Wind Characteristics and Wind Models for Wind Turbine Design in Japan

(2nd Report: Analysis of Measured Data Obtained by Ultrasonic Anemometer and Cup Anemometers).*

Tetsuya KOGAKI**, Hikaru MATSUMIYA**, Hiroyuki ABE**
and Susumu OGAWA***

**National Institute of Advanced Industrial Science and Technology (AIST),
1-2-1, Namiki, Tsukuba, Ibaraki 305-8564, Japan
E-mail: kogaki.t@aist.go.jp

***The Japan Electrical Manufacturers' Association (JEMA),
17-4, Ichibancho, Chiyoda-ku, Tokyo 102-0082, Japan

Abstract

Wind characteristics were measured at one of the sites suitable for wind turbine generation in Japan using an ultrasonic anemometer and cup anemometers. In particular, the ultrasonic anemometer is considered to be more suitable for analysis of turbulence and gust characteristics due to its lack of moving mechanisms. The reliability of the NEDO Field Test Data for turbulence intensity analysis used in the first report of this study was evaluated by this measured data. Gust characteristics in the wind models of IEC 61400-1 (Ed.3) were also analyzed, and compared with the current IEC gust model and new gust criteria obtained by integrating the new turbulence criteria proposed in the first report. As a result, it was found that the most extreme gust event measured in this study would be more severe than the Extreme Operating Gust (EOG) model in the current IEC 61400-1 (Ed.3). It was also found that the amplitude of the EOG model is adjusted by incorporating the new turbulence criteria. The applicability of the new turbulence criteria to other wind models was therefore confirmed to some extent in this research.

Key words: Wind Turbine, Wind Characteristics, Wind Models, Turbulence, Extreme Operating Gust (EOG), Complex Terrain, Velocimetry

1. Introduction

The total installed capacity of wind turbines in Japan exceeded 1,000 MW in 2006, and is being rapidly expanded to reach the goal of 3,000 MW by 2010. However, Japan's wind power generation development cannot necessarily be characterized as a success from an international perspective. In fact, the international market does not see Japan as an attractive destination for investment in wind power generation.⁽¹⁾ Contributing to this situation are the regular occurrence of typhoons and the prognosis of more severe wind conditions than the international standard, due to higher turbulence and gusts generated from Japan's mountainous topography. The first report analyzed wind data consisting of more than 500 datasets collected from more than 300 measurement points in Japan under a Field Test Project on Wind Power Generation conducted by the New Energy and Industrial

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Technology Development Organization (NEDO). Hereinafter, these data are referred to as “NEDO FT Data”⁽²⁾. The analysis described in the first report indicated that more than 65% of the datasets would exceed the highest turbulence Category A as defined by the current IEC standard (IEC 61400-1 Ed.3)⁽³⁾ and would thus be identified as Class S. This clearly shows that the turbulence characteristics in Japan are more severe than those specified in the IEC standard. As an improvement to the situation, a new turbulence model and new turbulence categories were proposed, covering most of the turbulence intensity levels seen at sites suitable for wind power generation in Japan. However, the NEDO FT Data used in the first report were primarily collected through the use of cup anemometers manufactured by NRG Systems (Hinesburg, USA). The reliability of cup anemometers by NRG Systems for the analysis of turbulence characteristics is questionable. Furthermore, the first report only focused on analysis of the normal turbulence model defined in IEC 61400-1. Other models such as the Extreme Operating Gust (EOG) model could not be analyzed, since the NEDO FT Data consisted only of statistical data taken over either 1-hour or 10-minute durations. This second report discusses the reliability of the NEDO FT Data used in the first report. Further discussion of gust characteristics other than turbulence intensity is also presented here. To better support these discussions, actual measurements were taken with an ultrasonic anemometer, which has a high sampling rate and is considered to be more suitable for turbulence and gust analysis due to its lack of moving components.

