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Numerical study of maximum wind load on wind turbine towers under operating conditions

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ABSTRACT: Dynamic response analyses of a pitch-regulated 2 MW wind turbine were carried out for the estimation of maximum wind loads acting on support structures. The average and maximum tower base moments increase with the increase in the wind speed below the rated wind speed. Above the rated wind speed, the maximum base moment increases due to the pitch control when the turbulence intensity is high although the average base moment decreases with the increase in the wind speed. Simplified formulas for the estimation of the maximum base moment were proposed and verified by the field test of the commercial 1.5 MW wind turbine. Proposed method shows a good agreement with field measurement data. The extrapolation coefficient was also investigated to estimate maximum wind load with a 50 years return period. The extrapolation coefficient increases as the annual mean wind speed increases and it approaches to 1.5, the recommended value in IEC61400-1.

1 INTRODUCTION

These days the wind energy increases as one of renewable energy resources around the world. In Japan, the construction of wind turbines has been increasing since the 1990s. However, many accidents and damages of wind turbines were reported. According to NEDO (New Energy and Industrial Technology Development Organization), the accidents and the damages in wind turbines were observed in 11 percent of total wind turbines in 2004[1)]. This value is comparatively higher than those reported for the other civil structures such as buildings or bridges.

The prime cause of such incidents was that the wind conditions at site didn’t satisfy those used in the design of wind turbines. The design of wind turbines is based on the standardized class, which includes the 50 years return period, annual mean wind speed and turbulence intensity, defined in IEC61400-1 (International Electrotechnical Commission). Often in Japan, the actual wind conditions at site are higher than those specifies in IEC class. For this reason, the owner has to complete the assessment of structural integrity based on the site wind condition[2)].

The extreme wind loads on wind turbines have to be assessed for two different cases. The first one is the extreme wind event with a 50 years return period and the other one is the maximum wind load during operation. Under extreme wind event, the wind speed is higher than the cut out wind speed and the wind turbines are idling or standing still. In such a condition, the wind loads can be accurately estimated by using an equivalent static wind load evaluation considering non-Gaussian assumption[3)]. On the other hand, under operating condition, the wind loads is affected by the pitch control. Therefore, the wind load cannot be explained by the conventional quasi-static theory.

In this paper, the mechanism of wind load characteristics under operating conditions are investigated using the time history analysis of 2 MW wind turbine model based on the finite element method. Then, simplified formulas for the estimation of expected maximum base moment are proposed using simulation data. These formulas are verified by the field test of the commercial 1.5 MW wind turbine. Finally, the extrapolation coefficient is investigated to estimate maximum wind load with a 50 years return period for different annual mean wind speed.

2 WIND TURBINE MODEL

Under operating conditions, the wind load on the wind turbine strongly depends on the pitch control of the blade. In this study, the software GH Bladed was used, which can simulate the time series of wind loads under pitch control. The wind turbine is modeled using beam element model. The first two mode of the tower and the first mode of the blade are considered. The structural damping ratio of the first mode is 0.8 percent and those of the higher mode are assumed to be proportional to the stiffness. The pitch and the torque of the wind turbine are controlled by PI control.

$$\Delta Q_{Dem} = 380y + 80.85y_1 \tag{1}$$

$$\Delta \theta_{Dem} = 0.1152y + 0.05486y_1 \tag{2}$$

where y is the deviation of generator speed, y_1 is the residuals of generator speed, ΔQ_{Dem} is the demand of torque, and $\Delta\theta_{Dem}$ is the demand of pitch angle. The wind turbine considered in this study is a typical onshore wind turbine as shown in Table 1.

Table 1 Characteristics of wind turbine model

Rated power	2 (MW)
Hub height	76.5 (m)
Type	Upwind
Rotor diameter	80 (m)
Control	Variable speed
	Variable pitch angle
Rotating speed	10~18 (rpm)
Range of operation	4~25 (m/s)
Rated wind speed	12 (m/s)
Gross weight	249.4 (ton)

The wind was modeled according to the normal wind profile model and the turbulence was modeled according to the Kaimal spectrum model and the exponential coherence model in IEC61400-1. Turbulence intensity was calculated by the normal turbulence model as given by

