

Rolling Bearings for Wind Turbine Generator

Y. KURASHITA

Interest in natural energy, which emits no global-warming-causing carbon dioxide, has been increasing since the Kyoto Protocol came into effect. The use of wind turbine generators is growing rapidly, particularly in Europe, and the power generation capacity of such generators has been increasing year by year. Recently the development of large-sized wind turbine generators having a power capacity of 3 MW or more and a blade diameter of 100 meters or more is advancing, requiring the use of larger rolling bearings.

Key Words: wind power, gearbox, generator, spherical roller bearing, non-conductivity, ceramic

1. Introduction

In recent years, the utilization of natural energy, which does not emit carbon dioxide causing the global warming, has increasingly attracted interest. Especially, the wind turbine generator (here-in-after referred to as wind turbine) has been increasingly used mainly in Europe and the power generation capacity has increased year by year. **Figure 1** shows the transition¹⁾ of the installed capacity of the wind power generation in the world. In this report, the characteristics and selection criteria of the rolling bearing for the wind turbine, which requires high reliability during the required life of more than 20 years, are introduced.

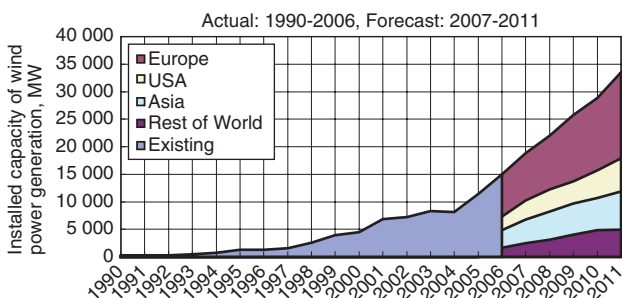


Fig. 1 Transition of installed capacity of wind power generation in the world

2. Structure and Types of Wind Turbine

In general, the wind turbine has a structure of: receiving the wind with blades, rotating the main shaft through the rotor, accelerating that rotation up to the rotational speed needed for power generation by gearbox and generating power by the generator (Asynchronous generator type). The structure of the wind turbine is shown in **Fig. 2**.

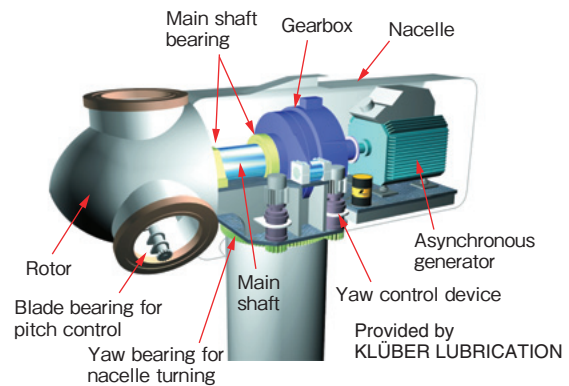


Fig. 2 Structure of wind turbine²⁾

The mainstream of the current wind turbine is the asynchronous generator with gearbox, which the capacity of the wind power generation is 1.0 ~ 2.0 MW. However, there is also another type of wind turbines which uses the synchronous generator without gearbox. The wind turbine has been designed on a larger scale in order to obtain a higher power capacity. The average amount of the power generation per wind turbine in 2006 was 3.3 times larger than that in 1995. **Figure 3** shows the average amount of the power generation per wind turbine in the world. Recently, the large-sized models, as shown in **Table 1**, have been developed. In the wind turbines, many bearings are used. Here the bearings for the main shaft, the gearbox and the generator are introduced.