2. Summary of Analyzed data

Measurement sites for NEDO FT Data are distributed throughout Japan. As a result, the turbulence intensity characteristics of the NEDO FT Data presented in the first report should be indicative of typical sites suitable for wind power generation in Japan. Therefore, although the NEDO FT Data allow us to understand the present status of average wind characteristics at sites suitable for wind power generation in Japan, since raw data measured at higher sampling rates are not available, gust characteristics other than turbulence intensity as defined in IEC 61400-1 (Ed.3) cannot be confirmed. To better understand detailed gust characteristics, which cannot be deciphered from the NEDO FT Data, we took measurements at a higher sampling rate using an ultrasonic anemometer in Oga City, Akita Prefecture.

Many wind farms have been constructed in the coastal areas of Hokkaido and Tohoku. In some of these farms, wind turbine bearing failures and rotor blade cracks have been observed, even though the equipment is located in relatively simple terrain. It is not clear whether such issues are directly attributable to the wind characteristics of these regions. To clarify whether wind characteristics that exceed those in the IEC standard are at the root of these issues, we selected a measurement site on the coast of Oga City in Akita Prefecture that has similar terrain to the current wind-farm locations in the coastal areas of Hokkaido and Tohoku.

Figure 1 shows a contour map of the area around the measurement site. The measurement site is located at the base of the Oga Peninsula, approximately 100 m from the coast, at 139°58'16.71" east longitude and 39°52'51.36" north latitude (approximate values using GPS). For reference, Mt. Kanpuu (altitude 354.8 m) is located approximately 10 km northwest of the measurement site, Mt. Honzan (altitude 716.3 m) 20 km to the west, and Mt. Taihei (altitude 1171 m) and the Taihei Mountains approximately 30 km to the east. However, all terrain in the immediate area (within a few kilometers) is rather flat, and similar to the terrain where many wind farms are located in Hokkaido and Tohoku. The measurement site itself is surrounded by the Hachirogata tract of reclaimed land, which consists mainly of agricultural fields. Within approximately 100 m of the measurement mast is a vacant area with trimmed vegetation. Outside of this area is a conservation forest with

an approximate height of 5 m or less and 20 to 50 m in width on the land side. A 1.5 MW wind turbine, approximately 500 m to the southeast, acts as an added obstruction.

Fig. 1 Contour map around measurement site.

The photographs in Fig. 2 show the measurement sensor setup. A 50.0 m measurement mast was used, supplied by NRG Systems. Cup anemometers and wind vanes supplied by NRG Systems were mounted at heights above ground of 30.0, 40.0, and 50.0 m, as shown in the photo. The sampling frequency of the anemometers and wind vanes (also by NRG Systems) was set at 1 Hz. However, as was the case for most of the NEDO FT Data, only the statistical values are recorded in the logger (normally, statistical values for durations of 10 minutes and 1 hour). To analyze detailed wind characteristics, such as Extreme Operating Gust (EOG) characteristics as defined in IEC 61400-1 (Ed.3), we employed an SAT-550 ultrasonic anemometer (SONIC Corporation, Tokyo) attached to a mounting arm. This anemometer has a high sampling frequency of 50 Hz and allowed acquisition of raw data at a height above ground of 49.2 m.

Figure 3 shows a plan view of the setup, indicating the relative location of the obstructive wind turbine and directions of protrusion of the mounting arms for the anemometers and wind vanes. It should be noted that an arm-mounted anemometer will likely be affected by the wake flow of the measurement mast. Therefore, unless otherwise stated in this report, all wind data recorded within wind direction of ± 45 deg. from the anemometer to the measurement mast were excluded from the analysis.

The observation period for the ultrasonic anemometer used in this report was from August 29, 2003 to January 9, 2004. Considering raw data for a 10-minute interval as 1 dataset, there are a total of 8,991 datasets (the total includes the impact of missing data).

(a) Overview.

(b) Enlarged view near the top of the measurement mast.

Fig. 2 Photographs of the measurement sensors at the wind characteristics measurement site in Oga City, Akita Prefecture.