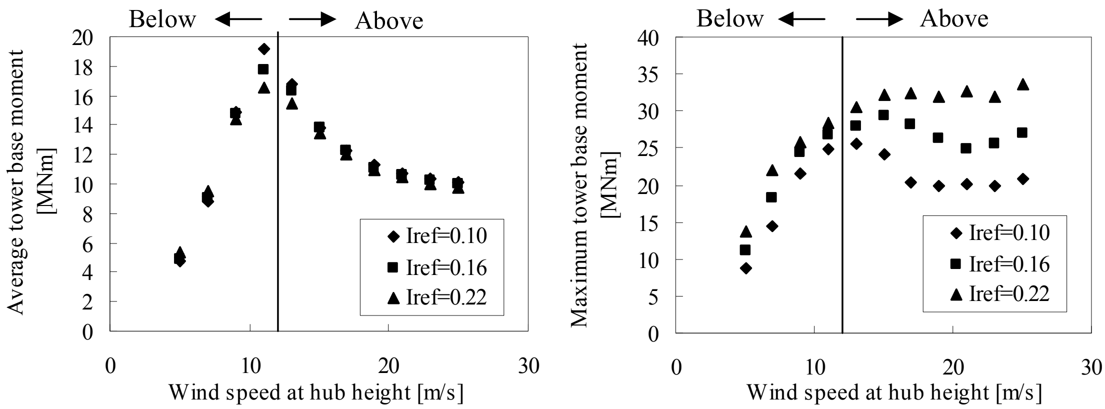
$$I_1 = I_{ref}\left(0.75 + 5.6/V_{hub}\right) \tag{3}$$

where I_{ref} is the expected value of the turbulence intensity when the mean wind speed at the hub height is 15 m/s; and V_{hub} is the mean wind speed at the hub height. In this study, 3 different turbulence intensities were considered, assuming onshore (0.10), offshore (0.16) and mountain areas (0.22).

3 AVERAGE AND MAXIMUM TOWER BASE MOMENT

For civil structures, the maximum base moment usually decreases as the average base moment decreases. However, the wind load characteristics of wind turbines are different due to the pitch control. In this chapter, to examine these characteristics, the wind loads are calculated for the 11 different mean wind speeds, from 5 m/s to 25 m/s with 2 m/s interval, and 3 different turbulence intensities as explained in the previous chapter. For each case, 35 simulations for 10 minutes were carried out. These were randomly grouped into 7 sets of simulations. For each set of simulations, the median values were calculated. In order to eliminate any remarkable large value, the average of 7 median values was used.

Figure 1 shows the average and maximum tower base moment calculated for all the cases. Below the rated wind speed (<12 m/s), both average and maximum base moment increases with the increase in the mean wind speed. On the other hand, above the rated wind speed, the average base moment decreases along with the increase in the mean wind speed. This happens as the surface area of the blade, which is subjected to wind, becomes smaller due to the pitch control. For the maximum base moment, it decreases at low turbulence intensity, but increases at high turbulence intensity. The dependence of the maximum base moment on turbulence intensity is more remarkable for those that are above the rated wind speed than those below the rated wind speed.



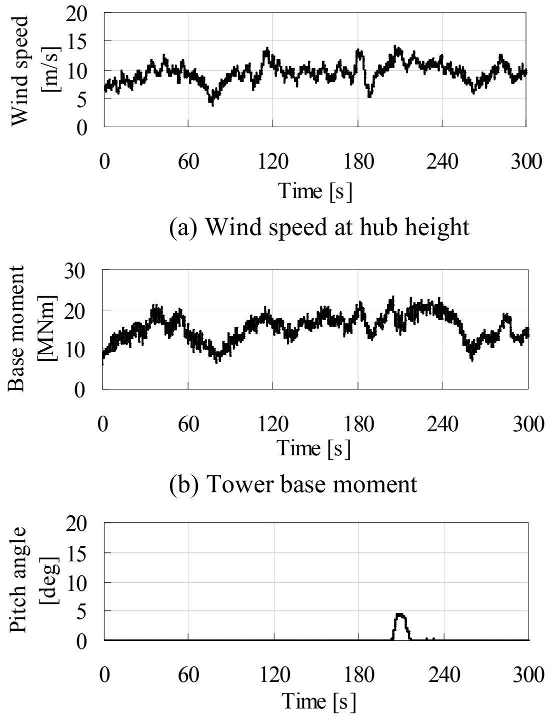
(a) Average tower base moment (b) Maximum tower base moment

Figure 1. Variation of average and maximum tower base moments with wind speed at hub height

To investigate the reason why the maximum base moment increases as the average base moment decreases, time histories of the wind speed, the tower base moment and the pitch angle were examined for average wind speed of 9 m/s and 15m/s when I_{ref} is 0.16 (Figure 2 and 3).

