Improvement of Reliability for Main Shaft Bearings of Multi-megawatt Class Wind Turbine Generators

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Many countries around the world are showing a great interest in renewable energy. Wind power, as the most practical renewable energy, has been spreading throughout the world since the year 2000. Recently, installations of wind turbine generators at offshore sites have increased, leading to the introduction of multi-megawatt wind turbine generators. A bigger bearing size and a various type of bearings are employed on multi-MW wind turbines. Our company has developed bearings for the main shaft of multi-megawatt wind turbine generators, and verified reliability for these bearings.

Key Words: *bearing, renewable energy, wind power generation, onshore, offshore, multi-MW*

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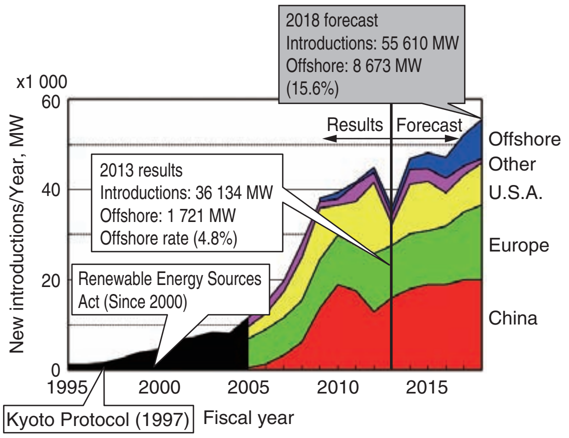
1. Introduction

As renewable energy draws increasing attention throughout the world, the introduction of wind power generation continues to accelerate mainly in Europe, as well as the United States and China. The trend in introduction of new wind turbine generators is shown in **Fig. 1**[1)], revealing a rapid upsurge in new installations since 2005. Furthermore, the introduction of offshore wind turbine generators has expanded since 2010, although this is due to the introduction of mainly multi-megawatt wind turbine generators from the perspective of profitability. This report summarizes the market trends of multi-megawatt wind turbine generators and introduces the actions undertaken by JTEKT to raise the reliability of main shaft bearings.



2018 forecast
Introductions: 55 610 MW
Offshore: 8 673 MW
(15.6%)

2013 results
Introductions: 36 134 MW
Offshore: 1 721 MW
Offshore rate (4.8%)

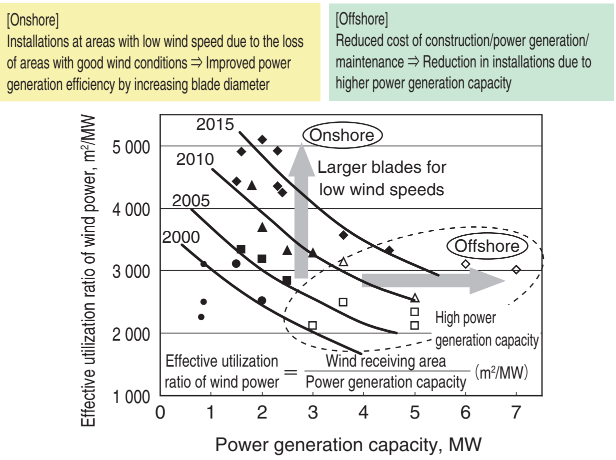
Renewable Energy Sources Act (Since 2000)

Kyoto Protocol (1997)

Fig. 1 Global trends in the introduction of wind turbine generators

2. Market trends of multi-megawatt wind turbine generators

Figure 2 shows the effective utilization ratio[2)] of wind power starting with the first actual introduction of wind power generation in 2000.