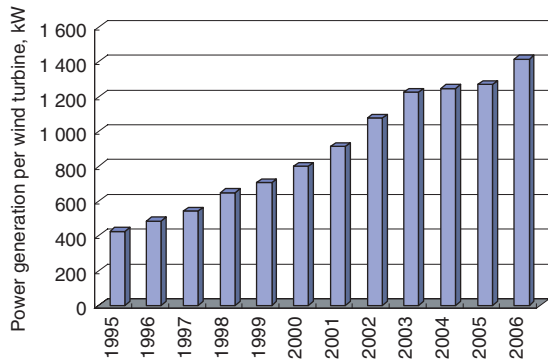


Fig. 3 Average amount of power generation per wind turbine in the world

Table 1 Large-sized models under development at each manufacturer

Power generation capacity	Blade diameter	Transmission system	Generator
2.4 MW	92 m	Gearbox	Asynchronous
2.5 MW	90 m	Gearbox	Asynchronous
3 MW	90 m	Gearbox	Synchronous
	90 m	Gearbox	Asynchronous
	94 m	Gearbox	Asynchronous
3.6 MW	107 m	Gearbox	Asynchronous
	111 m	Gearbox	Asynchronous
4.2 MW	110 m	Gearbox	Asynchronous
4.5 MW	114 m	Direct	Synchronous
	120 m	Gearbox	Asynchronous
5 MW	116 m	Gearbox	Synchronous
	126 m	Gearbox	Asynchronous

3. Main Shaft Bearing

The main shaft bearing is mounted at important positions where the load by the wind force through the rotor is applied and the rotational torque is transmitted to the gearbox, also there are various types. The bearings used mainly for the main shaft are spherical roller bearings, which are excellent in alignment ability and load carrying capacity. Figure 4 shows a 3-dimensional model of the main shaft bearing (spherical roller bearing) and Table 2 shows application examples of the main shaft bearings.

3.1 Application Conditions

The load on the main shaft of the wind turbine fluctuates by the second and changes in a wide range from a light load up to a heavy load. The load at the time of pausing must be considered. Figure 5 shows a directional diagram of the load and the moment on the center of the rotor. Figure 6 shows an example of application conditions when selecting bearings.

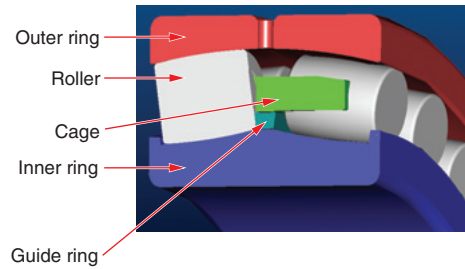


Fig. 4 Main shaft bearing (spherical roller bearing)

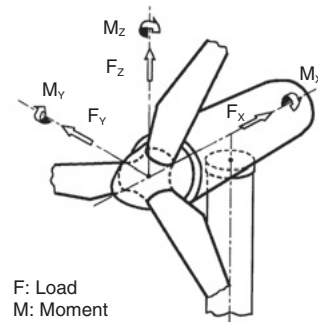


Fig. 5 Directional diagram of load and moment

3.2 Bearing Selection

For the bearing selection, a guideline³⁾ issued by Germanischer Lloyd (here-in-after referred to as GL), which is an international audit and inspection agency, is applied as a standard.

3.2.1 Static Strength

$$f_0 = C_0/P_0$$

Criterion: $f_0 \geq 2.0$

Here, f_0 : Static safety factor, C_0 : Basic static load rating (kN), P_0 : Maximum static equivalent load (kN)

3.2.2 Dynamic Strength and Study of Bearing Life

The equivalent load is calculated from the fluctuating load presented and the bearing life is calculated based on ISO method.

At this time, the correction coefficient with consideration of the bearing internal specifications and the stiffness of the shaft and the housing etc., which is required by GL, is obtained with JTEKT's shaft system analysis program, and then the bearing life is calculated with the following life formula.

$$L_h = a_x \cdot a_y \cdot \frac{10^6}{60 \cdot n} \cdot \left[\frac{C}{P} \right]^p \quad (h)$$