At 9 m/s, the pitch angle is kept at near 0 degree to maximize the power production. In this case, the change of tower base moment follows the change in wind speed, which phenomenon is similar to the civil structures. These fluctuations are excited by the wind gust.

At 15 m/s, large decreases in the pitch angle are observed when the wind speed decreases (e.g. 30~40, 170~180 second) in order to receive the wind effectively, which causes the sudden increase of the tower base moment. The maximum base moment is recorded when this sudden increase takes place. Above the rated wind speed, the maximum tower base moment is excited by the pitch control.

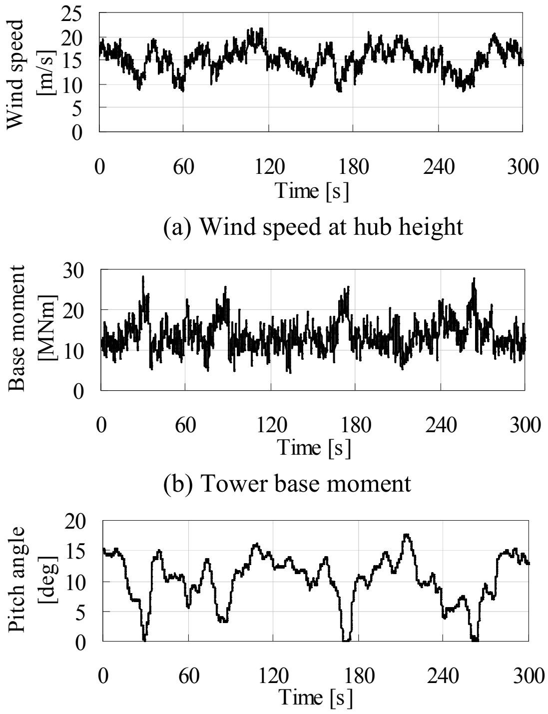


(a) Wind speed at hub height

(b) Tower base moment

(c) Pitch angle

Figure 2. Time histories at 9 m/s



(a) Wind speed at hub height

(b) Tower base moment

(c) Pitch angle

Figure 3. Time histories at 15 m/s

4 SIMPLIFIED FORMULAS FOR WIND LOAD ESTIMATION

As discussed in the previous section, the wind loads under operating conditions are affected strongly by the pitch control. In this chapter, simplified formulas for the estimation of the maximum wind load during operation are proposed.

The maximum tower base moment (M_{Dmax}) in operating conditions is expressed as follows

$$M_{D\max} = M_D \times G_D \tag{4}$$

where M_D is the average tower base moment and G_D is the gust factor. The average base moment can be expressed as,

$$M_D = \frac{1}{2}\rho U_H{}^2 \pi R^2 H C_{MD} \tag{5}$$

where ρ is the air density, U_H is the wind speed at the hub height, H is the hub height, R is the rotor radius and C_{MD} is the tower base moment coefficient and is expressed as follows

$$C_{MD} = \varepsilon_T C_{DT} C_g + \varepsilon_N C_{DN} + C_T\,, \quad C_g = \frac{1}{3+3\alpha} + \frac{1}{6} \tag{6}$$

where C_{DT} is the average drag coefficient of the tower, C_{DN} is the average drag coefficient of the nacelle, C_T is the thrust coefficient of the rotor, ε_T is the ratio of the projected tower area to the rotor area, ε_N is the ratio of the projected nacelle area to the rotor area, C_g is the correction coefficient according to the vertical profile of mean wind speed and α is the power law exponent of the normal wind profile. C_{DN}, C_{DT} and α were assumed 1.2, 0.6 and 0.2 respectively in this study. ε_T and ε_N are relatively small, and C_T is dominant in C_{MD}.

