NUMERICAL AND THEORETICAL STUDY ON SEISMIC RESPONSE OF WIND TURBINES

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ABSTRACT: When located in seismically active region like Japan, seismic loads may become critical for the safety of wind turbines. Therefore, Japanese code impose strict regulations for designing and assessing the safety of wind farms that require the use of design formula based on response spectrum method and time domain analysis for low and high structures respectively. This paper presents investigations on wind turbine modeling technique for the time domain analysis, and the formulation of semi-theoratical design formula that is developed based on the assessment of seismic loads acting on buildings (BSL, 2004). A full FEM model is developed to include the tower-rotor coupling and time doamin analysis is carried out to investigate the contribution of higher modes to the response characteristics of wind turbines. Suitability of semi-theoratical codified method is examined against the time history analysis and a safety factor is introduced to the proposed semi-theoratical formulation for the assessment of seismic loads acting on wind turbines.
Keywords: Wind Turbine, Seismic, Response spectrum, Time domain analysis

1 INTRODUCTION

The prediction of seismic response of wind turbines becomes of great importance when wind farms are designed and developed in seismically active regions. Being a seismically active region, Japan has strict design procedure to avoid collapse under seismic excitation. Stability of wind turbine structures against level II earthquakes is required (BSL, 2004), which is carried out depending upon tower height either by time domain analysis(H>60m) or by codified design formula(H<60m).

Unlike wind loads, a wide range of frequencies are involved in seismic waves that may excite higher modes of the wind turbine system. Therefore, it becomes important to include higher modes for predicting the response characteristics of wind turbines under seismic loads. To simulate the response of wind turbines, modal method is widely used in the field of wind energy engineering. In the modal method, displacements are expressed as linear combination of mode shapes and the equations of motion are simplified as a set of single degree of freedom equations. Bosanyi(2005) used the modal model and the whole wind turbine is divided into two substructures: one is the rotor, and other is the tower. Since the rotor and the tower are calculated separately, it requires coupling between them to model their interaction. However, this coupling is not sufficient in the modal model because only very limited degrees of freedom are modeled.

In this study, a full nonlinear FEM model is developed that takes into account the geometric nonlinearity and the coupling between the rotor and the tower. Aim of present study is to examine response characteristics of wind turbines in time domain, and to formulate design formula for prediction of seismic loads using response spectrum method. First response spectrum according to Japanese building standard law (BSL, 2004) is introduced and process of earthquake wave generation is discussed. Then investigations on modal contribution to response of wind turbine are discussed, and finally suitability of building response spectrum to estimate the seismic loads acting on the wind turbines is discussed.

2 SEISMIC CONDITIONS

Japanese design code requires evaluation of wind turbine structural safety against level II earthquakes that correspond to 500 years return period. In this study, generated earthquake waves that fit the specified acceleration response spectrum (BSL, 2004) are used to conduct the analysis for soil type 1.

2.1 Acceleration response spectrum

An acceleration response spectrum $S_{a0}(T, 0.05)$ specifies the basic peak ground acceleration at the engineering bed rock a_0 along with the frequency characteristic of the ground motions. For the level II earthquake, the response spectrum at the engineering bed rock is defined as follows:

$$S_{a0}(T,0.05)=\begin{cases} a_0 Z(0.6+5.625T) & (T\le 0.16)\\ 1.5a_0 Z & (0.16<T<0.64)\\ 0.96\, a_0 Z/T & (T\ge 0.64)\end{cases}$$

where, a_0 is peak acceleration of 3.2 m/sec^2, Z is the regional factor defined by BSL and T is the natural period (sec). A soil amplification factor (Gs) is introduced to obtain the response spectrum $S_{as}(T,0.05)$ at the soil surface so that,

$$S_{as}(T,0.05)=S_{a0}(T,0.05)G_s$$

where

$$G_s=\begin{cases} 1.5 & (T\le 0.576)\\ 0.864/T & (0.576<T<0.64)\\ 1.35 & (T\ge 0.64)\end{cases}$$

The corresponding response spectrum of a building with damping ratio ζ is obtained as follows:

$$S_{aB}(T,\zeta)=S_{as}(T,0.05)F_\zeta$$

where

$F_\zeta = 1.5/(1+10\zeta)$ is the damping correction factor.