Fig. 3 Directions of arms and position of the wind turbine.

3. Effect of anemometers on turbulence measurement

Cup anemometers and wind vanes supplied by NRG Systems were used for most of the NEDO FT Data acquisition. Although such sensors may be sufficiently reliable for the purpose of business risk assessment by wind power producers, or for prediction of annual power generation, it is doubtful whether they are appropriate for reliable turbulence and gust characteristics analysis and assessment as desired in this study. For our measurement purposes, the cup and ultrasonic anemometers were placed at approximately the same heights above ground. We investigated the impact of using different sensors by comparing the turbulence characteristics detected by each sensor.

Figure 4 compares the 90% quantiles of turbulence intensity, as measured by the cup anemometer and ultrasonic anemometer, using the Normal Turbulence Model (NTM) proposed in the first report. The value of the 90% quantile of turbulence intensity was calculated by setting the width of the speed bin to 1 m/s, and by assuming a normal distribution for turbulence intensity distribution in each bin. The sensors were installed at approximately the same heights above ground: 49.2 m in the case of the ultrasonic anemometer and 50.0 m in the case of the cup anemometer. The cup anemometer was mounted at the top of the measurement mast, while the ultrasonic vane anemometer was mounted on a separate mounting arm. As a result, the measurement points of the cup anemometer and ultrasonic anemometer were out of alignment by 1.0 m horizontally. This misalignment is not believed to have a significant impact on the statistical characteristics of the turbulence intensity.

Fig. 4 Comparison of 90% quantiles of turbulence intensities as a function of 10-minute average wind speed.

Through a comparison of the data shown in Fig. 4, it is evident that the turbulence intensity measured by the ultrasonic anemometer is 10 to 20% higher at wind speeds between 3 and 15 m/s. Conversely, at higher wind speeds, near 17 m/s, the cup anemometer recorded a higher turbulence intensity. These differences are comparable to the differences between the NTM categories themselves, and hence, the effect of using different anemometer types is extensive.

It is known that some error in measurement using a cup-type anemometer results from wind speed following capability (good response to acceleration, but poor response to deceleration) as well as the rotational inertia of the cups themselves. On the other hand, the ultrasonic anemometer has high following capability with a theoretical distance constant of 0 (m). However, the effect of the mounting arm on the measured turbulence intensity needs to be considered. Although these factors may contribute to the discrepancies seen in Fig. 4, the root cause of the discrepancies or causal association has not been determined. Furthermore, it may not be conclusive that the accuracy of the ultrasonic anemometer is actually superior in this comparison. In any case, it is clear that the severe turbulence characteristics of Japan, as described in the first report, are not an overestimation due to instrumentation error, since the measurements were taken using the same NRG Systems cup anemometer.

The results shown in Fig. 4 illustrate one example of the difference in measured turbulence intensity characteristics between an ultrasonic anemometer and a cup-type anemometer. Since it is possible that the measured turbulence intensity characteristics may be affected by the shape of the associated mounting arms in the case of ultrasonic anemometers, and by cup shape and rotational inertia differences in the case of cup-type anemometers, caution must be exercised. In any event, it is clear that the measured turbulence intensity will be affected by 10 to 20% depending on the anemometer type used. Therefore, when analyzing measured turbulence intensity and gust characteristics, consideration needs to be given to the specific sensor types that were used to obtain the data.

Incidentally, since the measurement site in Oga City, Akita Prefecture, is generally flat and close to the coast, we had anticipated that the turbulence category would be relatively low. However, when comparing the measured turbulence intensity to the NTM in Fig. 4, the data obtained by cup anemometer measurements show an intensity equivalent to Category A. Looking at the same figure, the data obtained by ultrasonic anemometer measurements are equivalent to Category J2 to J1. The reason for the relatively high measured turbulence intensity may have something to do with the mountainous terrain further inland. However, after further turbulence intensity analysis segregating the data according to wind direction, the intensity of turbulence from the coastal direction was not found to be significantly lower compared with that from other directions. Although a clear cause cannot be understood from the measured data alone, other possible hypotheses include the effect of ground surface “roughness” due to vegetation around the measurement site, as well as the complex terrain effect caused by strong winds and the associated rough waves in the ocean.