[Onshore]
Installations at areas with low wind speed due to the loss of areas with good wind conditions ⇒ Improved power generation efficiency by increasing blade diameter

[Offshore]
Reduced cost of construction/power generation/maintenance ⇒ Reduction in installations due to higher power generation capacity

$$\text{Effective utilization ratio of wind power} = \frac{\text{Wind receiving area}}{\text{Power generation capacity}}\ (\mathrm{m^2/MW})$$

Fig. 2 High availability for wind power of wind turbine generators

Higher value of vertical axis in **Fig. 2**, indicates wind receiving area per power generation capacity means more effective use of wind. **Figure 2** demonstrates the improvement in effective utilization ratio of recent onshore multi-megawatt wind turbine generators through the enlargement of blade diameter, as well as the shift to high power generation capacity (large wind turbine generators) for offshore generators.

<Onshore wind turbine generators>

Despite the rise in offshore wind turbine generators in the past few years, the majority of generators are installed on land. The following activities to increase power generation capacity and curb power generation costs are conducted in onshore market.

(1) In Europe, as areas with good wind conditions have already been occupied, the installation of generators in areas with low wind speed is expanding due to the enlargement of wind turbine blades.

(2) Securement of power generation amount by increasing power generation capacity (Increased introductions of wind turbine generators of 2 MW and above)

(3) Extension of power generation time by improving reliability

<Offshore wind turbine generators>

As the ocean has more stable wind conditions and less turbulence than land, large scale wind farms are being installed at shallow offshore locations, mainly in Europe. Recently, there have been ongoing efforts to improve the profitability of such installations.

(1) Reduction of equipment costs and power generation costs by increasing the power generation capacity of offshore wind turbine generators.
(Due to accessibility by boat and easier transport of large wind turbine generators compared with land transport)

(2) Expansion of installable locations by switching from shallow coastal areas (fixed foundation type) to deep sea areas (floating type).

The development and commercialization of large wind turbine generators over 2 MW is accelerating both onshore and offshore, as described above. **Table 1** shows the typical specifications of a multi-megawatt wind turbine generator.

Wind turbine generators over 2 MW often have the same structure as wind turbine generators of the 2 MW class. **Table 2** shows the characteristics of main shaft bearings for this class of generator[3)].

Table 1 Specifications for wind turbine generators over 2 MW

Generation capacity (MW)	Blade diameter (m)	Transmission type	Generator type
2.3	82	Direct	Synchronous
	113	Gearbox	Inductive
2.4	92	Gearbox	Inductive
2.5	114	Gearbox	Inductive
2.5	100	Gearbox	Inductive
2.75/2.85	103	Gearbox	Inductive
3.0	101	Direct	Synchronous
	90/112	Gearbox	Inductive
3.4	104	Gearbox	Inductive
3.6	120	Gearbox	Inductive
4.5/5.0	128	Gearbox	Synchronous
6.0	154	Direct	Synchronous
8.0	164	Direct	Synchronous

The increased weight and size of each component for wind turbine generators over 3 MW poses problems for their procurement and transportability.

In recent years, a gearbox with a low speed by decreasing speed ratio has been developed which combines the strengths of types 1-3 listed in **Table 2**, along with a hybrid type used in small synchronous power generators. JTEKT has collaborated with customers to complete the design, development and evaluations of main shaft bearings for these developed products. The results of these activities are introduced below.

3. Lightweight technology utilizing CAE analysis

Figure 3 shows a drive train which is the target of JTEKT development activities. The main shaft consists of an assembled single row tapered roller bearing (Front: ϕ1 550 × ϕ1 920 × 200, Rear: ϕ1 400 ×ϕ1 700 × 160), and the gearbox is directly connected to the main shaft. The bearings, shaft and housing have been designed thinner structure in order to reduce weight.

The bearing has become more lightweight due to a thinner structure, although this has also become more susceptible of elastic deformation caused by the support load of blades and rotor as well as input torque, which has led to concerns regarding the bearing's reliability to satisfy required service life. Therefore, JTEKT verifies how rolling element load distribution of each bearing has changed in elastic condition through FEM analysis. **Figure 4** shows the analysis model.

Distortion in the rear housing, which does not occur in normal investigation, was confirmed in the results of this analysis model shown in **Fig. 5** when running torque (Mx) was applied. The results of the bearing rolling element load distribution are shown in **Fig. 6**, revealing a large difference in the rolling element load distribution of the rear bearing when running torque is applied due to distortion of the housing. A bearing which sufficiently fulfills required service life (20 years, 175 000 hours) was designed in consideration to these loads.

