Seismic Load Evaluation of Wind Turbine Support Structures Considering Low Structural Damping and Soil Structure Interaction

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Abstract

Wind turbine development has recently gained new dimensions and environment in different parts of the world. In Asia, special features of the environmental conditions greatly differ from other areas like Europe that prominently includes high seismic activity, which rattles the region frequently. Seismically active regions require design method for simple and accurate evaluation of seismic load to ensure structural integrity of wind turbine support structures. This paper specifies response spectrum method for prediction of seismic loads with consideration of intensity of the earthquake, soil and structural properties. In this paper, a damping correction factor for the wind turbine support structures with low damping ratios, considering natural period and reliability (quantile) is proposed. Moreover, vivacity of modified damping correction factor is also checked for other structures. This study further presents SR (Sway-Rocking) model to take into account soil structure interaction effects and to evaluate seismic response of footing structure. First five tower modes are found to have modal mass participation more than 85% and the effect of foundation can be taken into account when up to 5th mode is considered. The expected maximum seismic load is obtained by combining five modal responses using CQC (Complete Quadratic Combination) method. The accuracy and reliability of specified design response spectrum is evaluated through comparison with time history analysis of different sized wind turbines, i.e., 400 kW, 500 KW and 2 MW.

Keywords: wind turbine, seismic load, response spectrum, Low damping, soil structure interaction

1 Introduction

Rapid expansion of wind energy and growing number of wind turbines construction in earthquake areas are required to propose a design method for simple and accurate evaluation of seismic load to ensure structural integrity. A wind turbine support structure was damaged due to seismic loading in Kashima city, Japan during March 11, 2011 earthquake. Therefore stability of wind turbine support structures under such extreme conditions needs to be investigated for reliable design in seismically active regions. The IEC [1], a worldwide organization for standardization, specified three methods i.e. simplified, time domain and response spectrum method for the prediction of seismic loads. There are several literatures [1, 2, 3, 4] available on Simplified method, which use the SDOF (Single Degree of Freedom) model to estimate wind turbine seismic response. This model results in linear seismic load profile. However, seismic load profile is found to be largely affected by the higher modes [5] of wind turbines. This approach is inaccurate, which sometimes overestimates and for some cases underestimates the response of wind turbines. Moreover, there are many former researches on dynamic analysis, in which wind turbine support structure in time domain has been studied in view of examining the response [6, 7, 8, 9, 10, 11]. Wind turbine analysis by using time domain method is accurate but time consuming moreover, too many information like time history of seismic waves and soil conditions at a particular site etc. are required. Further, several calculation steps and Monte Carlo simulation are performed to find structural reliability level. Response spectrum method specified in this research is accurate, reliable, time efficient and easy to use requires items as mentioned in Table 1 to calculate maximum seismic loads. There is no any literature, existing code and standard available to specify response spectrum for wind turbine support structure. IEC refers to the response spectrum available in the design building codes. The design building code is not applicable to wind turbine support structures owing to its unique characteristics like long period, low damping, heavy top and different mass ratio between super and substructure. These support structures are extremely low damped and experience a wide range of frequencies when subjected to seismic excitations [5]. Response spectrum of such low damped structures shows excessive fluctuations and such uncertainty in response can not be captured by existing damping
correction factor models defined in Eurocode [12] and BSL [13]. In this paper response spectrum is specified for prediction of seismic loads with consideration of intensity of the earthquake, soil and structural properties. Modified damping correction factor that accounts for uncertainty in response spectrum with low damping ratios, considering natural period and reliability (quantile) is proposed. This study further presents SR model [14] to take into account soil structure interaction effects and to evaluate seismic response of footing structure. First five tower modes are found to have significant contributions to the seismic load of wind turbine towers and having modal mass participation more than 85%. The effect of foundation can be taken into account while considering five numbers of modes. The expected maximum seismic load is obtained by combining five modal responses using CQC [15, 16] method. The accuracy and reliability of specified design response spectrum is then evaluated through comparison with time series analysis of different sized wind turbines, i.e., 400 kW, 500 KW and 2 MW.

