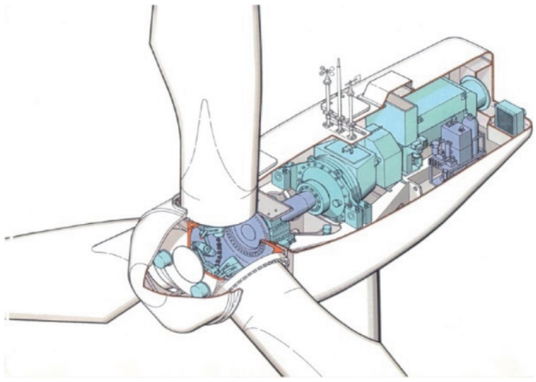
Lifetime Estimation of Wind Turbine Machinery Components Based on Measurement Data



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Wind turbines operate in a natural environment, so their fatigue life depends on the characteristics of wind flowing into the wind turbine. Among the wind characteristics, turbulence intensity may vary depending on the location of the wind turbine, resulting in differences in the fatigue life even for wind turbines located at the same wind farm. On the other hand, it is important for safe, secure, and efficient wind turbine operation to understand the fatigue life of each wind turbine in detail and to take countermeasures. To address this issue, we have developed a technology that combines analysis of data accumulated in wind turbines and a load analysis method to accurately evaluate the expected life of each wind turbine in a wind farm. This report outlines the developed technology.

1. Introduction

In general, wind turbines are designed to have a specified design life based on fatigue load analysis performed assuming the wind conditions specified in standards, such as International Electrotechnical Commission (IEC) standards. Since wind turbines are finite-life designed (designed taking into account the possibility of failure if repetitive loads are applied more than a finite number of times), estimating the magnitude and number of times of repetitive loads is important. In the estimation of repetitive loads, understanding the characteristics of the wind flowing into the wind turbine, i.e., the wind conditions, is required.

On the other hand, the actual wind conditions at the location of a wind turbine may differ significantly from the assumed wind conditions specified in the standards. If the actual wind conditions are more benign (less turbulent) than the assumed wind conditions and the expected lifetime extended as a result enables the operation period to be longer, more lifetime power generation can be obtained than in the original project plan. Conversely, if the actual wind conditions are more severe (more turbulent) than the assumed wind conditions, measures such as suspension or limitation of the operation to ensure safety must be taken. Since both cases are directly related to the levelized cost of electricity (LCOE), the quantitative understanding of the expected lifetime is a serious concern for power generation companies that operate wind turbines.

Therefore, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) collected long-term wind turbine operation data from customers to estimate the expected life of each wind turbine under actual wind conditions.

This report presents a case study of verifying the integrity of wind turbines during long-term operation by calculating the expected life of the main structural components based on approximately 13 years of actual operation data.

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2. Analysis of wind and operating conditions, and fatigue load analysis

2.1 Analysis of wind and operating conditions

Figure 1 shows an external view and wind turbine layout of the wind farm described in this report. The wind farm consists of 20 MHI 1 MW wind turbines (MWT-1000A [(1)]) located on a ridge line. Since the elevation of the installed location and the topography of the surrounding areas are different for each wind turbine, it is also expected that wind flowing into wind turbines will be different for each of them.

In fatigue load analysis of wind turbines, turbulence intensity (ratio of standard deviation of wind speed to mean wind speed), which is the magnitude of variation of wind speed with time, is particularly important among the various quantities representing wind conditions.

As such, we calculated turbulence intensity (**Figure 2**) using the operational data of all wind turbines accumulated in the supervisory control and data acquisition (SCADA) system, and then identified the characteristic value of turbulence intensity for each wind turbine, using long-term data for approximately 13 years to eliminate the influence of variation (**Figure 3**(a)). As a result, it was found that the turbulence intensity of Unit 16, at which the turbulence is the largest, is 1.4 times that of Unit 1, at which the turbulence is the smallest. Besides, we examined the number of times an overpower alarm, which is issued when the output exceeds the specified value and operation is suspended, was issued (Figure 3(b)), and it was found that the number of alarms was the highest for Unit 16 and relatively low for Unit 1. Since the cause of these alarms is that the pitch control of the wind turbine could not sufficiently follow the large fluctuations in wind speed and the output exceeded the specified value, the number of alarms is considered to be correlated with the magnitude of the turbulence intensity.