Gust factor (G_D) is the ratio of the mean value to the maximum value and expressed as

$$G_D = \frac{M_{D\max}}{M_D} = \frac{M_D + g_D \sigma_{MD}}{M_D} \tag{7}$$

where g_D is the peak factor, and σ_{MD} is the standard deviation of the tower base moment. The variance of the tower base moment ($\sigma_{MD}{}^2$) can be divided into the background response variance ($\sigma_{MDQ}{}^2$) and the resonance response variance ($\sigma_{MDR}{}^2$). Because of difficulty in direct estimation of σ_{MDR}, the ratio of the resonance response variance to the background response variance was used in this model. Therefore, Equation (7) can be written as

$$G_D \simeq 1 + g_D \frac{1}{M_D} \sqrt{\sigma_{MDQ}{}^2 + \sigma_{MDR}{}^2} = 1 + g_D \frac{\sigma_{MDQ}}{M_D} \sqrt{1 + R_D}\ ,\ R_D = \frac{\sigma_{MDR}{}^2}{\sigma_{MDQ}{}^2} \tag{8}$$

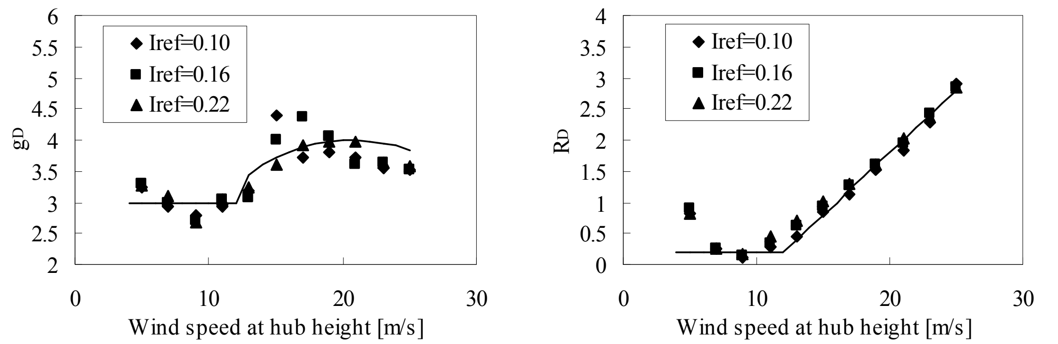
This equation shows that to estimate the gust factor (G_D), the modeling of peak factor (g_D), the standard deviation of background response (σ_{MDQ}) and the ratio (R_D) are needed. In general, the standard deviation of background response is expressed as a function of the turbulence intensity (I_1), the average tower base moment (M_D) and the size reduction factor (K).

$$\sigma_{MDQ} = 2 M_D I_1 \sqrt{K} \tag{9}$$

From the Equation (8) and (9), the gust factor can be expressed as

$$G_D \simeq 1 + 2 I_1 g_D \sqrt{K} \sqrt{1 + R_D} \tag{10}$$

To investigate the characteristics of g_D and R_D with wind speed under operating conditions, the simulation data were shown in Figure 4. The dots are the average of 7 median derived from 35 simulation data. Both g_D and R_D are nearly constant below the rated wind speed. Above the rated wind speed, these values shows the higher value as the function of wind speed because of the increase in the resonance response excited by the pitch control. The peak occurring at 5 m/s in Figure 4(b) was due to the resonance between the frequency of the blade rotation and that of the tower, and can be neglected because the wind load at 5 m/s is relatively small.



(a) Peak factor (b) Ratio of resonance variance to background response variance

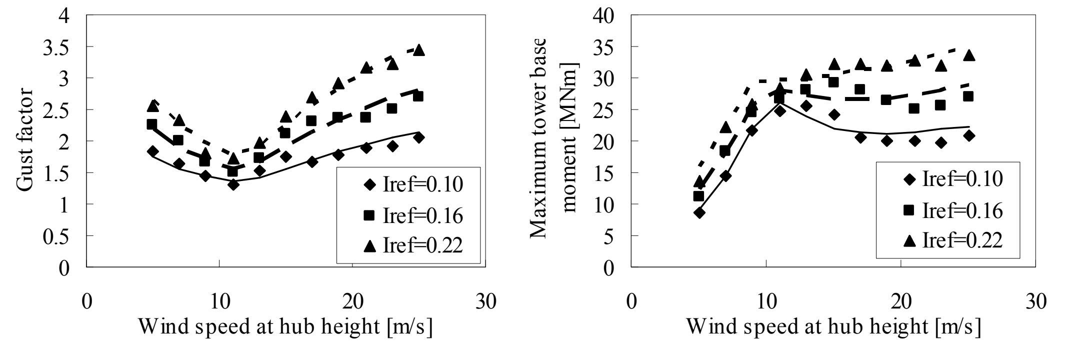
Figure 4. the variation of g_D and R_D with wind speed at hub height

In this study, empirical models for g_D , R_D and K were proposed (Table 2). These models are shown as a solid line in Figure 4.