Here,

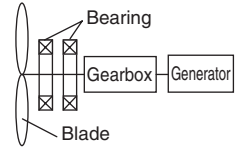
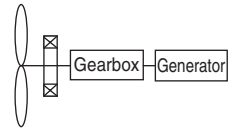
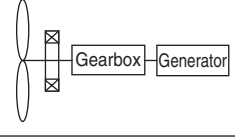
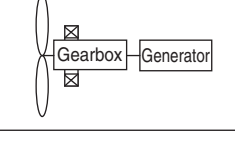
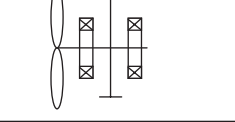
a_x : Correction coefficient (① ~ ⑤ as follows)

a_y : Lubrication coefficient (⑥ as follows)

n : Average rotational speed (min^{-1})

C : Basic dynamic load rating (kN)

Table 2 Application examples of main shaft bearings

Type	Structure	Bearing at blade side	Bearing at generator side	Characteristics
1		SRB SRB CRB	SRB CRB 2-row TRB	Asynchronous generator Main shaft is supported by two bearings General structure
2		SRB	–	Asynchronous generator Load at rear side is supported by bearing in gearbox
3		2-row TRB	–	Asynchronous generator Supported by blade side bearing only
4		2-row TRB	–	Asynchronous generator Unitizing main shaft bearing with gearbox
5		SRB TRB 2-row TRB CRB	CRB TRB CRB 2-row TRB	Synchronous generator (Gearless type)

SRB: Spherical roller bearing CRB: Cylindrical roller bearing

2-row TRB: Double-row tapered roller bearing TRB: Single-row tapered roller bearing

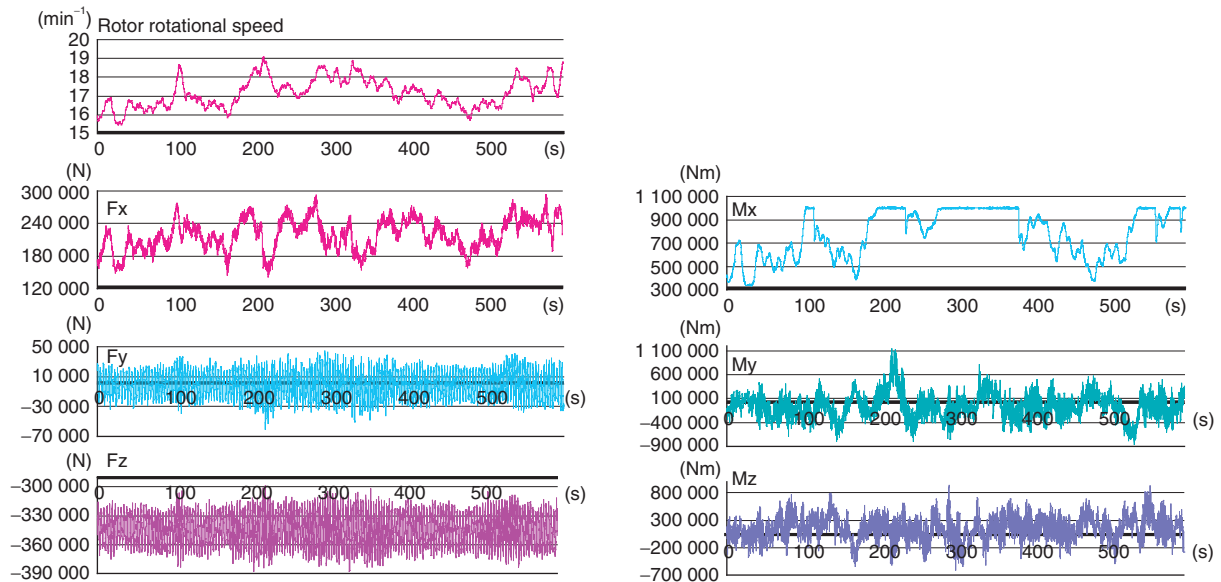


Fig. 6 Example of application conditions when selecting bearings: 600 sec. (rotor speed, load and moment)

P : Average dynamic equivalent load (kN)

p : For ball bearing $p = 3$

For roller bearing $p = 10/3$

Items to be considered as correction coefficients (required by GL)