Based on the above, we selected Unit 1 and Unit 16 as target wind turbines for the fatigue load analysis, and Unit 10 as a wind turbine with moderate turbulence intensity.

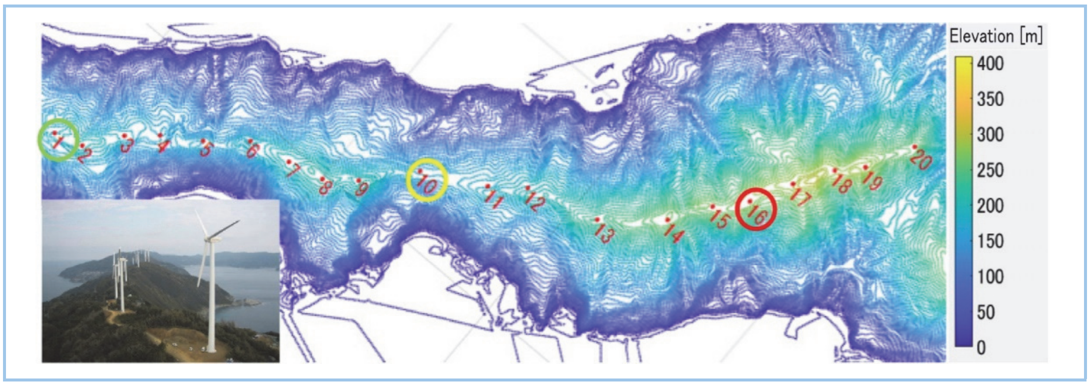

Figure 1 External view and wind turbine layout of wind farm

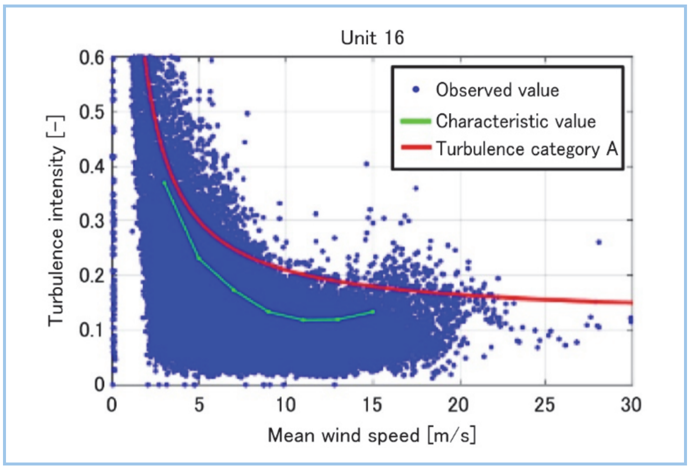

Figure 2 Turbulence intensity (Unit 16 is shown for example)