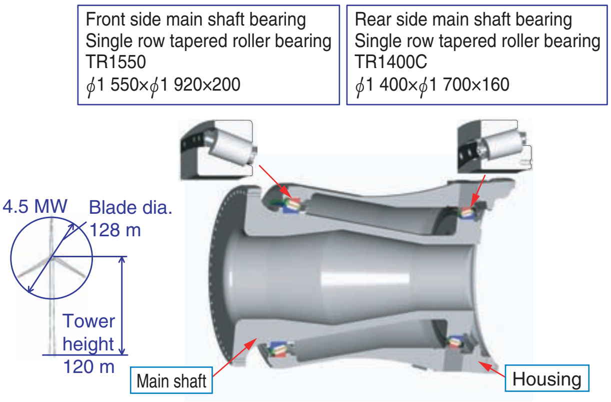
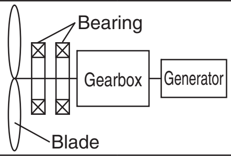
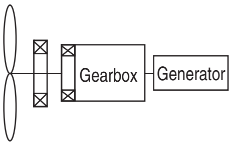
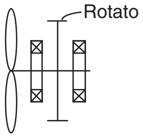
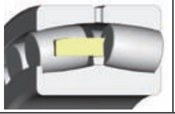
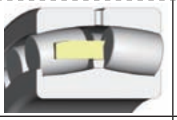
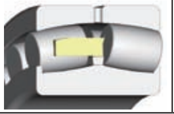
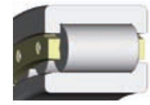


Fig. 3 Structure of drive train for multi-MW wind turbine generators

Table 2 Characteristics of drive train and main shaft bearings for 2 MW wind turbine generators

Type		1		2		3	
Wind turbine generator	Rough structural drawing						
	Characteristics	• Configured from a main shaft, gearbox, generator • Wind load supported by two main shaft bearings (separate housing)		• Configured from a main shaft, gearbox, generator • Wind load supported by two bearings, the one for the main shaft and the other for the gearbox carrier (separate housing)		• Generator rotor supported by the main shaft bearings • Wind load supported by two main shaft bearings (integrated housing) • No gear box	
	Generator type	Induction generator		Induction generator		Synchronous generator	
	Cost	○		◎		△	
	Reliability	○		○		◎	
	Efficiency	◎		◎		○	
Main shaft bearing	Location	Front	Rear	Front	Rear	Front	Rear
		Free side	Fixed side	Fixed side	• Supported by the gear box carrier bearing • Bearing type differs between gear box manufacturers	Fixed side	Free side
	Structural drawing	Spherical roller bearings 	Spherical roller bearings 	Spherical roller bearings 		Double row tapered roller bearings 	Cylindrical roller bearings 
	Number	2		1		2	
	Installation ability	◎	◎	◎	–	△	△
	Radial load performance	◎	◎	◎		◎	◎
	Axial load performance	○	○	○	–	◎	Not applicable
	Vibration resistance	○	○	○		◎ (if preloading)	○
	Allowable misalignment on inner ring/outer ring	◎	◎	◎	–	△	△
	Axial direction allowance	△	Not applicable	Not applicable	–	Not applicable	◎
Remarks		• Problem with reliability of gearbox • Problem of electric pitting of generator bearing		• Problem with reliability of gearbox • Problem of electric pitting of generator bearing		• High cost compared to induction generator • High reliability as there is no gearbox	

