博士論文（要約）

Fatigue Prediction and Damage Detection of Wind Turbine High-tension Bolts Based on Field Measurement and Updated Numerical Model

（現地観測と精緻化した数値モデルを用いた

風車高力ボルトの疲労予測と損傷検知に関する研究）

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Bolted joints are always preferred for wind turbines fabrication at the site due to transport reasons. Therefore, the bolt fatigue life is influenced by the construction quality to a great extent. With the rapid development of wind energy, more wind turbine accidents are occurring. One of the wind turbine's nacelle at Taikoyama wind farm collapsed, at the early age of its designed service life, due to the fatigue failure of high-tension bolts. Besides, the high-tension bolts suffered from frequent damages such as cracking, loosening and breaking. Moreover, every time the damages were observed not more than three months after the periodical maintenance which is conducted twice a year. The reason behind the occurrence of damages and also mechanism to prevent them need to address in a detailed manner. Therefore in this research, firstly, an updated wind turbine aerodynamic model which is able to represent the real wind turbine response is developed accurately. Secondly, the FEM model considering real nacelle shape and structural components at tower nacelle is built, for the purpose of accurate recreation of the tower stress distribution. Thirdly, two methods on high-tension bolt damage detection are proposed and compared. The algorithm of pre-tension prediction and diagnose is also proposed based on the FEM. The application of damage detection based on FEM is verified, and detection system is presented in this thesis.

In Chapter 1, the general background of this study, review of accident background, motivation, literature review and outline of this thesis are presented.

In Chapter 2, the introduction of the measurements related to this research, including wind turbine performance and tower top stress distribution are described. The measured wind data from the Taikoyama No.1 wind turbine at three different heights range for the whole operating wind speed range, with measurement period for one month. The result shows high turbulence intensity on-site corresponding to the IEC A requirement for complex terrain. The power generation and rotor speed are analyzed from SCADA. In addition, the tower base moment is measured through eight strain gauges attached to the tower wall, in order to verify the response of the aerodynamic model. At last, the tower top strain distribution is measured by strain gauges as well, because an accurate distribution of the tower top strain distribution is essential for the bolt damage detection and prediction.

In Chapter 3, an updated aerodynamic model calls 'pitch delay' model is built. The dynamic aerodynamic model is built by GL Bladed, considering 5 degrees of pitch delay which means the blades are always rotated by 5 degrees. The delayed pitch angle φ results in the decrease of angle of attack α, and thus reduces the blade element thrust dT and element torque dQ simultaneously. The 'pitch delay' model reduces both the simulated power generation and tower base moment compares to the existing aerodynamic model called 'mechanical loss' model. The 'mechanical loss' model overestimates the tower base moment when wind speed is over rated with electromagnetic torque reduced by 31.85%. This is due to the increased mechanical torque Γ_{mec} caused by the torque loss Γ_{loss} at the rated power generation criteria. The 'pitch delay' model is verified by the field measurement as described in Chapter 2.

In Chapter 4, the updated full flange FEM model is built and verified by measured tower wall strain distribution. The complex components at tower nacelle connection are carefully recreated including yaw bearing, ball bearing, yaw breaks and yaw motors. The nacelle is built based on real shape. High-tension bolt is built with beam element and shows good agreement with solid element bolt, and reduces the calculation time significantly. By comparing the existing FEM models, the tower wall strain distribution by updated full flange FEM model shows good agreement with measurement because it considers the great influence to the strain redistribution by yaw motors. Consequently, the high-tension bolt fatigue life of the updated FEM model is evaluated, and also the reason for the accident is revealed. It is in accordance with the real situation according to the accident investigation, that the bolt broke within only three months. It is proved that the reason for the broken bolt is due to the complex structure rather than the high turbulence onsite.

In chapter 5, bolt damage detection by utilizing the strain change on the tower of the wind turbine is proposed based on the updated full flange FEM model. By utilizing the updated full flange FEM model, the bolt damage can be detected successfully under the situation when only one bolt is suffering from damage. The bolt pre-tension predicted by the updated full flange FEM model shows good agreement with measurement as well. The algorithm for damage detection is based on one sub-method of MT system calls T3 method. It is based on pattern recognition so that the massive information of multivariate data can be compressed into few variables for convenient use. The degree of abnormality is evaluated by Mahalanobis Distance (MD), which is a useful measurement since it accounts for the correlation of the variables in a multidimensional system. The prediction of bolt damage is proposed based on another sub-method of MT system calls T1 method due to the fact of convenience and ease of use.

Chapter 6 summarizes the conclusions of this presented research study.