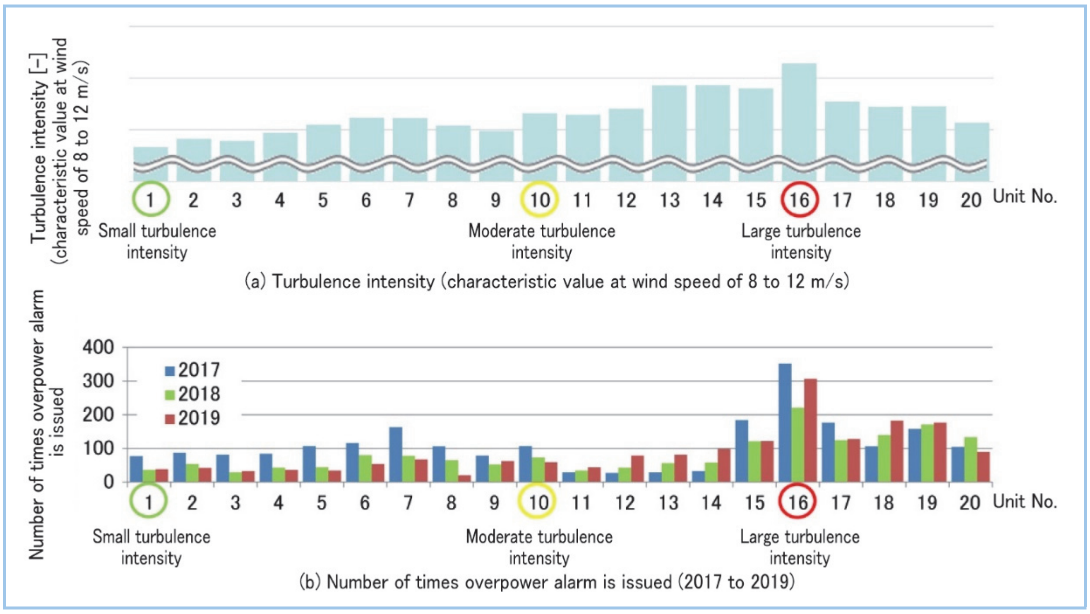

Figure 3 Turbulence intensity and number of times overpower alarm is issued for each wind turbine

2.2 Fatigue load analysis

This section outlines the flow of fatigue load analysis of wind turbines.

Fatigue load of a wind turbine is obtained by time history response simulation using a dynamic response model of the entire wind turbine consisting of blades, nacelle, and tower (**Figure 4**). Prior to the analysis, we prepared a three-component velocity field having a prescribed statistic with respect to a grid plane covering the entire wind turbine, and performed numerical integration sequentially while applying this field to the wind turbine to enable the simulation of the temporal variation and spatial distribution of wind speed. As wind conditions, the vertical wind speed distribution (wind shear), the gradient of the airflow relative to the horizontal plane (flow inclination), and the air density were used in addition to the turbulence intensity described in 2.1.

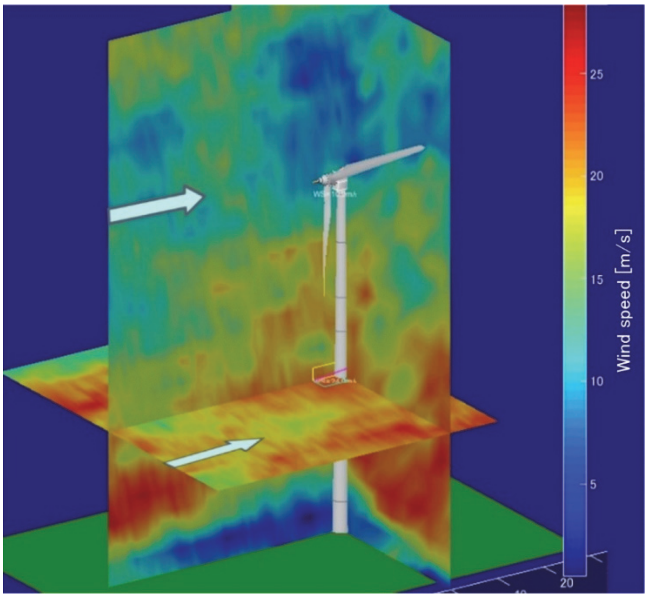

Figure 4 Time history response simulation

Next, we simulated the operating wind speed range (from the cut-in wind speed at which power generation starts to the cut-out wind speed at which power generation stops) in 2 m/s increments, and the stopping operation due to an overpower alarm as described above. Then, we used the rainflow counting method to organize the load time series waveforms of each part of the wind turbine obtained from the simulation as the number of repetitions for each repetitive load amplitude (rainflow matrix), multiplied the number of repetitions by the frequency of occurrence of each wind speed and the number of alarms obtained from the operation data to find the number of repetitions during the evaluation period, and finally considered the material properties of the part being evaluated (m: Wöhler coefficient) in the rainflow matrix to obtain the fatigue equivalent load.