Table 2 Simplified formulas under operating conditions

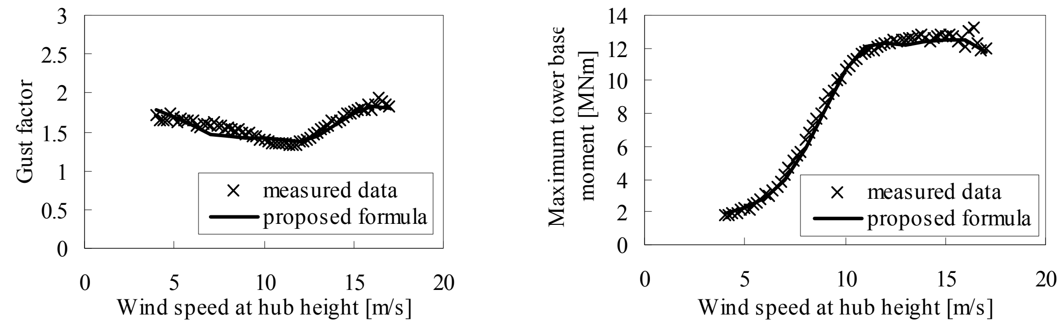
	Below rated wind speed (V_h<V_r)	Above rated wind speed (V_h<V_r)	
K	$0.25\frac{V_h - V_r}{V_{in} - V_r} + 0.15$	$0.45\frac{V_h - V_r}{V_{out} - V_r} + 0.15$	V_h: wind speed at hub height [m/s] V_r: rated wind speed [m/s]
g_D	3.0	$\sqrt{\sin\left(\frac{3\pi}{4}\left(\frac{V_h - V_r}{V_{out} - V_r}\right)\right)} + 3.0$	V_{in}: cut-in wind speed [m/s] V_{out}: cut-out wind speed [m/s]
R_D	0.2	$2.6\frac{V_h - V_r}{V_{out} - V_r} + 0.2$	

To verify the accuracy of the proposed formulas, the loads estimated by the proposed formulas were compared with the simulated data from 2 MW wind turbine model and the measured data from 1.5 MW GE wind turbine[4)] respectively. The comparison of the loads estimated by the formulas to those obtained from the simulation data is shown in Figure 5. Figure 6 shows the comparison of the loads estimated by the formulas using the measured wind and turbulence intensity data to the measured load data. The loads estimated by the proposed formulas agree well with both the simulated data and the measured data.



(a) Gust factor (b) Maximum tower base moment

Figure 5. Comparison simulation data with estimation result



(a) Gust factor (b) Maximum tower base moment

Figure 6. Comparison between measured and predicted gust factor and maximum base moment

5 EXTRAPOLATION COEFFICIENT

It is required to calculate the wind load with a 50 years return period for design purpose. To estimate the wind load with a 50 years return period, it is necessary to multiply the equation (4) by the extrapolation coefficient.

When the observation period is T, the probability that the extreme value exceeds s is obtained as follows[5].

$$F_{ext}(s;T) = \int_{V_{in}}^{V_{out}} F_{ext}(s|V;T) f(V) dV \tag{11}$$

where $F_{ext}(s|V;T)$ is the probability distribution of extreme value (s) when mean wind speed is V and the observation period is T. In order to estimate $F_{ext}(s|V;T)$, 32 maximum data were used out of 35 maximum data explained in chapter 3 by excluding the largest 10 percent values. In this study, $F_{ext}(s|V;T)$ is assumed to follow the three parameter Weibull distribution and three parameters are estimated by the method of moments. $f(V)$ is the frequency distribution of the mean wind speeds and assumed to follow Rayleigh distribution.