In this research, wind turbine tower is modeled as multi-degree of freedom system and rotor and nacelle masses are modeled as a lumped mass concentrated at hub height. To evaluate the response of wind turbine towers, a fixed support structural model can be used to facilitate ease in design practices which shows a good agreement in comparing seismic response with SR model. To determine seismic loads under operating conditions, seismic load under parked conditions is combined with the operational wind loads [2].

Table 1: Items in response spectrum method

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>Response spectrum</td>
</tr>
<tr>
<td>2</td>
<td>Soil amplification factor</td>
</tr>
<tr>
<td>3</td>
<td>Damping correction factor</td>
</tr>
<tr>
<td>4</td>
<td>Combination of modes</td>
</tr>
<tr>
<td>5</td>
<td>Reliability Level</td>
</tr>
</tbody>
</table>

2 Wind Turbine Support Structure Damage Survey

A wind turbine support structure was damaged due to seismic loading in Kashima city, Japan during March 11, 2011 earthquake. A survey was conducted to the damage site to identify the cause of damage. Kashima wind farm is equipped with 10 wind turbines all of which has rated power of 2 MW. In this quake,
wind turbine marked as red point in Figure 1 was damaged and due to this tower was tilted (towards N-E direction) by 1.8 degree (1 to 4 in Figure 1). The directions of small arrows in the Figure 1 are corresponded to the direction of the photos taken from 1 to 8. This damage was mainly associated to the wind turbine footing structure. A detailed study based on response spectrum method has been performed not only to assess the damage but to specify response spectrum for simple and accurate seismic load evaluation of wind turbine support structures.

3 Evaluation of Seismic Load

This section describes response spectrum method to capture seismic load profile for wind turbine support structures. Response spectrum available in all design codes is not applicable for wind turbine support structures owing to its unique characteristics, different from the buildings and other structures. In this section, specified acceleration response spectrum for wind turbine support structures is discussed in detail. SR model is also considered to take into account soil structure interaction effects and to evaluate seismic response of footing structures. Further, a number of structural modes required to capture safe and accurate load profile is described in detail. Finally accuracy and reliability of modified response spectrum is checked in comparison with time history analysis for safe and accurate estimation of the design loads.

Response spectrum method requires natural period, mode shape and mass distribution of the structure to calculate maximum seismic loads. Response spectrum method is based on acceleration response spectrum of SDOF system that is used to determine maximum response of MDOF system. Following is the equation of motion for j-th mode of a MDOF system,

\[ \ddot{q}_j + 2\zeta_j \omega_j q_j + \omega_j^2 q_j = -\gamma_j \ddot{x}_g \] (1)

Where, \( \omega_j \) is the natural angular frequency, \( \zeta_j \) is the damping ratio and \( \gamma_j \) is the modal participation factor. Maximum force for each mode depends upon the modal participation factor, mode shapes and acceleration of response spectrum corresponding to the natural period of respective modes. For example, the maximum shear force corresponding to j-th mode of the i-th node can be estimated as follows:

\[ F_{ij} = \gamma_j X_{ij} S_a(T_j, \zeta) m_i \] (2)

Where, \( X_{ij} \) is the j-th mode shape where, \( j \) is representing mode number and \( i \) is position of mass.

\( S_a(T, \zeta) \) is the amplitude of acceleration response spectrum corresponding to natural period \( T \) and damping ratio \( \zeta \).

Seismic load profile in terms of shear force and bending moment acting on wind turbine support structure can be calculated using load formula for MDOF system as shown in (3) and (4). But estimation of design loads for MDOF system as shown in Figure 2 require prior knowledge of natural periods and modal participation function \( \gamma_j X_{ij} \).

