A Study of the Normal Turbulence Model in IEC 61400-1

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ABSTRACT
This study examines applicability of Normal Turbulence Model (NTM) in IEC61400-1 for offshore conditions using wind records obtained at an offshore site. The model parameters for estimation of the standard deviation of longitudinal fluctuating velocity, σ_1, in NTM are presented. The identified model parameters for the mean value of σ_1 agree well with those of IEC Normal Turbulence Model, but parameters for the standard deviation of σ_1 are found to be larger than those used in IEC. As a result, the standard deviation of σ_1 obtained by IEC Normal Turbulence Model parameters is underestimated and predicted that by the proposed model parameters shows a good agreement with the observation.

Keywords: Normal Turbulence Model, Model parameters, Standard deviation of longitudinal fluctuating velocity

1. INTRODUCTION
Wind turbulence significantly influences the fatigue loads acting on the wind turbines and accurate modeling of the standard deviation of fluctuating wind velocity becomes important. In general, a large change in turbulence intensity is observed with a change in wind direction and, rather small turbulence intensities are experienced offshore compared to on-land locations[1)]. In international standard IEC61400-1 Ed. 3[2)] (hereafter called IEC), Normal Turbulence Model (NTM) is presented to define turbulence under normal operation conditions. The parameters of NTM in the IEC 61400-1 were determined by few observation data. Recently, Tanigaki et al.[3)] reported a discrepancy between the parameters of NTM proposed by the IEC and those identified by using onshore wind observation data. Especially model parameters concerning the standard deviation of σ_1 (the standard deviation of the longitudinal fluctuating velocity) are significantly underestimated by the NTM of IEC.

In this study, the characteristics of the standard deviation of the offshore wind are examined by using observation data measured in Eastern seas of Japan, and the applicability of NTM of IEC for offshore locations is investigated. Model parameters are proposed for offshore wind conditions and accuracy of the proposed NTM is verified by offshore wind observation data.

2. OBSERVATION OF OFFSHORE WIND
Offshore wind speed and direction, used in this study, were measured using a propeller-vane anemometer installed at the top of a tower located on a platform for natural gas mining in Iwaki

gas field, 37 km offshore from the coast of Naraha-machi, Fukushima Prefecture. The platform (Lon. 141°27'35"E, Lat. 37°18'00"N) is surrounded by the Pacific Ocean from east to south and by Japanese island from southwest to northwest direction as shown in Figure 1. Figure 2 shows an overview of the offshore wind observation system. Wind speed and direction were measured at 95 m above sea level from the sea surface and 4 lightening rods for safety purposes were placed around the observation system. The diameter of the lightening rods was 61 mm, and the horizontal distance between the lightening rods and the anemometer was kept 30 times the diameter of the rods, i.e., 1832 mm. The effect of the lightening rods presence on wind measurements is ignored since this distance was larger than 8.2 times of the diameter as specified by IEC 1400-12-1[4].

Table 1 shows the specification of the offshore observation system. A propeller-vane anemometer with optical fiber sensor was adopted, because use of explosion-proof type

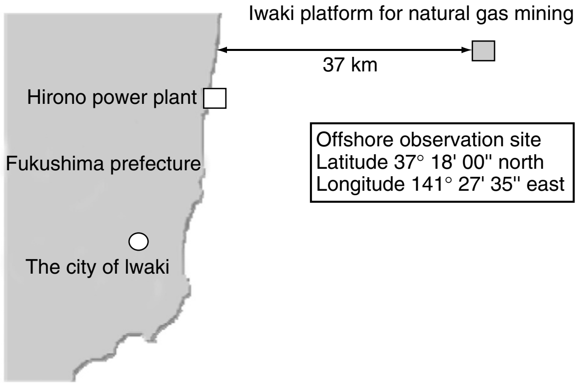

Figure 1: Offshore observation site.

(a) A drilling derrick

(b) Propeller-vane anemometer

Figure 2: View of offshore observation system.

Table 1: Descriptions of offshore observation system

Anemometer	Manufacturer	Ogasawara Keiki Seisakusho Co., LTD
	Type	Propeller-vane anemometer
	Detection method	7-optical fibers type
	Wind direction	16 directions
	Wind speed	0~60m/s
Logger	Manufacturer	NRG System
	Type	SYMPHONIE/2000-J
	Sampling interval	2 seconds
	Observed data	10-minutes average wind speed and wind direction 10-minutes wind speed standard deviation
	Observation period	Oct. 2004~Sept. 2006

equipment was obligated on the natural gas mining facilities. The measurement data was first recorded in the local data logger, and data statistics were transmitted to onshore facility everyday. In this study, the measurement was carried out for two years from October 2004 to September 2006. The measurement data include 10 minutes mean wind speed, wind direction and standard deviation of wind speed, and are used to estimate model parameters of NTM.