We measure the load on wind turbines located on adjacent similar topography to quantify the increase in fatigue loads due to turbulence in the spatial distribution of wind speed as a load magnification factor. Also at this wind farm, since the increase in fatigue load due to turbulence in the spatial distribution of wind speed which cannot be observed by the nacelle wind speed meter was expected to occur, the load magnification factor was added to improve the accuracy of the fatigue load estimation.

Figure 5 shows the fatigue equivalent load of the hub moments (rotational and fixed coordinates) for m=10 for each wind turbine (ratio to the design fatigue equivalent load). The figure shows that the fatigue equivalent load of Unit 16, at which the turbulence intensity is the largest, was 8% to 27% larger than that of the other wind turbines, and it was estimated that the fatigue equivalent load may exceed the design assumption.

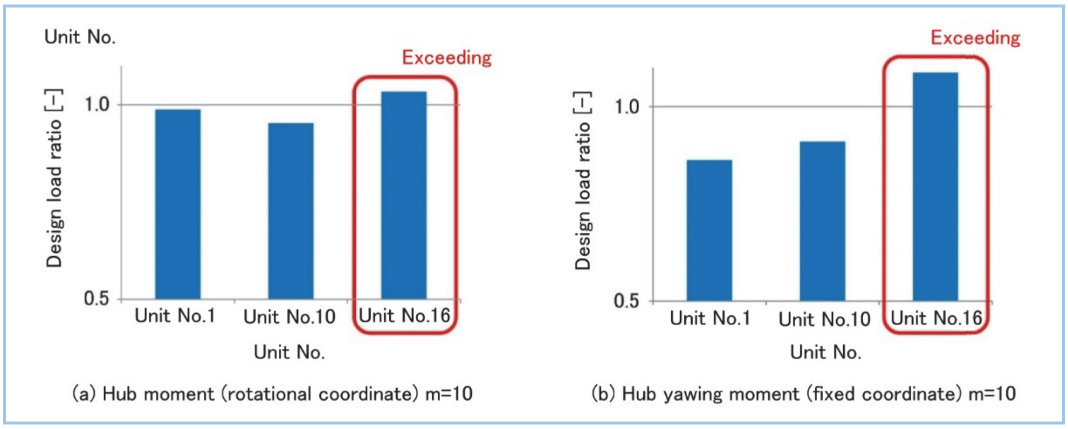

Figure 5 Fatigue equivalent load of hub moment (ratio to design load)

3. Fatigue strength evaluation and countermeasure planning

Stresses in wind turbine components can be expressed as a linear sum of the generated stresses for several load components at the load input point. In most such cases, one or two load components are dominant. Which load component is dominant can be identified by examining the influence coefficient (i.e., a matrix that defines the relationship between the acting load component and the generated stress) prepared for each machine component using the finite element method. Therefore, the increase or decrease in stress can be obtained from the increase or decrease in the dominant load component, and by applying this to the fatigue limit diagram, the expected life, which here refers to the period of operation during which a given survival probability and confidence level can be maintained, can be estimated.

Based on the fatigue equivalent load obtained in the previous section, we estimated the expected lives of the main structural components on the load transfer path (blade, hub, main shaft, main bearing base, and nacelle base plate). **Figure 6** illustrates the components evaluated here.

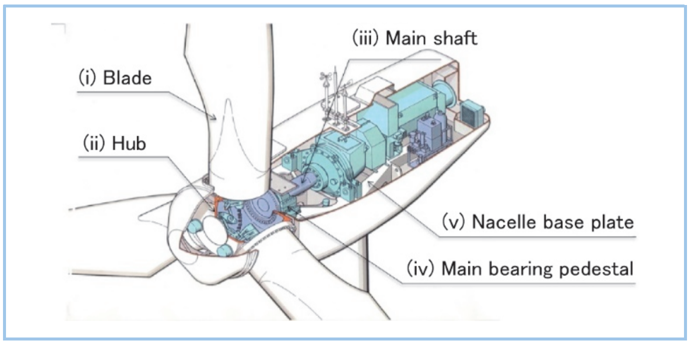

Figure 6 Evaluated components

We selected stress evaluation points (177 points) from the stress contour diagram obtained by the finite element method, extracted the weakest points (11 points), and estimated the expected life using the fatigue equivalent load shown in the previous section. **Figure 7** shows the estimation results. As shown in the figure, it was found that Unit 16, at which the turbulence intensity is the largest, has a part (radius chamfered section of the main bearing pedestal) with a fatigue life of less than the planned operation period, 20 years.

