flow correction factor by least square method

not a problem in the site calibration because the wind speed data above the limit of 5 m/s are used. Figure 8 shows the correlation of wind speed data measured at the two different meteorological masts. The center line in these figures is the optimal line in the sense of the least square curve fit. Figures 7 and 8 use the same wind data, but show some different aspects in interpreting the data.

The flow distortion correction factor, K_{CF} is calculated based on the data of Figs. 7 and 8. Figures 9(a) and (b) show K_{CF} for the wind direction from 40° to 100° and for the direction from 220° to 280°, which is obtained using the bin-averaging ratio method. Also, Fig. 10(a) and (b) show K_{CF}, which is the result of using the least square method. In order to evaluate the efficacy of each site calibration method, the result of the flow correction using two different K_{CF} is compared. The wind data which are used in this comparison are depicted in Fig. 11 and Fig. 12, which are the wind direction and speed, respectively, collected from the 22-nd to the 25-th day from the day of July 9, 2002. In Fig. 11, there is 2° difference in the mean between the wind direction measured at the reference

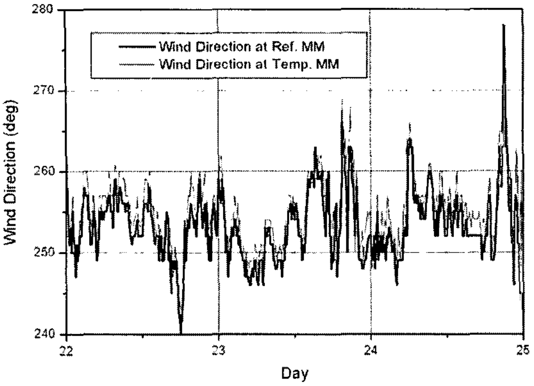


Fig. 11 Wind direction data measured at two masts

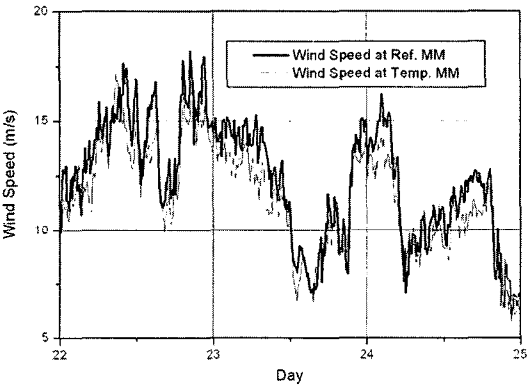
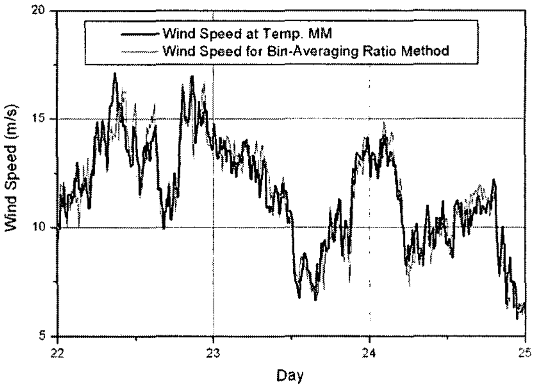
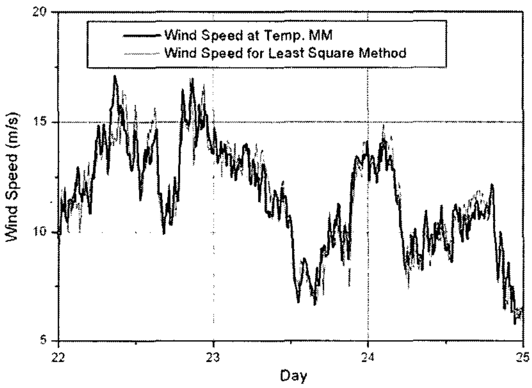


Fig. 12 Wind speed data measured at two masts



(a) Bin-averaging ratio method



(b) Least square method

Fig. 13 Flow correction result for the west wind

meteorological mast and that at the temporal mast. The causes of this difference are considered coming from the misalignment in setting the true north for each mast and the dead band characteristics of the wind vane sensor. The dead band of the wind vane sensor which means the range of directions for which the output signal is undefined amounts typically 4° (NRG, 1996). It can be also noticed in Fig. 12 that the wind speed measured at the reference meteorological mast is usually greater than that at the temporal mast. The site calibration results based on the above wind data are shown in Figs. 13(a) and (b). The wind speed at the hub height of the wind turbine is estimated by using the flow distortion correction factor, K_{CF}, and compared with the real wind data measured at the temporal meteorological mast. Fig. 13(a) shows the flow correction based on the bin-averaging ratio method, and Fig. 13(b) is for using the least square method. Comparing these two figures with Fig. 12, it can be concluded that the site calibration works well. However, relatively large amounts of the flow correction errors in both figures exist around the time axis of 22.5 day and 24.7 day, where there is a lot of deviation between two measurements in the wind direction and speed (see Figs. 11 and 12). The statistical results of the site calibration are summarized in Table 1. The average and the standard deviation of the difference between the wind speed measured at the temporal meteorological mast and that at the reference mast are listed in the 2-nd and 3-rd column for the east and west wind. The average and the standard deviation of the difference between the wind speed predicted by using the bin-averaging ratio method and the real wind speed measurement at the temporal mast are listed in the 4-th and 5-th column for each wind. The same data for using the least square method are

Table 1 Statistical data of the site calibration results

wind dir.\speed (m/s)	difference in wind speed		bin-averaging ratio method		least square method	
	average	std. deviation	average	std. deviation	average	std. deviation
east wind	0.1390	0.5916	0.0865	0.5390	0.0891	0.5343
west wind	−0.7722	0.9174	0.0183	0.7898	0.0144	0.7838

summarized in the 6-th and 7-th column. It's difficult to decide which method among the bin-averaging ratio and the least square method is better for the flow correction. Two methods show almost the same performance in the site calibration.