![Figure 2: MDOF fixed support model](image)

These structural characteristics i.e. natural period and mode shapes are calculated by performing eigen value analysis.

\[ Q_{ij} = \sum_{k=1}^{n} F_{ik} = \sum_{k=1}^{n} \gamma_j X_{ij} S_a(T_j, \zeta) m_k \] (3)

\[ M_{ij} = \sum_{k=1}^{n} F_{ik}(z_k - z_i) = \sum_{k=1}^{n} \gamma_j X_{ij} S_a(T_j, \zeta) m_i (z_k - z_i) \] (4)

Where,

\[ \gamma_j X_{ij} = \frac{\sum_{i=1}^{n} m_i X_{ij}}{\sum_{i=1}^{n} m_i X_{ij}^2} \times X_{ij} \]

3.1 Acceleration Response Spectrum

The design acceleration response spectrum \( (S_a) \) is a function of soil amplification factor (soil property) due to soil part between bedrock and ground surface and damping correction factor (structural damping property). Acceleration response spectrum is specified for wind turbine support structures as shown in (5).
The soil model used in BSL is a function of frequency unlike Eurocode and is based on two layers of soil. For reliable value of soil amplification factor there is a need to consider multilayered soil model. A bore log data is required in this regard. For large wind turbines like in case 7 MW, where height is more than 100m, soil properties at site plays an important role to evaluate the actual seismic response. Soil model considering multilayered soil will be presented in another paper. In this paper soil model as used in BSL is considered in design response spectrum for the seismic load evaluation.

3.2 Damping Correction Factor

Wind turbine support structures are significantly low damped, and response spectrum for such low damped structures shows excessive fluctuations. Such uncertainty in response of these structures cannot be captured by existing models of the damping correction factors defined in Eurocode and BSL.

To account for excessive fluctuations in the response spectrum of low damped systems, damping correction factor is proposed as a function of spectral uncertainty, natural period and damping ratio so that,

\[ F_\zeta(\zeta, T, \gamma) = \left( \frac{7}{2 + 100\zeta} \right)^\alpha, \quad \alpha = f(T, \gamma) \]  

Where, \( T \) is natural period, \( \zeta \) is damping ratio and \( \gamma \) is the quantile value for desired reliability level. BSL and Eurocode define damping correction factor as a function of damping ratio only and a constant value of 0.5 is used in Eurocode for the exponent \( \alpha \). However, when exponent \( \alpha \) is defined as a function of time period, \( f(T) \), it corresponds to a damping correction factor that considers the natural period of the structure. In addition to damping ratio and natural period of the structure, proposed damping correction factor also includes uncertainty of the response spectrum. To establish the proposed damping correction factor, first a set of 35 seismic waves, 5 with observed phase and 30 with random phase, were used to evaluate excessive fluctuations in the acceleration response spectrum for damping ratios ranging from 0.5% to 5%. Figure 3 shows acceleration response spectra for damping ratios of 0.5% and 5% that correspond to wind turbine structures and buildings respectively. It can be observed that at low damping ratio of 0.5%, in case of wind turbine support structures, excessive fluctuations in the spectral acceleration occur.
To determine the probability distribution that represents the uncertainty involved, the response spectrum is divided into three sections so that $0.05 < T < T_{B}$ refers to Section $I_{A}$, $T_{A} < T < T_{C}$ refers to Section $I_{B}$ and $T_{C} < T < 5$ refers to Section $I_{C}$. Sections $I_{A}$ and $I_{C}$ are divided into ten sub-sections $I_{A}^{(i)}$ and $I_{C}^{(i)}$ ($i = 1 ~ 10$), whereas Section $I_{B}$ is considered as a single section to calculate the statistical properties such as mean and standard deviation of the acceleration response. Figure 4 shows a cumulative relative frequency of the acceleration response in the sections $I_{A}^{(5)}$, $I_{B}$ and $I_{C}^{(5)}$. Also cumulative frequencies of lognormal distribution function derived from corresponding mean and standard deviation of each interval are drawn as solid lines. Log normal distribution is found to have well defined the uncertainty in all sections of the acceleration response spectrum as shown in Figure 4.

It is now possible to define the percent quantile $\gamma$ of acceleration for a desired reliability level by modeling the uncertainty of acceleration response with logarithm distribution function. Three quantile values of 20%, 50% and 80% are used to investigate exponent $\alpha$ of the damping correction factor by using equation (7).

$$\alpha = f (T, \gamma) = -0.07T + 0.7\gamma + 0.5 \quad (7)$$

The acceleration response spectrum calculated by the proposed formula agrees well with the calculated results for all quantile values $\gamma$ of response acceleration. Introduction of the natural period $T$ of structure has lead to accurate estimation of the response spectrum in the long period regions. Also uncertainty of the response spectrum can be incorporated by changing quantile value, $\gamma$.