2.2 Generation of accelerogram

A synthetic accelerogram is then generated that closely match the target spectrum described in previous section. In addition to the target spectrum, phase characteristics of real seismic waves are used to generate seismic waves. In this study, three types of earthquakes are chosen for the phase component that are i) standard waves such as El Centro and Taft waves, ii) in-land and off shore waves such as Kobe and Hachinohe waves, and iii) Local wave such as Tohoku wave. Figure 1 shows the flow chart for generation of the seismic waves.

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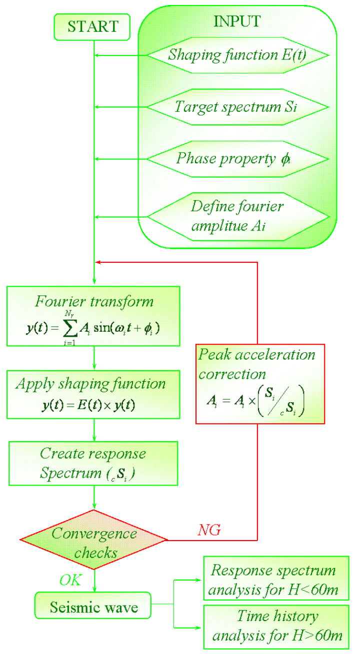


Figure 1: Flow of iterative process for generation of seismic waves for target response spectrum

The generated waves are required to meet the convergence criteria as described by AIJ (1993). Figure 2 shows the response spectrum of the generated earthquake waves in comparison with those specified by The Building Standard Law (BSL, 2004).

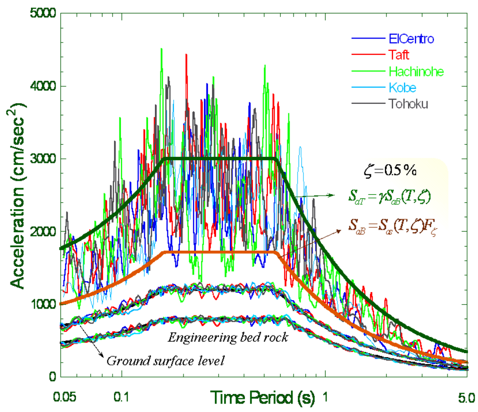


Figure 2: Response spectrum for level II generated seismic waves for stiff soil conditions (Soil type I)

It is evident from Figure 2 that generated seismic waves closely match the target response spectrum at the engineering bed rock and ground surface level. However, the response characteristics of low damped structures, i.e., wind turbines with damping ratio of 0.5% are not captured by the current response spectrum defined by BSL (2004). A new response spectrum is therefore proposed with a safety factor γ (=1.7) to account for the underestimation by current response spectrum. Both proposed and current response spectrum would be used to estimate the seismic loads acting on wind turbine by proposed semi-theoretical codified method.

3 NUMERICAL MODELING

3.1 Structural modeling

A full nonlinear FEM code (CAsT) is developed for the modeling of the rotor-tower coupling along with the geometrical non-linearity involved due to blade rotations. Beam elements are used to model the tower and blades of wind turbine with linear material model. The beam elements are of circular cross-sections with coinciding mass centre and pitch axis. The numerical scheme used in this study is summarized in Table 1.

Table 1: Numerical scheme

Dynamic analysis	The Newmark-Beta method
Eigenvalue analysis	Subspace iteration procedure
Element type	Beam element
Formulation	Total Lagrangian formulation
Geometric Non linearity	Newton-Raphson method
Aerodynamic force	BEM Theory
Damping	Rayleigh damping

3.2 Description of wind turbine models

The wind turbines used in this study are horizontal axis upwind turbines with rated powers of 400kW and 2MW. The three-bladed rotor is connected to fixed speed induction generator by shaft element and cylindrical steel tower is used as a supporting structure. Details of wind turbine basic parameters are summarized in Table 2.

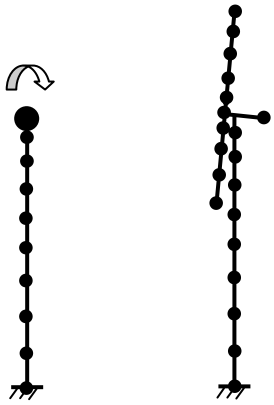
Table 2: Details of the wind turbine models

Model	Unit	Model 1	Model 2
Rated Power	kW	400	2000
Operating wind speed	m/s	15	15
Rotor diameter	m	31	80
Rotor tilt	deg	5	5
Tower height	m	35	67
Hub height	m	36	67
Blade mass	kg	1100	6800
Hub mass	kg	2500	16600
Nacelle mass	kg	12000	75000
Tower mass	kg	20910	165100