◎: Excellent, ○: Good, △: Possible, ×: Not possible

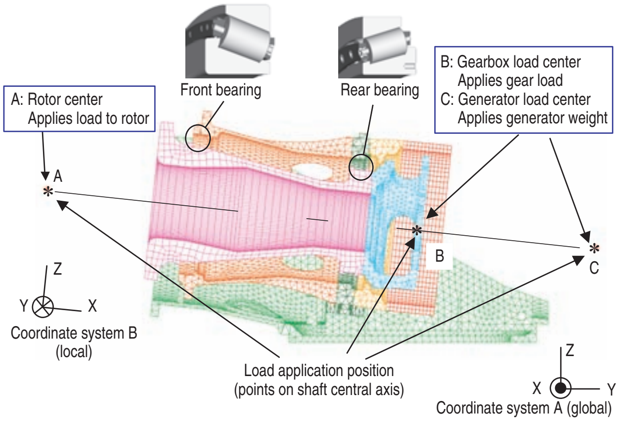


Fig. 4 Structure of FEM analysis

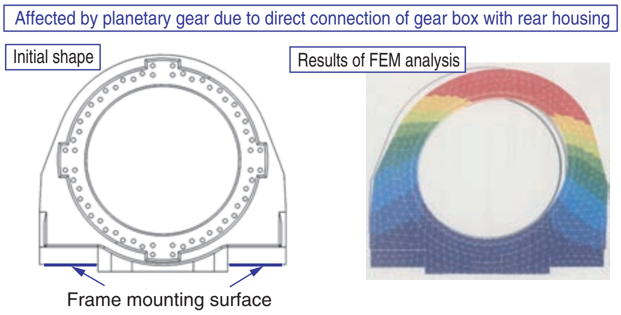


Fig. 5 FEM analysis results for Rear Housing

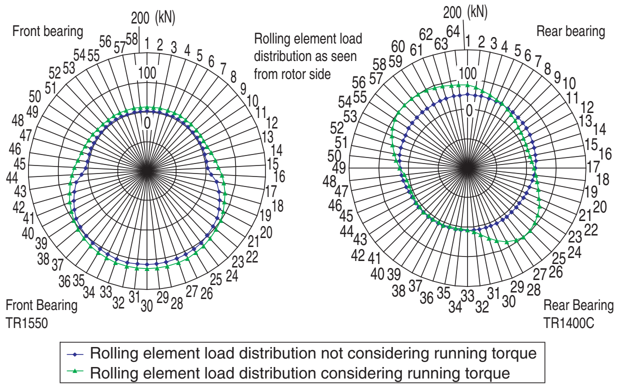


Fig. 6 Bearing rolling element load distribution

As seen from the FEM analysis results, exact verification of service life requires consideration of not only bearing deformation, but also the housing, base frame and gear box.

4. Measurement technology for rolling element load distribution

Calibration must be performed due to the possibility of variation between FEM analysis results and actual load. In addition to FEM analysis, this project incorporated the measurement of rolling element load distribution utilizing a contraction scale size actual machine model (scale size model), along with calibration by measuring housing deformation using an actual customer machine which served as a bench testing machine.

4. 1 2/5 scale size model testing machine

A 2/5 scale size model testing machine, shown in **Fig. 7**, was introduced in order to establish rolling element load measurement technology with high reliability. The shaft, housing and bearings, which greatly effect rolling element load, were designed and manufactured at a proportionate size. The bearings were given the following characteristics to enable the application of loads equivalent to those of an actual wind turbine.

(1) Able to apply loads (Fx, Fy, Fz) in all three axial directions (XYZ) in positions equivalent to the center of a rotor of an actual wind turbine

(2) Able to apply static torsion to the rear housing to replicate deformation of the rear housing as shown in **Fig. 5**

4. 2 Rolling element load measurement method

To measure the rolling element load of a bearing, a method[4)] exists where a notch groove is applied into the inner or outer ring of the bearing and a strain gauge attached to the machined groove. Focusing on the fact that the bearings for this project were hollow rolling elements, we developed a method[5)] to detect strain which occurs on the bore surface of hollow rolling elements. **Figure 8** shows the developed measuring mechanism. Strain gauges were attached to two locations along the length of the rolling element. The strain gauge output was stored via fixture in a micromini datalogger united with the rolling element. After measurement was completed and the bearing became stationary, the data was able to be retrieved and analyzed.