Figure 5 shows that the proposed damping correction factor agrees with all quantiles:

However, when the response spectrum is calculated based on the damping correction factor defined in Eurocode, it is found that it corresponds to only 20% quantile of acceleration response spectrum as shown in Figure 5. Moreover for the building structures where the damping ratio is 5 %, the proposed damping correction factor is quite in a good agreement with Eurocode as shown in Figure 6.
3.3 Soil Structure Interaction Effect

IEC specifies fixed support single degree of freedom model, which can not be used for seismic load evaluation of footing structure. In order to consider the effect of soil structure interaction and to evaluate seismic response of wind turbines footing structures SR (sway rocking model) is taken into account. SR model is a simplified form of multi spring model in which equivalent stiffness of soil underground is calculated and assign to the footing as spring as shown in figure 7. Where, 1 is the ground surface, 2 is the foundation, 3 is the spring for sway and 4 is the spring for rocking.

![Figure 7: Sway-rocking model](image)

By performing eigenvalue analysis, it is found that forth mode in SR model shows the sway motion of the foundation and is quite significant in terms of footing response. The rocking mode frequency is very large and does not appear while considering higher modes. It is found that tower response remains the same as in case of fixed support model. Mainly SR model is used to calculate the footing response. The effect of foundation can be taken in to account when up to 5th mode is considered as shown in Figure 8.

![Figure 8: Modal Participation function in SR model](image)

3.3.1 Combination of Modes

In this research, three different wind turbine models are taken into considerations to predict number of modes contributing to accurate estimation of seismic load. Following is the detail of wind turbine models used in this research as shown in Table 4.

<table>
<thead>
<tr>
<th>Model</th>
<th>Unit</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>kW</td>
<td>400</td>
<td>500</td>
<td>2000</td>
</tr>
<tr>
<td>Operating wind speed m/s</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>m</td>
<td>31</td>
<td>40.3</td>
<td>80</td>
</tr>
<tr>
<td>Rotor tilt</td>
<td>deg</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Tower height</td>
<td>m</td>
<td>35</td>
<td>42.2</td>
<td>67</td>
</tr>
<tr>
<td>Hub height</td>
<td>m</td>
<td>36</td>
<td>44</td>
<td>67</td>
</tr>
<tr>
<td>Blade mass</td>
<td>kg</td>
<td>1100</td>
<td>1050</td>
<td>6800</td>
</tr>
<tr>
<td>Hub mass</td>
<td>kg</td>
<td>2500</td>
<td>2500</td>
<td>16600</td>
</tr>
<tr>
<td>Nacelle mass</td>
<td>kg</td>
<td>12000</td>
<td>24000</td>
<td>75000</td>
</tr>
<tr>
<td>Tower mass</td>
<td>kg</td>
<td>20910</td>
<td>35255</td>
<td>165100</td>
</tr>
</tbody>
</table>

It is found that first five tower modes in many wind turbines have modal mass participation more than 85%. So the requirements specified by IEC and CICIND [17] are acceptable. Modal mass participation ratios of first five number of tower modes are shown in case of 500 kW wind turbine in Table 5. Furthermore, first five tower modes are enough to encompass accurate complex seismic load profile. Simplified SDOF model described in IEC calculates the load for a system in which the total rotor, nacelle and 50 % of tower mass is concentrated at the tower head, which is too conservative. In addition, use of the simplified SDOF model results in linear vertical load profiles. However, seismic load distribution is found to be largely affected by the higher modes. Unlike wind loads a wide range of frequencies are involved in seismic waves that may excite the higher modes of wind turbine structure system.