4. Analysis of extreme operating gust (EOG)

The EOG model as defined in IEC 61400-1 (Ed.3) is expressed as follows:

$$V(z, t) = \begin{cases} V(z) - 0.37V_{gust} \sin\left(\frac{3\pi t}{T}\right) \left\{1 - \cos\left(\frac{2\pi t}{T}\right)\right\} & \text{for } (0 \leq t \leq T) \\ V(z) & \text{for } (t < 0, t > T) \end{cases}, \quad (1)$$

$$V_{gust} = \min \left\{ 1.35(V_{el} - V_{hub}); 3.3 \left(\frac{\sigma_1}{1 + 0.1 \left(\frac{D}{\Lambda_1} \right)} \right) \right\}, \quad (2)$$

$$\sigma_1 = I_{ref} (0.75V_{hub} + b), \quad (3)$$

$$\Lambda_1 = \begin{cases} 0.7z & z \leq 60[m] \\ 42[m] & z \geq 60[m] \end{cases}, \quad (4)$$

where,

σ_1 : standard deviation of wind speed;

V_{hub} : average 10-minute wind speed at hub height (z);

V_{eN} : extreme wind speed within the recurrence period, N years;

I_{ref} : expected value of turbulence intensity;

b : constant, $b = 5.6$ [m/s];

Λ_1 : turbulence scale parameter;

T : $T = 10.5$ [sec];

D : rotor diameter [m];

t : time [sec].

The EOG model assumes that a wind turbine will experience a sudden gust (rapid increase in wind speed) at close to the maximum normal operating wind speed. Furthermore, it assumes that the turbine will experience this event once during a recurrence interval of N years.

To identify only EOG wind events within the large amount of measured raw data, the upgust/downgust⁽⁴⁾ methodology was used as defined in IEA Wind Task XVII (Database on Wind Characteristics), which is one of the international research collaboration activities of the International Energy Agency (IEA). The upgust/downgust approach is defined as the maximum absolute value of wind speed difference within a short timeframe, T_G (sec), as shown in Fig. 5. In Fig. 5, upgusts and downgusts are identified as $+VG$ and $-VG$ respectively.

Fig. 5 Upgust and downgust defined by the IEA Wnd Task XVII.

Wind speed data are divided into 10-minute intervals, with the maximum upgust and downgust in the time interval labeled as $\max\{+VG\}$ and $\max\{-VG\}$, respectively. The time interval T_G of the moving window was set at $T_G = 5$ sec, a commonly used value. Figure 6 shows the relationship between wind speed and maximum upgust/maximum downgust, as measured in Oga City. The highest upgust observed, at approximately 20-25 m/s, was defined as gust point A. This is a typical cutout wind speed for commercial wind turbines. Figure 7 shows a time history of wind upgusts, downgusts, and direction at 10-minute intervals, as observed at 9:10 p.m. on September 13, 2003, the date on which gust point A was observed. The fact that gust point A ($\max\{+VG\}$) corresponds well with the rapid increase in wind speed is an indication that the EOG event search was performed efficiently. During the EOG event, the wind direction was steady at roughly 240° , as shown in Fig. 7(b). The occurrence of an EOG event, with wind gusts stronger than that seen on flat terrain, may be attributed to the rough surface of the ocean due to the strong wind. This indicates the possibility of severe gust conditions even in coastal areas.