- ① Bearing internal specifications
 - ② Bearing internal clearance during operation
 - ③ Stiffness of bearing, shaft and housing
 - ④ Rolling element load distribution
 - ⑤ Contact stress distribution along roller length in considering with roller and raceway profiles
 - ⑥ Lubricant viscosity and cleanliness during operation
- Criterion: More than 20 years (175 000 h)

3. 2. 3 Case Study

Based on the study results with JTEKT's shaft system analysis program⁴⁾ and FEM analysis, the specifications such as the bearing internal specifications, the clearance and the crowning of the rolling element are fixed so that the above static and dynamic strength become maximum. As a case study, the result of FEM analysis (housing stiffness) is shown in **Fig. 7**.

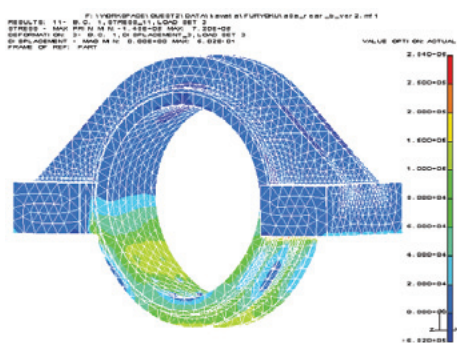


Fig. 7 FEM analysis result (housing stiffness)

4. Bearing for Gearbox

The gearbox consists of a carrier, planetary gears, a low speed shaft (sun gear), an intermediate shaft and a high speed shaft. **Figure 8** shows a general structure of the gearbox (1-stage planetary + 2-stage parallel) and **Table 3** shows the bearing types applied. In recent years, the type of the 2-stage planetary gear or the combination type (multibrid) of the synchronous generator and the gearbox is applied from the viewpoint of weight reduction.

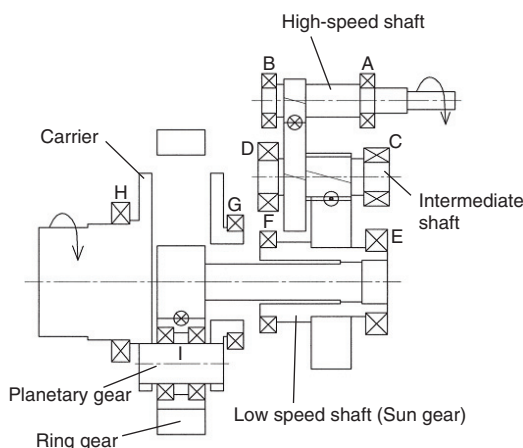


Fig. 8 Structure of gearbox

Table 3 Bearing types

	Application part	Bearing type
A	High-speed shaft	CRB, TRB, SRB, TRBX2
B		TRB + CRB, CRB + BB*
C	Intermediate shaft	CRB, SRB
D		TRBX2, CRB + BB*
E	Low speed shaft	CRB, SRB, TRBX2
F	(Sun gear)	2-row TRB
I	Planetary gear	CRBX2, SRBX2, TRBX2
G	Carrier	CRB, SRB, TRB, BB
H		

CRB: Cylindrical roller bearing

TRB: Single-row tapered roller bearing

SRB: Spherical roller bearing

BB: Single-row deep groove ball bearing

BB*: 4-point contact ball bearing

2-row TRB: Double-row tapered roller bearing

4. 1 Application Conditions

It is necessary to select the bearings based on the rotating torque (M_x) (**Fig. 6**), which fluctuates by the second with the same procedure as that for the main shaft.

4. 2 Bearing Selection

For the bearing selection, American Gear Manufacturers Association (here-in-after referred to as AGMA⁵⁾) shows its selection standard. Like the case for the main shaft, the study of the bearing life is required with consideration of the bearing internal specifications, the shaft and the housing stiffness and the lubrication condition. According to AGMA standard, the maximum contact pressure between the roller and raceway and the required bearing life (**Table 4**) are regulated for each application part.