Taking into account the design margin, no damage appeared to occur in practice and there would be no operational problems, but as a measure to ensure more stable operation, we decided to reduce the cut-out wind speed from 25 m/s to 16 m/s (**Figure 8**). As a result, we have the prospect of securing an expected life of more than 20 years.

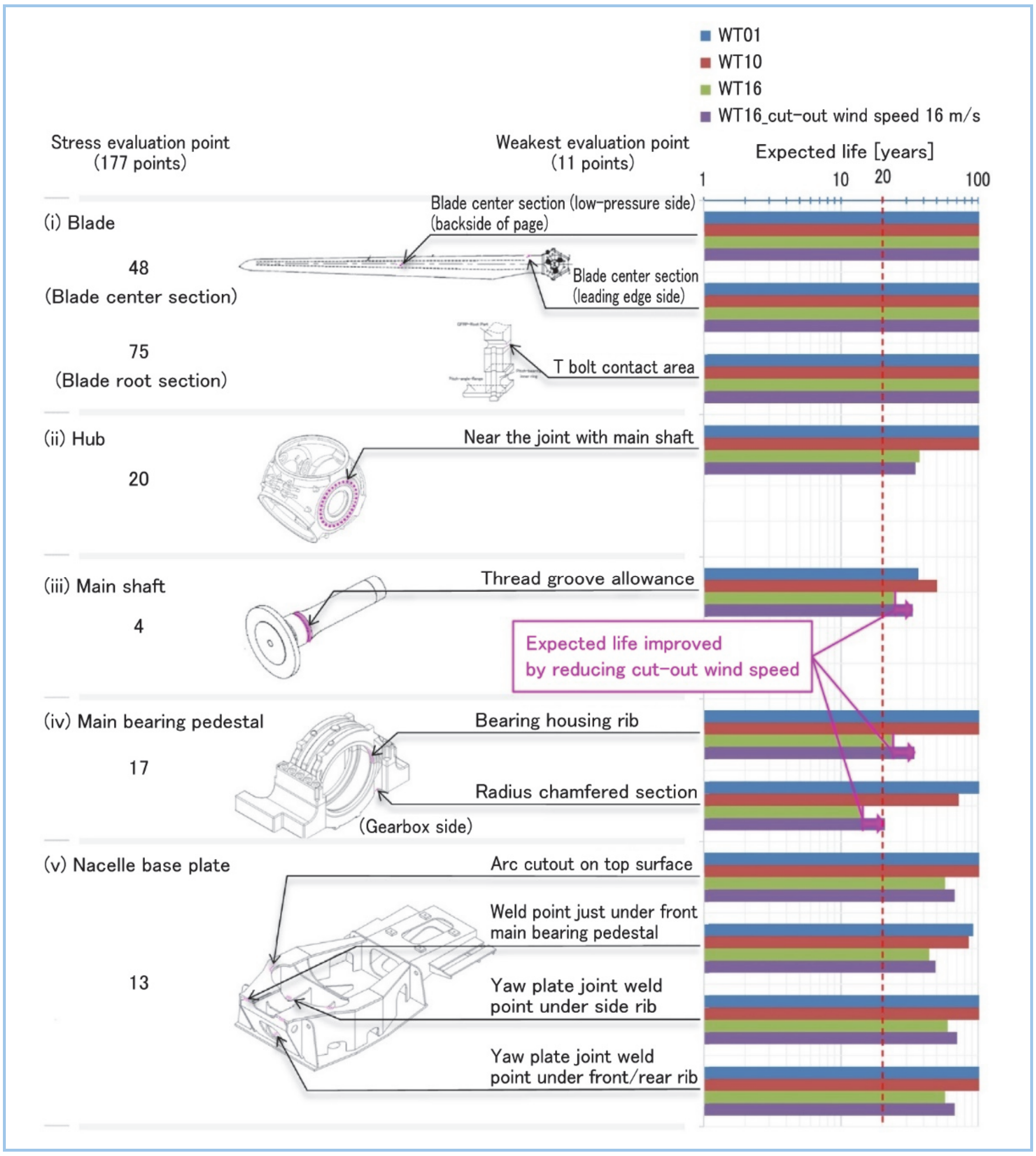

Figure 7 Evaluation results of expected life

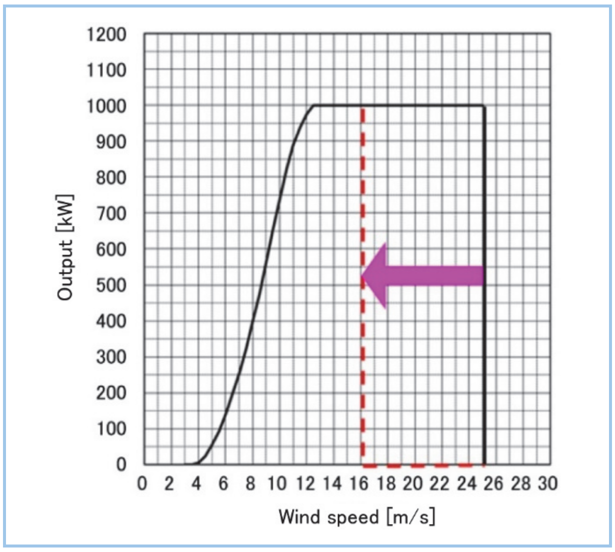

Figure 8 Example of countermeasure: Reduction of cut-out (power generation stop) wind speed (red dotted line)

4. Conclusion

This report exemplified analysis of long-term wind turbine operation data, fatigue load analysis, and fatigue life evaluation, showing that the expected life of wind turbines differs depending on the wind conditions even in the same wind farm in the case study. This report also presented a countermeasure against the expected life less than the planned operation period and its effect.