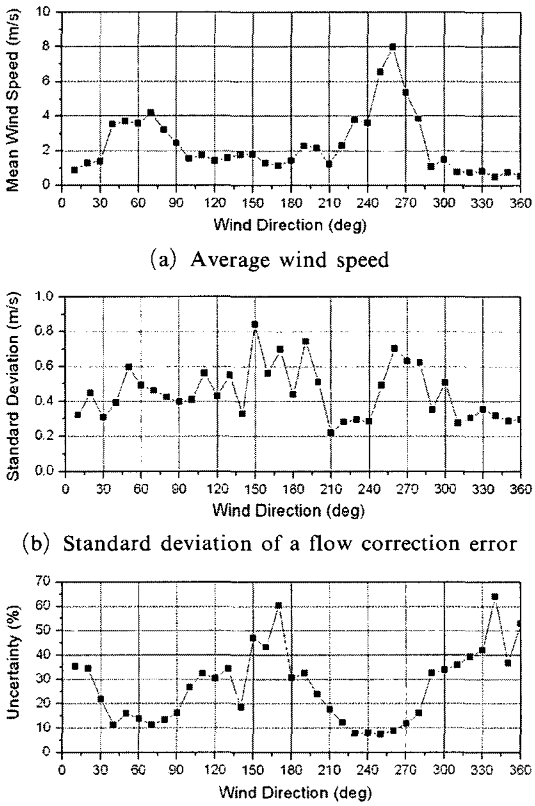
5. The Uncertainty Analysis of the Site Calibration

The accuracy in the measurement of the wind speed is the critical factor in the power performance testing of a wind turbine. The power curve and AEP (Annual Energy Product) characteristic of the wind turbine are directly affected by the nature of the wind speed. Therefore, the IEC 61400-12 claims the quantification of the uncertainty amount in the wind speed measurement. The uncertainty of the wind speed is to be determined by the Eq. (3)

$$U_{V,i}=\sqrt{U_{V1,i}^2+U_{V2,i}^2+U_{V3,i}^2+U_{V4,i}^2+U_{Vd,i}^2} \quad (3)$$

$U_{V1,i}$ is the uncertainty of the anemometer measurement, which is the maximum value of the nonlinearity stated in the manufacturer's specification. $U_{V2,i}$ is the uncertainty determined by the operating environments of the anemometer such as an atmospheric temperature and weather change. $U_{V3,i}$ represents the uncertainty coming from the installation problem of the anemometer on the meteorological mast. $U_{V4,i}$ is the uncertainty in the flow correction using the site calibration and a method of specifying $U_{V4,i}$ is explained in this section. Finally, $U_{Vd,i}$ is the uncertainty allocated for the data acquisition system.

By analyzing the flow correction error, the uncertainty level of this correction, $U_{V4,i}$, can be



(a) Average wind speed

(b) Standard deviation of a flow correction error

(c) Uncertainty of a flow correction

Fig. 14 Uncertainty allocation for a flow correction

determined. Figure 14(a) represents the averaged wind speed measured at the hub height of the wind turbine for all the wind direction sectors, which shows the similar distribution trend like the one in Fig. 5. Figure 14(b) shows the standard deviations of the wind speed error between the predicted wind speed by the flow correction and the measured data on the wind turbine's hub height for each wind direction sector. Figure 14(c) shows the ratio of the standard deviation of the flow correction error to the averaged wind speed for each wind direction sector. The magnitude of the flow correction uncertainty is about 10% for the main wind directions. The uncertainty magnitude in Fig. 14(c) seems to be reasonable, considering that the uncertainty due to the flow correction for a flat test site which does not require a site calibration shall be taken to be 3% or greater if the distance between the wind turbine and the meteorological mast is 3 to 4 times of the rotor diameter (IEC, 1998). The reason of having large magnitude of the flow correction uncertainty for the south and north winds is coming from that the enough data are not available for these wind directions (see Fig. 5). This, however, does not make any problem in the performance testing of a wind turbine at the TaeKwanRyung test site, because the main winds are the west and east winds.

6. Conclusions

The wind resources at the TaeKwanRyung test site are excellent for the wind power generation. A site calibration, however, is required because the test site has a complex terrain like mountains and small buildings. Throughout this study, a general methodology of a site calibration is introduced. After presenting the experimental data on the wind resources of the TaeKwanRyung test site, two methods for the flow distortion correction which are the bin-averaging ratio method and the least square method are explained. It turns out that there is almost no difference in performance-wise between the two methods in the point of the flow correction. For a systematic evaluation of the power performance of the wind turbine, it's very important to allocate the uncertainty level coming from the flow distortion correction error. The amount of the uncertainty in the flow correction is about 10% for the main winds at the test site, which is reasonable considering the IEC specification on the site calibration.

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