Two wind turbine systems, 400kW and 2MW, were modeled with 58 nodes and 57 beam elements for full FEM model. Where as for WEE, same number of tower elements are used with rotor and nacelle masses lumped along with inertial moment at the respective node as shown in Figure 3. Eigen value analysis was carried out and natural periods of first three tower modes are listed in Table 3. Both FEM and WEE models show close natural periods for 400kW turbine and relatively large difference occurs in case of 2MW model. However, this small difference in natural period may become critical considering the large fluctuation observed in the response spectrum of system with damping ratio equal to 0.5% as shown in Figure 2. The impact of these modeling methods will be discussed in next section.

Table 3: Natural periods of wind turbine models

Tower	2MW Turbine			400kW Turbine		
Modes	FEM	WEE	% ε	FEM	WEE	% ε
1st	2.584	2.534	1.93	1.232	1.225	0.57
2nd	0.347	0.347	0.06	0.151	0.153	1.33
3rd	0.128	0.125	2.34	0.056	0.057	1.78



a) WEE Model b) FEM Model

Figure 3: WEE and FEM representation of wind turbines

4 SEISMIC RESPONSE ANALYSIS IN TIME DOMAIN

It is necessary to understand the effect of modeling methods, i.e., full FEM and WEE, on the response characteristics of wind turbine systems. Eigen vector analysis and dynamic response analysis are conducted to investigate the contribution of higher modes towards the response of wind turbine models.

4.1 Contribution of higher modes

Modal strain energy shown in Figure 4 is calculated by taking second order differential of the 4th order polynomial fit to the modal shapes ϕ as shown below:

$$MSE = \frac{1}{2}\int EI\phi''^2 dx$$

For the 400kW turbine, the modal strain energy of WEE model remains close to that obtained by FEM model. However, in case of 2MW turbine, strain energy is overestimated by WEE model and is underestimated for the higher modes. This discrepancy in strain energy indicates that seismic loads estimated by WEE model would show large difference when compared with FEM model.

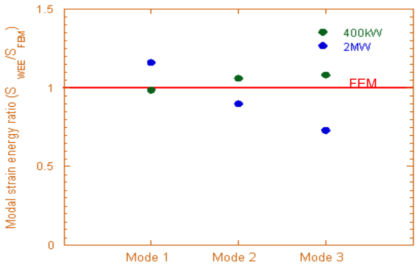


Figure 4: Comparison of modal strain energy

Figure 5 shows contribution of higher modes to the base moment of wind turbine tower under generated seismic waves. The contribution of higher modes is negligible in case of 400kW, but second mode contribution becomes significant for 2MW that has large natural period when subjected to Taft and Kobe. In addition, agreement of base moment obtained by both models is dependent on the type of earthquake used.

4.2 Dynamic response characteristics of wind turbines

A dynamic response analysis is carried out to investigate the influence of modeling method on the maximum base