For calibration, this measurement system was integrated into the rear bearings of the scale size model. A relationship diagram concerning rolling element load and strain was created prior to calibration by applying only pure axial load using a vertical testing machine.

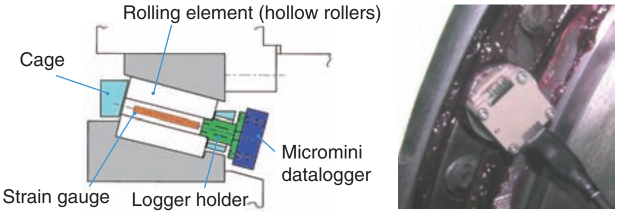


Fig. 8 Measurement method of rolling element load

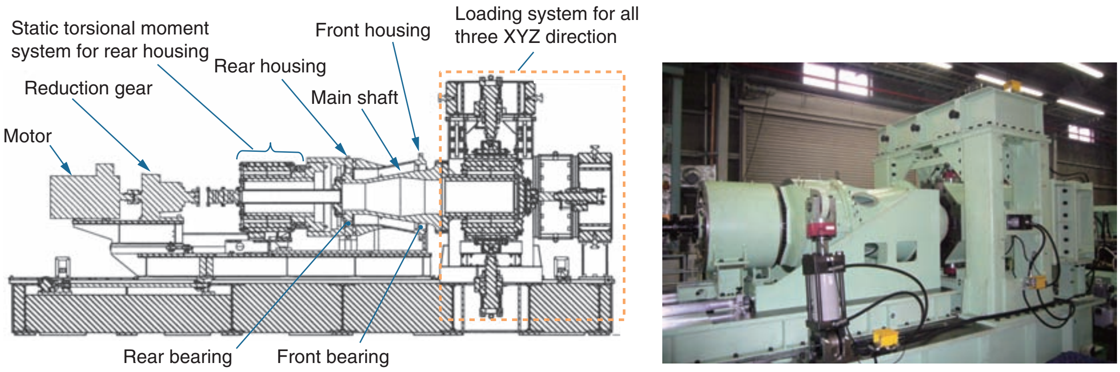


Fig. 7 Scale size model test machine

Figure 9 shows the results of the actual measurement of rolling element load using the scale size model testing machine and the rolling element load determined by FEM analysis. The load conditions for measurement and calculation are shown in **Table 3**. The results in **Fig. 9** demonstrate high similarity between the actual measured values and calculated values for the rolling element load and its distribution. It was also found that, in addition to the bearings, housing and shaft, the inclusion of the base frame (a fixed component of the housing) within the calculation model is important in the process of raising conformance.

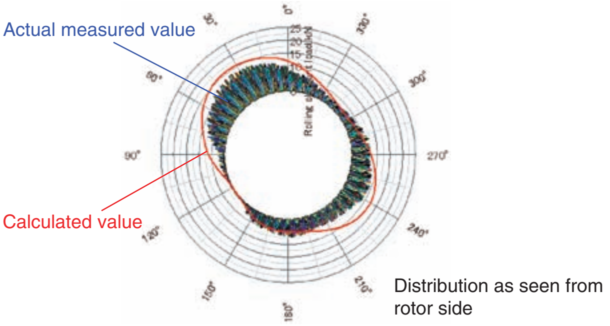
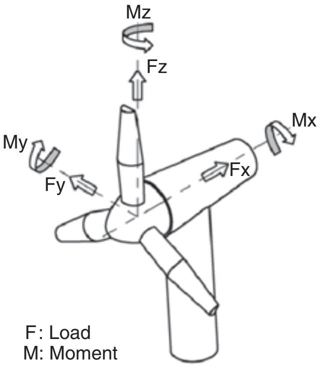


Fig. 9 Comparison of rolling element load measurement results and calculation results

Table 3 Load conditions



Fx	102 kN
Fy	2 kN
Fz	−126 kN
Mx	228 kN·m

Furthermore, a similar comparison of the actual measurements and the FEM calculation values was conducted on the deformation and maximum principle strain of the rear housing outer periphery face in order to evaluate consistency with the actual size bearings. This comparison was conducted using an actual customer machine which served as a bench testing machine. To measure the maximum principle strain, rosette gauges were attached at 11 locations on the outer periphery face of the rear housing. The amount of displacement was measured along with strain by installing nine laser displacement meters along the outer periphery face of the rear housing. The results of these measurements are shown in **Figs. 10** and **11**. The evaluation using the bench testing machine also confirmed that the actual measured values and calculated values were highly similar.