Table 4 Maximum contact pressure and required life

Application part	Maximum contact pressure, MPa	Required life, h
High-speed shaft	1 300	30 000
Intermediate shaft	1 650	40 000
Low speed shaft (Sun gear)	1 650	80 000
Planetary gear	1 450	100 000
Carrier	Not specified	100 000

4. 3 Case Study

The optimum bearing specifications are determined with the gearbox analysis program by the same study that is made for the main shaft bearing. An example of the analysis model is shown in **Fig. 9**.

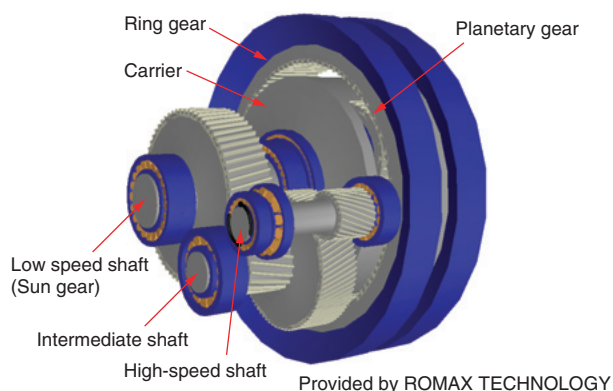


Fig. 9 Example of 3-D analysis model of gearbox⁶⁾

4. 4 Attention Points in Bearing Selection for Gearbox

4. 4. 1 Stiffness of Planetary Gear

The design of the planetary gear (**Fig. 10**) is required to consider its stiffness. In case of weak stiffness of the planetary gear, the deformation as shown in **Fig. 11** will occur and there is a possibility to reduce the lifetime of the bearing which is mounted inside of the planetary gear.

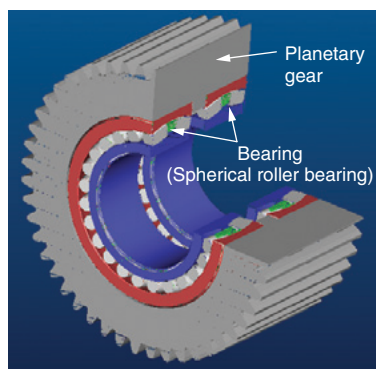


Fig. 10 3-D model of planetary gear

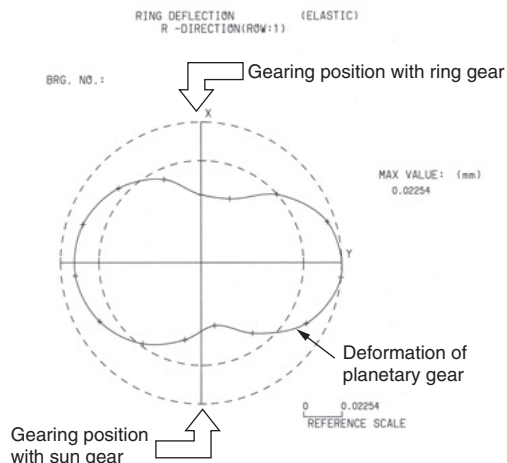


Fig. 11 Results of planetary gear stiffness study

4. 4. 2 Use in Contaminated Oil

As the bearings for the gearbox are lubricated in the circulating system of the same lubricating oil as used for the gears, this may result in a shorter life of the bearings due to contamination of wear particles into the lubricating oil. For these cases, the KE bearing^{7), 8)} developed by JTEKT with improved dent resistance has been recommended. Performance of this bearing in the contaminated oil has been greatly improved due to higher hardness of rolling surface and an optimized retained austenite amount. The condition of the life test of the KE bearings and the results are shown in **Table 5** and **Fig. 12**, respectively, and the dent resistance is shown in **Fig. 13**. However, as the cleanliness of the lubricating oil is specified by AGMA, it is most important to maintain the lubricating oil properly.