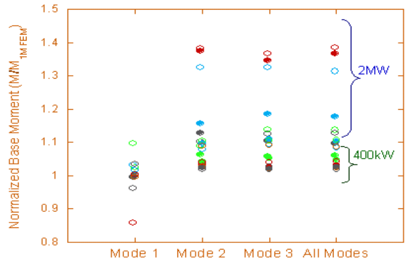


Figure 5: Contribution of higher modes to base moment

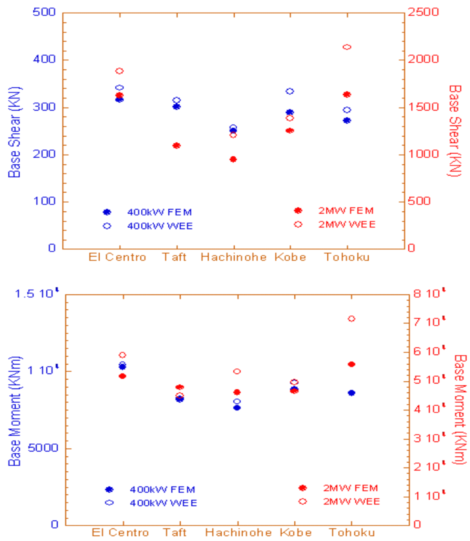


Figure 6: Maximum base shear and moment

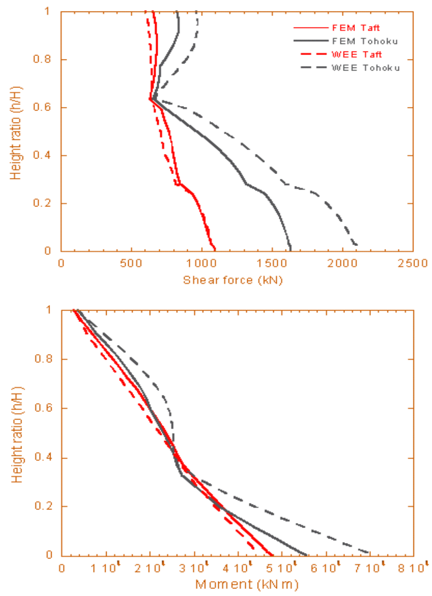


Figure 7: Shear and moment profile of 2MW

moments. The simulated base moments remain constant for both 400kW models, but in case of 2MW, there exists large variation depending upon generated seismic waves as shown in Figure 6. Shear and moment profiles for Taft and Tohoku waves, which show similar and different loads for both models, are shown in Figure 7. In short, WEE model may result in large overestimation of base moment for some earthquake type. Therefore, the use of full FEM model would be necessary to accurately estimate the seismic loads acting on wind turbines.

5 SEISMIC LOAD ANALYSIS BY RESPONSE SPECTRUM METHOD

The formulation of semi-theoretical codified method (JSCE 2007) is based on the assumptions that all wind turbines follow i) similar tower mass distribution and top mass ratio and, ii) similar first mode shapes. Figure 8 and 9 summarizes the data of six wind turbines. The mass distribution of can be approximated as follows:

$$m_i = \begin{cases} 0.05m & i=1 \\ G(z_i) - G(z_{i-1}) & 1<i<n \\ 0.44m & i=n \end{cases}$$

and

$$G(z_i) = \sum_{k=i}^{n} m_k \Big/ m = 0.05 + 0.84(z_i/H_t) - 0.33(z_i/H_t)^2$$

where H_t is the height of the tower, and $G(z)$ is the accumulative mass distribution.

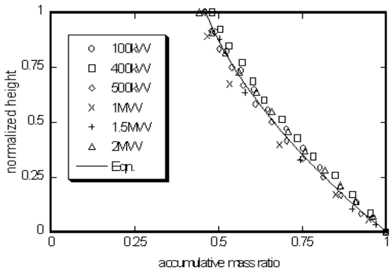


Figure 8: Accumulative mass distribution

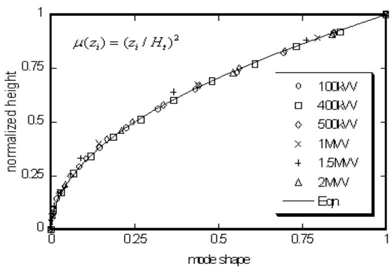


Figure 9: First mode shape of wind turbine tower

The base shear acting on wind turbines in parked conditions is estimated by summing up the shear force of the first mode Q_{11} obtained by using response spectrum and contribution of higher modes (ΔQ_1) to the shear force are obtained from FEM analysis as shown below:

$$Q_{s1} = Q_{11} + \Delta Q_1 = (1+C_s)Q_{11}$$
$$= \nu(1+C_s)S_a(T,\zeta)\sum_{i=1}^{n} m$$

where

$$\nu = \left(\sum_{j=1}^{n} m_j \mu(z_j)\right)^2 \Big/ m\sum_{j=1}^{n} m_j \mu(z_j)^2 = 0.641$$

$$C_s = \begin{cases} 0 & (T \le 0.7s) \\ 0.075(1-e^{0.7-T}) & (T > 0.7s) \end{cases}$$

$S_a(T,\varsigma)$ is the acceleration response spectrum of the structure with damping ratio ς and C_s is the shear modification factor for higher modes obtained by FEM analysis.

The profile of seismic loads acting on wind turbine in parked conditions can be estimated by the following expressions:

$$Q_{si} = 0.641(1+Cs)S_a(T,\zeta)\sum_{i=1}^{n} m_i A_{qi}$$

$$M_{si} = 0.641(1+Cs)S_a(T,\zeta)\sum_{i=1}^{n} m_i A_{mi} h_g$$

so that,

$$A_{qi} = 1 - 0.2(z_i/H_t)$$
$$A_{mi} = 1 - 0.97(z_i/H_t)$$
$$h_g = H_t(0.934 + 0.5C_s)/(1+C_s)$$

where A_{qi} and A_{mi} are the shear and moment distribution factors, and h_g is the nominal height of gravity centre.