The extreme load response (s_r) for the desired return period (T_r) is obtained from the following equation.

$$P_{ext} = F_{ext}(s_r;T) = \frac{T}{T_r} \tag{12}$$

where P_{ext} is the occurrence probability of extreme value for the desired period. In this study, 5 cases were considered about the annual mean wind speed (6, 7, 8, 9 and 10 m/s). The extreme load response with the return period of T_r is the load at which $F_{ext}(s|T)$ becomes T/T_r. When T_r is 50 years and T is 10 minutes in this study, the occurrence probability of extreme load (T/T_r) becomes 3.8×10^{-7}. Figure 7 shows the procedure to calculate the extreme load response when I_{ref} is 0.16 and the annual mean wind speed is 10 m/s. The line is the computed exceedance probability from Equation (11) and the dot line shows the occurrence probability of extreme value for the 50 years return period. The intersection of the two lines is the extreme load response with a 50 years return period (s_r is 38376.1 kNm).

The extrapolation coefficient is the ratio of s_r to s_{ave}, where s_{ave} is the mean of maximum load in 10 minutes under the operating condition. In this study, s_{ave} is the maximum extreme load in the average extreme loads for each bin wind speed.

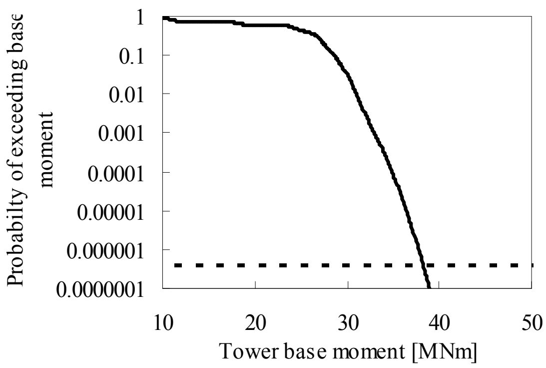


Figure 7. 50 years extreme (I_{ref}=0.16, V_a=10)

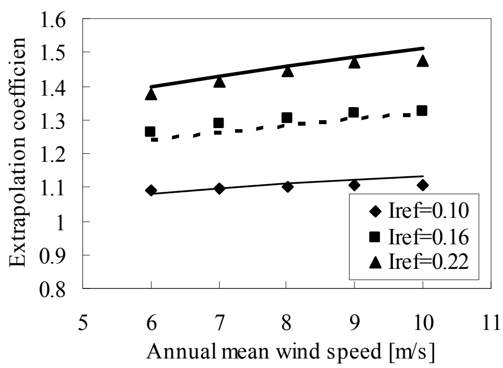


Figure 8. Extrapolation coefficient

Table 3. Extreme load with a 50 years return period

	S_r (kNm)					S_{ave} (kNm)
	Annual mean wind speed (m/s)					
Turbulence intensity	6	7	8	9	10	
0.10	27865.0	28012.3	28132.8	28230.6	28250.3	25505.79
0.16	36560.0	37297.9	37832.6	38246.1	38376.1	28967.70
0.22	45910.5	47272.0	48273.6	49055.4	49303.7	33411.53

The estimation formula about the extrapolation coefficient was proposed as follows.

$$r_e = I_{ref} \times (\ln(V_a) + 0.83) + 0.82 \tag{13}$$

where V_a is the annual mean wind speed.

Figure 8 shows the calculated extrapolation coefficients and the estimated extrapolation coefficients by Equation (13). The extrapolation coefficient increases with the increase in annual mean wind speeds and when the annual mean wind speed is 10 m/s and the turbulence intensity is 0.22, the coefficient is almost 1.5, the recommended value in IEC61400-1.

6 CONCLUSION

In the study, the dynamic response analysis of a 2 MW wind turbine model was carried out and empirical formulas were proposed for the estimation of wind loads. The extrapolation coefficient was investigated to estimate the maximum wind load on a wind turbine tower under operating conditions. The following conclusions were obtained.

1) Above the rated wind speed, the maximum base moment increases due to the pitch control when the turbulence intensity is high although the average base moment decreases.

2) Simplified formulas for the estimation of the expected maximum base moment were proposed, which cover different wind speeds and turbulence intensities under operating conditions. Estimated design loads by the proposed formulas showed a good agreement with those obtained from a field measurement data of 1.5 MW wind turbine.

3) The extrapolation coefficient to estimate the maximum wind load with a 50 years return period was investigated assuming that the frequency distribution of the mean wind speed follows Rayleigh distribution. The extrapolation coefficient increases with the increase in annual mean wind speeds and approaches to 1.5, a recommended value in IEC61400-1.

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