Figure 3 shows the wind rose and the frequency distribution of the wind speed at the site. 98.4% of the measurement data is found suitable for this investigation. The prevailing wind direction at the site is "northwesterly" during winter season, while southerly and northerly wind prevails during spring and autumn seasons. According to the frequency distribution of the wind speed, an occurrence frequency of 32% is observed for wind speeds exceeding 10 m/s that results in a higher mean wind speed, comparing with that of the onshore site. Figure 4 shows the variation of turbulence intensity with increase in wind speed. 90% quantile of measured turbulence intensity is calculated and shown in black circles. The expected value of the turbulence intensity at 15 m/s, called I_{ref}, is also calculated.

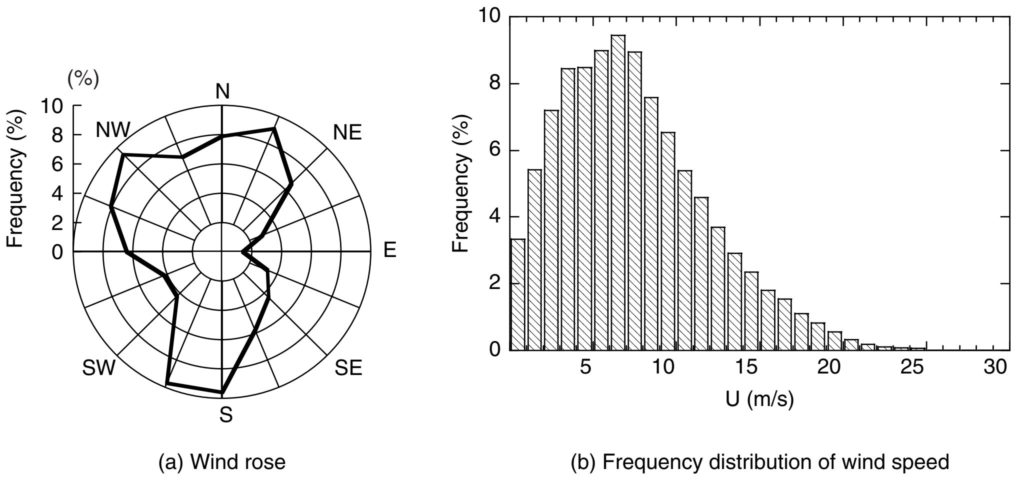

Figure 3: Characteristics of offshore wind conditions.

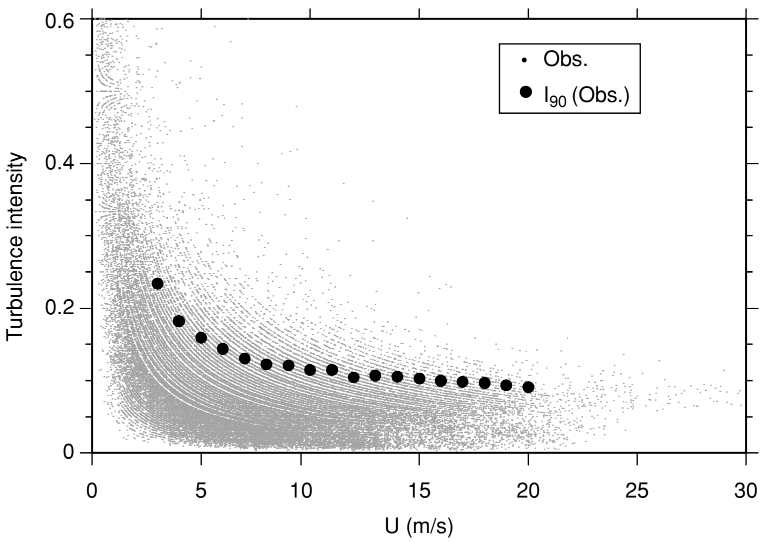

Figure 4: Variation of turbulence intensity with wind speed.

3. MODEL PARAMETERS FOR NTM

In this study, applicability of the NTM of IEC to the offshore wind is investigated and model parameters of NTM are proposed for offshore conditions. The mean value (σ_{ave}) and the standard deviation (σ_σ) of σ_1 are calculated for each wind speed bins between cut-in and cut-out wind speed, i.e., 3 to 25 m/s. The bin with 1.0 m/s interval is adopted and the wind speed bins with larger than 200 data are used for the analysis.