The acceleration response spectrums used to estimate the seismic load profiles are shown as follows:

Current response spectrum: $S_{aB}(T,\zeta)$

Proposed response spectrum: $S_{aT}(T,\zeta) = \gamma S_{aB}(T,\zeta)$

where constant safety factor $\gamma = 1.7$

Figure 10 and 11 show shear and moment profiles of the 400kW and the 2MW wind turbines for the generated seismic waves. The seismic load profiles calculated by the current and proposed response spectrums are also shown. Use of current response spectrum results in underestimation of the seismic load profiles for both wind turbines. This is because the current spectrum is developed only for the structures with higher damping ratio (1-5%) compared to that of wind turbines.

A safety factor (γ) is introduced in the proposed response spectrum and the estimated seismic load profiles cover well the variation of profiles obtained by time history analysis in time domain. In case of 400kW wind turbine, semi-theoretical formulation gives good prediction of seismic loads when used with the proposed response spectrum. However, in case of 2MW wind turbine, design formulation results in the overestimation of the moment. It can be concluded that a frequency dependent safety factor should be used to accurately estimate the seismic loads on wind turbines.

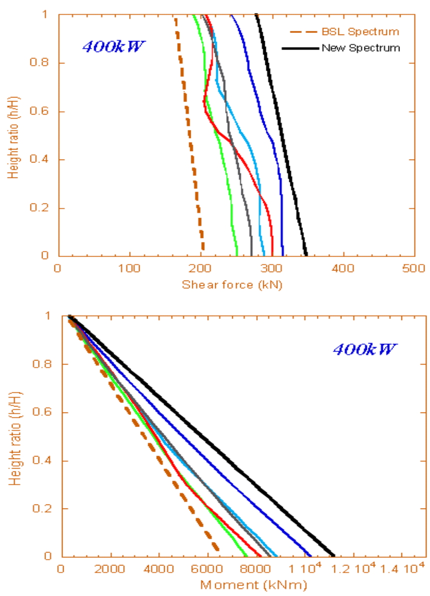


Figure 10: Profile of seismic loads acting on 400kW

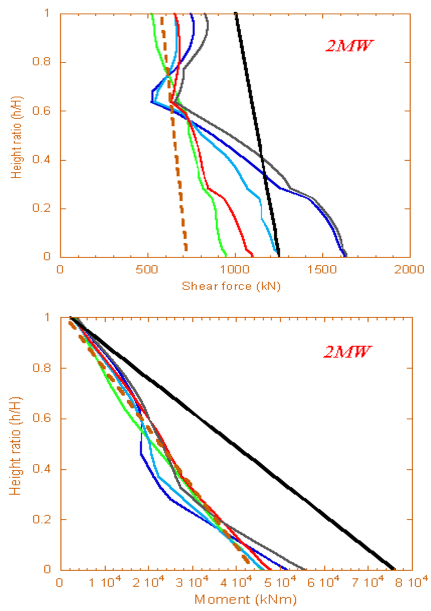


Figure 11: Profile of seismic loads acting on 2MW

6 CONCLUSIONS

A full nonlinear FEM model is developed that takes into account the geometric nonlinearity and the coupling between the rotor and the tower to perform the time domain analysis of wind turbines. A modal and a dynamic response analysis were carried out for level II earthquakes in accordance with new Japanese design code. Further semi-theoretical formulation for estimation of the shear and the moment profile is presented. The following summarizes the major conclusions of this study.

1) The contribution of higher modes towards the structural response is small for middle-size wind turbines. However it becomes important for large wind turbines resulting in overestimation of the base shear and the moment when WEE model is used.
2) Present response spectrum defined for building structures (BSL, 2004) in Japan could not capture the characteristics of acceleration response spectrum with very low damping such as wind turbines. A modification response spectrum is required to account for large response of systems.
3) A semi-theoretical formula using response spectrum, defined for buildings is proposed and a safety factor is introduced to account for the large response of the systems with the low structural damping.
4) The estimated moment by the proposed formula captures the maximum value of the moments by dynamic response analysis in the time domain, but the estimated shear is still underestimated. Since the moments are the main design parameters, the proposed semi-theoretical formula ensures the usefulness.

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