A Numerical and Semi-theoretical Formulation of Seismic Response Analysis of Wind Turbines in Time Domain

Takeshi ISHIHARA* and Muhammad Waheed SARWAR*

*School of Engineering, The University of Tokyo
ishihara@bridge.u-tokyo.ac.jp, sarwar@bridge.u-tokyo.ac.jp

Objective

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 procedures to avoid collapse under seismic excitation. Stability of wind turbine structures against level II earthquake is required, which is carried out depending on tower height either by time domain analysis or by design formulas.

Unlike wind loads, a wide range of frequencies are involved in seismic loads 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 turbine under seismic loads. To simulate the response of wind turbine, modal analysis is widely used in the field of wind energy engineering. In 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 (Bladed, 2005) used the modal model and the whole wind turbine is divided into two subsystems: one is the rotor, and other is the tower. Since rotor and tower are calculated separately, it requires coupling between them to model interaction between rotor and tower. However, this coupling is not sufficient in the modal model because only very limited modes of degrees are modeled.

In this study, a full nonlinear FEM model is developed that takes into account the nonlinear centrifugal and coupling between the rotor and tower. Aim of present study is to examine response characteristics of wind turbines in time domain, and to formulate equations for prediction of seismic loads using response spectrum. First response spectrum according to Japanese building standard is introduced and process of earthquake wave generation is discussed. Then investigations on modal coupling to response of wind turbine are discussed, and finally semi-theoretical formulation for seismic load estimation is discussed.

Numerical Modeling

- The equation of motion of the FOWTS is written as follows.

\[
\frac{u}{\omega} = \left[\begin{array}{c}
\sum_{i=1}^{n=5} \sum_{j=1}^{m=5} \sum_{k=1}^{l=5} q_{ij}\xi^{ij}\partial^2 \xi^{ij}\partial t^2 \\
-1
\end{array}\right]
\]

where \(q_{ij}\xi^{ij}\partial^2 \xi^{ij}\partial t^2\) are the arrangement factor and the seismic force respectively, and \(\xi^{ij}\) is a rectangular mode shape.

- Two wind turbine systems, 400kW and 2MW, were modeled using beam elements with 57 nodes and 57 elements for FEM model. For WEE, same number of tower and nacelle elements are used with rotor and nacelle masses lumped at the respective nodes.

Seismic Load Analysis by Response Spectrum

Estimation of vertical load profile

A linear distribution of the shear force and moment profile is shown. The response spectrum defined by BSL is based on damping ratio \(\xi\) in 5% that results in considerable overestimation of the seismic loads. Therefore a modification is introduced to the response spectrum definition, called as safety factor, \(\gamma\), to account for the damping ratio such that

\[
\frac{a_{TS}(1+\gamma)}{a_{BM}(1+\gamma)} = \frac{a_{T}(1+\gamma)}{a_{B}(1+\gamma)} \left(\frac{1+\gamma}{1+\gamma}\right)
\]

where \(\gamma = 1.7\) is used in the present study.

Seismic Conditions

- Earthquake waves generated according to specification are usually used to conduct stability analysis of full structures. Phase of real seismic wave is used to generate an excitation for the desired type of response spectrum.

In the study, three types of earthquakes are chosen for the tower codes for the standard waves such as El Centro and Taft waves, 400kW and offshore waves such as Kobe and Tohoku waves, and 2MW loads such as Tohoku wave.

Seismic Response Analysis in Time Domain

Contribution of higher modes

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

- The first mode shapes agree well for both models. However, second modes and third modes have shown different behavior for the two models.
- Modal strain energy, calculated from eigen vectors, suggests that both WEE and FEM would result in similar response for the 400kW turbine. However larger contribution of higher modes is observed in case of 2MW turbine.
- Base moment for the two models agrees well for the 400kW turbine and show smaller contribution of higher modes. In case of 2MW turbine, high contributions from 2nd mode occurs for Taft and Kobe waves that have significantly excited the second mode of wind turbine.
- The consistency of the seismic load profile, obtained by FEM and WEE model, is significantly influenced by the type of earthquake phase used.

Dynamic Response Characteristics

To investigate the response behavior of wind turbine systems, a dynamic response analysis was carried out for waves generated from the target spectrum of Level II. For WEE model tends to overestimate the base reactions for dynamic analysis, which becomes as large as 25% in case of 2MW turbine.

A close agreement between the simulated seismic loads exists for two modes of 400kW, that is consistent with outcome of the modal strain energy analysis.

Conclusions

A full nonlinear FEM model is developed that takes into account the geometric nonlinearity and the coupling between the rotor and tower to perform the time domain analysis of wind turbines. A modal and dynamic response analysis was carried out for level II earthquake in accordance with new japanese design code. And semi-theoretical formulation for estimation of shear and moment profile along the tower height are discussed.

- The contribution of higher modes towards the structural response is small for wind turbines with low natural period. However it becomes important for tall wind turbines resulting in significant overestimation of base moment when WEE model is used.
- Present response spectrum used for building structures (BSL, 2004) in Japan could not capture the characteristics of acceleration response spectrum with very low damping ratio as wind turbines. A modification response spectrum is required current to account for large response of low damping systems.
- The semi-theoretical formulation when used along with present response spectrum, defined for buildings, underestimates the seismic loads acting on the wind turbines. A safety factor is introduced to account for the low structural damping and the estimated base loads agree well with base moment when modified response spectrum is used.
- Base shear is still underestimated by modified spectrum but moment being the main design parameter ensures the usefulness of proposed semi-theoretical formula. Further investigations on the safety factor are needed to accurately predict the seismic loads acting on wind turbines.

References