In accordance with Tanigaki et al.[3], the mean value and the standard deviation of σ_1 can be expressed as below.

$$\sigma_{ave} = I_{ref}(aU + b) \tag{1}$$

$$\sigma_\sigma = I_{ref}(\alpha U + \beta) \tag{2}$$

Here σ_{ave} is the mean value of σ_1, σ_σ is the standard deviation of σ_1, U is 10 minutes mean wind speed, I_{ref} is the expected value of turbulence intensity at 15 m/s and the parameters a, b and α, β are the model parameters to estimate the mean value and the standard deviation of σ_1. In IEC61400-1, the model parameters a, b, α, and β are defined as 0.75, 3.8, 0, and 1.4 respectively, as shown in Table 2.

The representative value of the turbulence standard deviation (σ_{90}) given by 90% quantile of σ_1 is approximated as follows:

$$\sigma_{90} = \sigma_{ave} + 1.28\,\sigma_\sigma \tag{3}$$

90% quantile value of turbulence intensity (I_{90}) is obtained by substituting eqns (1–2) in eqn (3).

$$I_{90} = \sigma_{90}/U = I_{ref}\,(a + 1.28\alpha + (b + 1.28\beta)/U) \tag{4}$$

Figure 5 shows the variation of σ_{ave}/I_{ref} with wind speed for the observations. It tends to increase linearly with increase in the wind speed, and IEC model parameters could successfully represent observation data with reasonable accuracy. Values of the model parameters a and b, defined in NTM of IEC are considered suitable for estimation of σ_{ave} under offshore conditions. The mean values of the standard deviation are calculated from eqn. (1) for NTM parameters of IEC. The Root Mean Square Error (RMSE) is relatively smaller value of 6.5%. This indicates that the model parameters of IEC for estimation of σ_{ave} is suitable for the offshore conditions.

Figure 6 shows the variation of σ_σ/I_{ref} with wind speed. It also tends to increase linearly with increase in the wind speed. However, NTM of IEC fails to capture this tendency of offshore wind. The similar discrepancy in σ_σ/I_{ref} is also reported for the onshore wind observations by Tanigaki et al.[3]. It is clear from Fig. 6 that observed σ_σ/I_{ref} are considerably larger than NTM

Table 2: Proposed and IEC model parameters

	Present study	IEC
a	0.75	0.75
b	3.8	3.8
α	0.27	0
β	2.7	1.4

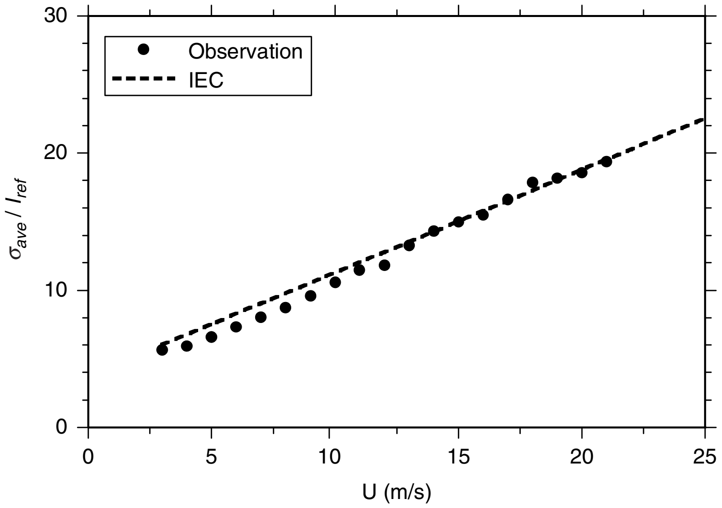

Figure 5: Variation of σ_{ave}/I_{ref} with wind speed.

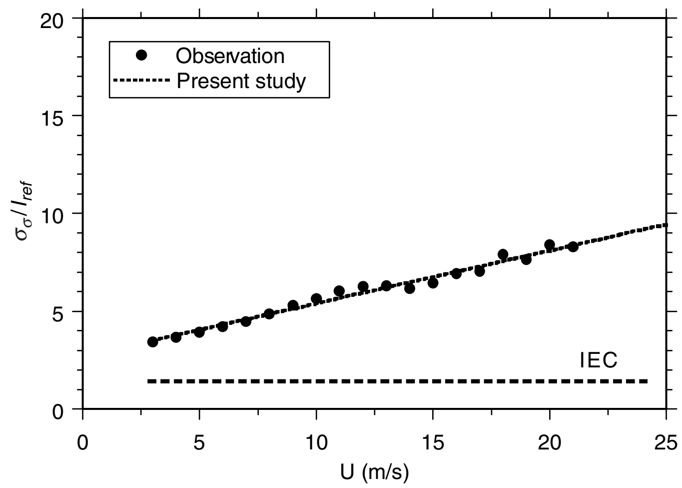

Figure 6: Variation of σ_{σ}/I_{ref} with wind speed.