Table 5 Test conditions

Boundary dimensions of test bearing, mm	$\phi 30 \times \phi 72 \times 20.75$	
Radial load, kN	20.6	
Axial load, kN	13.7	
Rotational speed, min ⁻¹	2 000	
Lubrication conditions	Contaminated oil*1	Clean oil

*1 Amount of foreign particles in contaminated oil

Hardness, Hv	830	700
Average particle diameter, μm	27	125
Amount, g/L	0.55	0.55

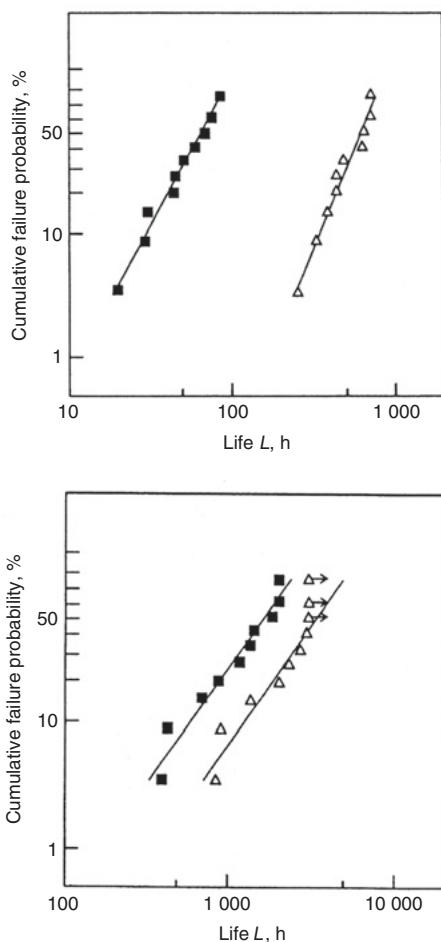


Fig. 12 Life characteristics of KE bearing

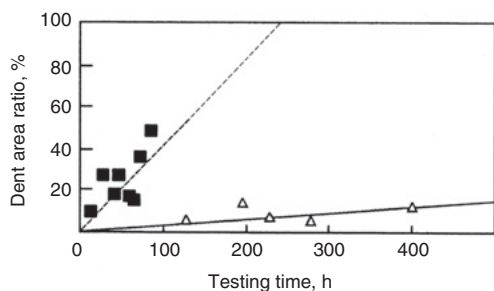


Fig. 13 Dent resistance of KE bearing (Comparison results of specimens tested in contaminated oil shown in Fig. 12)

5. Bearings for Generator

Concerning the bearings used for the generators, damage due to electric pitting (the phenomenon that a spark occurs through a very thin oil film on the rolling contact area and the surface partially melts when an electric current passes through the inside of the bearing during rotation) is likely to occur, which is one of the causes of failures. In order to avoid the damage, Insulated Hybrid Ceramic Bearings⁹⁾ (Fig. 14), in which the rolling elements made of ceramic with superior insulation capability are used, has been adopted. In addition to the above characteristics, the reduction of the maintenance cost (man-hour) due to a longer grease life can be expected because of its excellent characteristics of low temperature rise (Fig. 15).



Fig. 14 Insulated Hybrid Ceramic Bearings

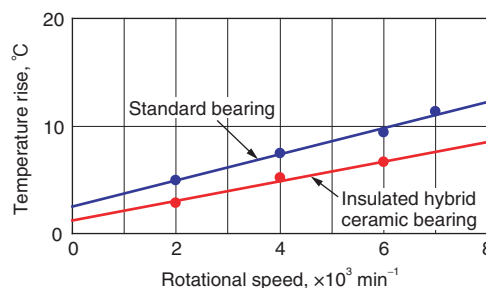


Fig. 15 Characteristics of temperature rise in Insulated Hybrid Ceramic Bearings

6. Conclusion

While the trend for larger sized wind turbines will continue in the future, it becomes more important to make the optimized design of the bearings for required functions with high reliability in order to satisfy the needs for reducing weight and downsizing. JTEKT would like to contribute to the global environmental protection by development and supply of the products in compliance with these needs.

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Y. KURASHITA *

* *Industrial Machinery Application Engineering
Department, Bearing & Driveline Operations
Headquarters*