Figure 8 shows a comparison between the IEC EOG standard and the rapid increase in wind speed noted at gust point A. Here, we defined the cutout wind speed V_{hub} as 20 m/s and the measurement height above ground Z_{hub} as 50 m (for other parameters, refer to the figure captions). Since the measurement site in Oga City has relatively flat terrain, we were expecting rapid changes in wind speed (due to gusts) to be below the level of the IEC standard. However, a rapid increase in wind speed, exceeding the current IEC 61400-1 (Ed.3) standard, can be observed in Fig. 8. It should be noted that the wind speed changes shown in Fig. 8 were obtained as point measurements, whereas the EOG as defined in IEC 61400-1 (Ed.3) seems to specify changes in wind speed over the entire turbine rotor. Point measurements capture wind speed changes due to turbulence eddies that are smaller than the rotor plane. As a result, there is a danger of overvaluing the effect of wind speed changes if the EOG model is directly compared with the point measurement wind speed changes. Unfortunately, we are not able to discuss this in greater detail since spatial correlation measurements were not taken in this study. However, since the duration of the wind speed fluctuation cycles is more than a few seconds, it can be assumed that the wind speed changes seen in Fig. 8 were due to the presence of relatively large-scale turbulence eddies (spatially and temporally). Looking further at Fig. 8, we believe that, even though the detected wind speed changes are from point measurements, those with relatively long time cycles can be legitimately compared with the EOG model of the IEC. As a result, the wind speed changes shown in Fig. 8 are more severe than those in the current IEC standard (Ed.3).

Since V_{gust} , the magnitude of change in speed of the EOG model, is a function of I_{ref} as shown in Eq. (2), it is dependent on the turbulence category. In the first report, turbulence categories J1 and J2 were proposed reflecting the severe wind characteristics of Japan. By comparing the EOG model supposing J1 and J2 with the measured gusts (only the long-period cycle portion), it can be seen that the measured gusts fall somewhere between Categories J2 and J1, as is evident in Fig. 8. This trend coincides with the observation from Fig. 4, that the measured turbulence intensity (ultrasonic anemometer) was between Categories J2 and J1 in the NTM. Therefore, the amplitudes of the EOG model can be somewhat adjusted by the turbulence categories proposed in the first report.

In addition, from Fig. 6 we selected several points having a large $\max\{+VG\}$ of approximately 20-30 m/s, and compared these wind speed changes with the EOG model. None of the selected points exceeded gust point A.

Fig. 6 Upgusts and downgusts as a function of wind speed.

(a) Wind speed and gusts.

(b) Wind direction.

Fig. 7 Time history of the instantaneous wind speed, gusts and the instantaneous wind direction.

Fig. 8 Comparison between the measured gusts and the EOG model.
(Gust point A, Parameters: $D = 50$ (m), $Z_{hub} = 50$ (m), $V_{hub} = 20$ (m/s), $V_{e1} = 56$ (m/s), Wind turbine Class I)

5. Conclusion

The validity of the NEDO FT Data used in the first report was verified through the use of an ultrasonic anemometer. The ultrasonic anemometer is considered to be better suited to the evaluation of turbulence and gusts, as it has a high sampling rate and no moving parts. Measurements with the ultrasonic anemometer were taken in the coastal area of Oga City, Akita Prefecture. Gust characteristics were analyzed, comparing the current IEC standard with the new wind model proposed in the first report. As a result, the following conclusions were reached:

- (1) The measured turbulence intensity level can differ by a magnitude as large as the

IEC turbulence category differences themselves. Therefore, when selecting a turbulence category, the design characteristics of the anemometers used for turbulence intensity measurements must be taken into account.

(2) For the identification of EOG events within large amounts of data, the search method proposed for upgusts and downgusts in IEA Wind Task XVII was found to be highly efficient.

(3) The rapid wind speed changes measured in this study identified gusts exceeding those defined in the model of the current IEC 61400-1 (Ed.3).

Based on the above findings, it was verified that the turbulence categories proposed in the first report are capable of capturing not only the severe turbulence characteristics of Japan, but also the gust characteristics to some extent. However, we acknowledge that further investigation is required, since the analysis of the EOG model presented here is based on point measurements that lack stringency and were taken over a relatively short duration. Furthermore, before the newly proposed turbulence categories can be adopted as an IEC international standard, additional model validation must be conducted.

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