of IEC. In order to model the standard deviation of σ_1, parameters α and β shown in eqn. (2) are identified by using the least squares method as 0.27 and 2.7 respectively, which are larger than 0 and 1.4 defined in NTM of IEC and are close to 0.15 and 2.0 proposed by Tanigaki et al.[3)] based on onshore wind observations. σ_{σ} is estimated using both proposed and IEC model parameters. It is clear that use of IEC model parameters results in considerable underestimation of σ_{σ}, while the predicted σ_{σ} by the proposed model parameters shows better agreement with the observed ones. The RMSE of σ_{σ} is reduced from 80.2% for NTM of IEC to 4.0% for the proposed model.

To examine overall performance parameters of the proposed model parameters (a, b, α, and β), the turbulence intensities I_{90} estimated by NTM of IEC and proposed model are presented in Figure 7. Model parameters of NTM of IEC result in significant underestimation of I_{90}, while I_{90} calculated using proposed parameters agrees well with the measurement. This indicates that it is necessary to use proposed values of parameters α and β for accurate estimation of turbulence intensity, I_{90}.

As mentioned above, the parameters for the mean value and the standard deviation of σ_1 in the IEC 61400-1 Ed. 3 were determined by few observation data. The accuracy of the mean

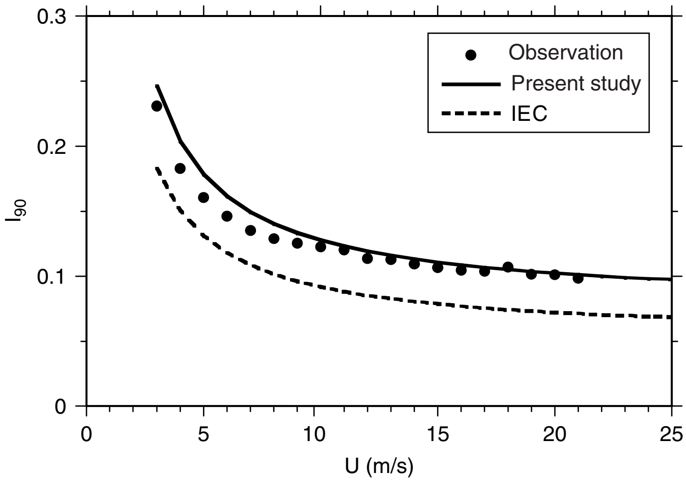

Figure 7: Variation of I_{90} with wind speed.

value of σ_1 is verified by several researches, while the parameters for the standard deviation of σ_1 in the IEC 61400-1 are less than those obtained by the recent observations. It implies that the parameters for the standard deviation of σ_1 should be modified in the next edition of the IEC 61400-1.

4. CONCLUSION

The characteristics of the turbulence standard deviation are investigated using offshore wind observations data and limitations of the Normal Turbulence Model of IEC are clarified. The conclusions from this study are summarized as follows:

1. The model parameters (a, b) identified from the offshore wind observations show close agreement with those defined in NTM of IEC for estimation of the mean value of σ_1, while the identified model parameters (α, β) corresponding to the standard deviation of σ_1 are significantly larger than those defined in NTM of IEC.
2. The model parameters defined in NTM of IEC leads to accurate estimation of mean value of σ_1, but significant underestimation of standard deviation of σ_1 is observed. This results in underestimation of the turbulence intensity I_{90}. The proposed model parameters in this study improve estimation accuracy of I_{90} and show good agreement with the observation.

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REFERENCES

[1] Tsuchiya, M., Ishihara, T., Fukumoto, Y., The wind observation on the pacific ocean for offshore wind farm, *Proceedings of EWEC 2006*, 2006.

[2] IEC 61400-1, *Wind turbines – Part 1: Design requirements*, Ed.3, 2005.

[3] Tanigaki, S., Kogaki, T., Matsumiya, H., Imamura, H., Japanese wind turbulence characteristics in relation to turbulence model in IEC 61400-1 Ed. 3, *Proceedings of EWEC 2010*, 2010.

[4] IEC 61400-12-1, *Wind turbines – Part12-1: Power performance measurements of electricity producing wind turbines*, 2010.