Since the evaluation presented in this report utilizes wind turbine operation data, it can be applied to the safety evaluation of projects that have been in operation for a certain period of time and to the decision on whether to extend their operation. On the other hand, for new projects for which no operational data are available, it is necessary to evaluate wind conditions that vary for each wind turbine using a method different from that presented in this report.

Specifically, combining unsteady flow analysis of complex topography (**Figure 9**) with time history response simulation (Figure 4) is considered to enable evaluation that reproduces the spatial distribution of wind speed caused by differences in topography around the wind turbine, and this method needs to be discussed in the future.

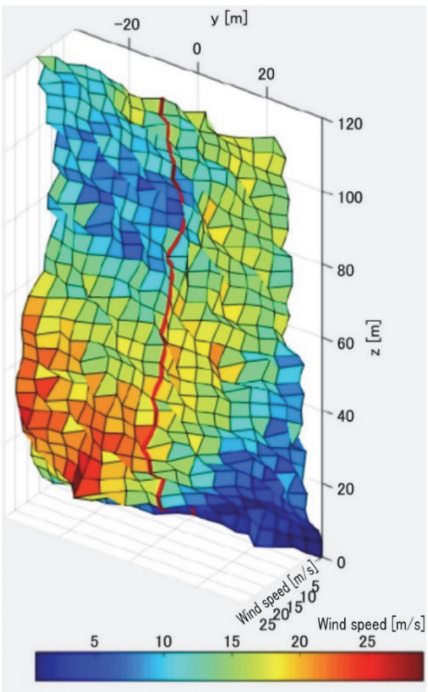

Figure 9 Example of unsteady flow analysis result

The wind turbine data used in this report were provided by Misaki Wind Power Co. and Marubeni Corporation. We would like to express our gratitude to them.

Reference

(1) Ueda et al, Mitsubishi New Wind Turbine, MWT-1000A, Mitsubishi Juko Giho Vol.41 No.1 (2004) p.28 ～29 (in Japanese)