論文の内容の要旨

論文題目　Seismic response of wind turbine in the parked and operating conditions

（風力発電設備の停止時と発電時における地震応答に関する研究）

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The wind load is usually the dominant load in wind turbine support structure design. However, Japan is a seismic active region and the seismic load may become the dominant load. Few researches on this issue have been performed. One of the approaches is the dynamic response analysis in time domain to evaluate the seismic performance of wind turbine support structures, in which the modal model with a weak coupling of the rotor and the tower and the lumped mass model are used and both model overestimate the seismic response. An alternative approach is the equivalent static force analysis in which Uniform building code and IEC 61400-1 are used. But the former adopts 5% damping ratio, which is not the case for wind turbine support structures. The latter adopts a simplified uniform shear profile. This thesis is aimed to develop a full nonlinear FEM model to investigate the effects of the coupling of the rotor and the tower, distributed mass of the rotor, aerodynamic damping and the direction of wind and earthquake, and to propose semi-theoretical formulas for seismic design of wind turbine support structures in the parked and operating conditions.

Chapter 1 introduces the background of this research, explains the specific dynamic characteristics of the wind turbine, proposes the research objectives and presents the outline of this thesis.

Chapter 2 reviews the previous research. The numerical models for the dynamic response analysis of wind turbine are summarized, and the seismic research for wind turbines in time domain and the response spectrum methods for the prediction of equivalent static force are surveyed.

Chapter 3 proposes a seismic response spectrum for the design of wind turbine support structures. The proposed spectrum is defined from the engineering bedrock and transferred to the ground level by using soil amplification factor and a reasonable damping correction factor. The proposed spectrum covers the spectra of six representative seismic waves in the range of long period, which corresponds to modern large wind turbine.

Chapter 4 develops a full nonlinear numerical model with the details of the rotor and the support structures. The coupling between the rotor and the tower is realized and the geometric nonlinearity due to the rotor rotation is considered by using Newton-Raphson iteration. It is

found that the coupling and the distributed rotor mass have almost no effect on the first mode, but a great effect on the higher modes, in comparison with the modal model and lumped mass model.

Chapter 5 performs the seismic analysis of the wind turbine in time domain by using the developed code and shows the proposed model can accurately predict the seismic responses in the parked condition, while the modal model and lumped mass model overestimate them because the former adopts a weak coupling and the latter ignores the distributed mass of the rotor. During operation, when the angle of the wind and earthquake is 45 degree, the maximum response is observed and is slightly larger than the case of 0 degree because of the rotation of the rotor. Contrastingly, the simplified numerical model using thrust coefficient to calculate wind force can only simulate the collinear case but fails to deal with other angles since it omits the rotor rotation. When the wind and seismic load act simultaneously, the total response is lower than the simple combination of both loads due to the aerodynamic damping and is even lower than the seismic load alone when the seismic intensity is large.

Chapter 6 establishes semi-theoretical formulas for the seismic design of wind turbine support structures. Formulas for the base shear and moment, as well as the profiles of them, are theoretically derived and a modification factor is proposed to account for the effect of higher modes on the base shear. A formula for the seismic response analysis in the operating condition is derived, considering the aerodynamic damping due to the rotation of rotor. The proposed formulas show good agreement with the numerical results and give more accurate results than conventional models. The comparison between the extreme wind load and the seismic load in Japan indicates that the seismic load is dominant for small wind turbines when the design wind speed is low, while the wind load is dominant for large wind turbines.

Chapter 7 concludes this thesis. A full nonlinear FEM model is developed, which takes into account the geometric nonlinearity and the coupling between the rotor and the tower. The seismic analysis in the parked and operating conditions shows that both the weak coupling of the rotor and the tower and the neglect of the distributed mass of rotor cause overestimation of the seismic response. The response by simultaneous wind and earthquake load is lower than the simple combination of both loads due to the aerodynamic damping, and the maximum response may occur when the angle of the wind and earthquake is 45 degree due to the rotation of rotor. Semi-theoretical formulas for seismic design of wind turbine support structures in the parked and operating conditions, considering the profiles of shear and moment, and the aerodynamic damping, are established, which agree with the numerical simulation and yield more accurate results than conventional models.