From these results, we were able to determine that the calculated results of the FEM analysis by JTEKT are reliable and can be sufficiently utilized as a means of verifying bearing service life.

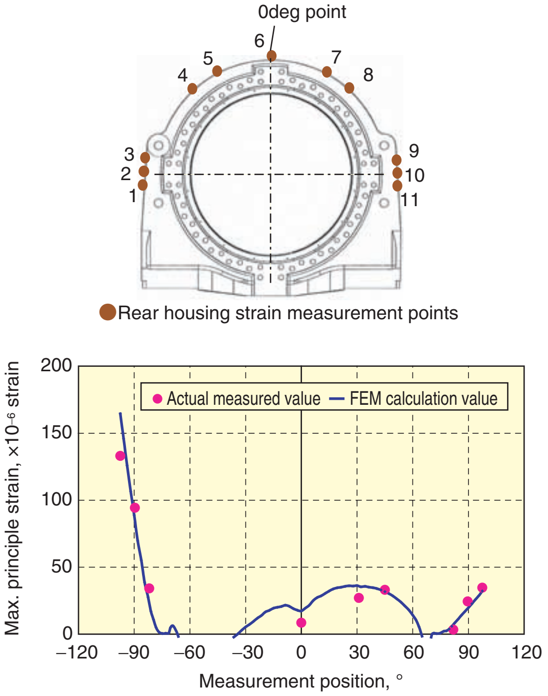


Fig. 10 Comparison of max. principle strain measurement results and calculation results

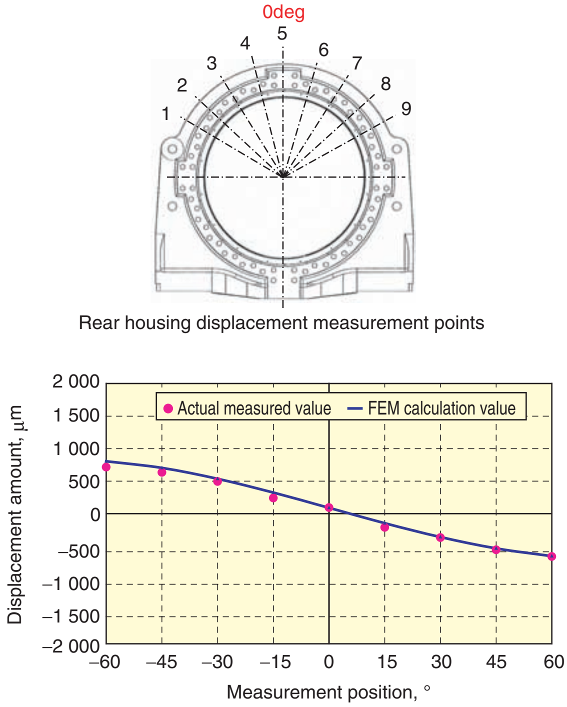


Fig. 11 Comparison of deformation measurement results and calculation results

5. Conclusion

Although there are great expectations for wind power generation as a renewable energy, less than ten years have passed since its full-scale commercialization, and its reliability has not been sufficiently verified. JTEKT has been engaged in reducing the weight of wind turbine generators through optimal bearing design and improving reliability using evaluation equipment with the evaluation machines and technologies introduced in this report. In addition, our company has introduced evaluation equipment able to evaluate actual size bearings for multi-megawatt wind turbine generators. Using this equipment, JTEKT will reduce development time for customers and contribute to the advancement of future sources of renewable energy.

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