Seismic loads are calculated using (3) and (4). A CQC (complete quadratic combination) method is proposed as shown in (8) for the combination of responses of different modes, which reduces errors in all examples studied.
Where,

\[
Q_i = \sqrt{\sum_{i=1}^{n} \sum_{k=1}^{n} S_i \rho_{i,k} S_k}
\]

(8)

Where, \(S_i\) is the maximum response quantity in the \(i\)th mode of vibration. \(\xi_i, \xi_k\) are the damping ratios for the \(i\)th and \(k\)th mode, respectively. \(X\) is the ratio of \(i\)th mode natural frequency to the \(k\)th mode natural frequency.

Seismic load profiles obtained from RSM (Response Spectrum Method) considering five modes and using quantile, \(r = 0.5\) are compared with mean values of THA (Time History Analysis) results. In this study four actual phase i.e. Hachinohe NS, Elcentro NS, Kobe NS, Taft EW and six random phase earthquake waves compatible to acceleration response spectrum [13] have been used to compare results with response spectrum method. Seismic load profiles (shear and moment) in Figure 9 for 2MW turbine are shown. It shows good agreement in comparison with THA. The load profile shown as red line in Figure 9 refers to seismic load profile by considering IEC. The simplified method described in IEC shows linear profile in comparison with THA and overestimates the response up to large extent. Further, in order to confirm the accuracy of specified response spectrum, base shear and moment comparison for all wind turbines are shown in figure 10. This comparison shows good agreement between RSM and THA.

\[
Q_p = Q_B + KW_F
\]

(9)

Where, \(Q_p\) is the shear at the base of footing or at the top of pile, \(Q_B\) is base shear at the tower base, \(W_F\) is weight of foundation and \(K\) is underground seismic coefficient. The value ‘\(K\)’ mentioned in the design
code [13] is 0.1. This value significantly underestimates shear at the footing base and is one of the reasons of wind turbine support structure failure in Kashima city, Japan in addition to neglecting the low damping fact of tower structure.

Figure 12 shows the shear at the pile head in case 500 KW turbine structure, contributing from both tower and footing structure. So, conventional method underestimates the response of footing structure. Underground seismic coefficient, K value used in the conventional method is needed to revise for wind turbine support structures. Further, response contributing from tower (tower base shear) is also underestimated because damping correction factors available in the existing design codes do not cover uncertainty in response for low damping structures as explained in Section 3.2.

3.4 Determination of Quantile $\gamma$ for Reliability Levels

In Section 3.2, quantile $\gamma$ was described to the damping correction factor that accounted for large uncertainty in the response spectrum. Therefore, it is necessary to determine suitable quantile value $\gamma$ for defining reliable design spectrum. Based on reliability theory, code calibration method [18] is an effective approach to ensure essentially similar reliability level as that of the current design codes. In Japan, BSL requires time history analysis of structures for at least three earthquake waves to obtain structural design certification. These waves include two local waves, such as Kobe and Hachinohe that are onshore & offshore waves respectively, and one famous earthquake such as Elcentro or Taft. In this study, in addition to four of the above mentioned seismic waves six random phase waves are used to identify suitable quantile $\gamma$ for defining the specified design response spectrum. The seismic load profiles obtained by time history analysis of selected wind turbines are shown in Figure 13.

A $\gamma$-value of 0.85, i.e., 85% quantile, is identified against the time history analysis results to obtain reliability level. This value of quantile covers most of the earthquakes in addition to the four stated actual phase earthquakes.

4 Conclusions

This research has presented response spectrum method for seismic load evaluation of wind turbine support structures. Different parameters involved in response spectrum were discussed in detail. Sway-rocking model was discussed to take into account soil structure interaction and seismic response of
foundation of wind turbine structure. Finally, accuracy and reliability of the proposed method for evaluation of seismic design loads were examined against time history analysis.

The following summarizes the major conclusions of this study.

1) A response spectrum for wind turbine support structures is specified for prediction of seismic loads with consideration of intensity of the earthquake, soil and structural properties.

2) Modified damping correction factor in design response spectrum accounts for the excessive fluctuations of response spectrum and predicts accurate response comparing with time history analysis.

3) First five number of tower modes have modal mass participation more than 85% in all wind turbine structures and are enough for encompassing safe and accurate seismic loads distribution of wind turbine towers and foundations.

4) The quantile, γ value of 0.85, i.e. 85 % quantile is decided to obtain reliability level.

References


