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SELF-ALIGNING TAPERED ROLLER BEARING PILLOW BLOCK FOR WIND TURBINE GENERATOR'S MAIN SHAFT ROTOR SUPPORT

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Introduction

This paper reviews the benefits of applying an alternative bearing type at the main shaft pillow block position of a modular style wind turbine generator (WTG). Analysis shows that compared with conventional pillow blocks using spherical roller bearings, an improved style pillow block can be substituted that has superior features and operating characteristics, making it ideally suited for use on larger multi-megawatt wind turbine generators being designed today for tomorrow's global energy needs.

Conventional Main Shaft Pillow Block Design with Spherical Roller Bearing

The bearing most commonly specified for use in main shaft pillow blocks is the two row spherical roller bearing (abbreviated SRB) as shown in Fig. 1. This bearing design continues to serve the wind energy industry reasonably well; however, it needs to be recognized that under the unique combination of wind loads, this bearing type does not optimize performance.

FIGURE 1 – TYPICAL MAIN SHAFT PILLOW BLOCK WITH SRB

The SRB is generally supplied from the bearing factory with sufficient radial clearance (usually CN which in the example to follow using bearing part number 230/600CAW33 would be .31 mm to .48 mm radial clearance). Inner races are generally mounted on the main shaft with tight fitting practice specification p6 while outer races are generally mounted into the housing block with loose fitting practice specification H7. Average mounted radial clearance in this example is .29 mm.

Mounted clearance plays a major role in developing the bearing spring stiffness in both the radial and axial directions. Therefore, the radial translation of the main shaft axis and the axial shaft movement are ultimately affected by the initial clearances and fitting practices specified.

Minimizing radial translation and axial shaft movement have beneficial effects on both the bearing and system performance; but care must be taken while using the SRB not to specify radial clearance that is too tight. Reduction of all clearance from thermal effects during operation can lead to excessive bearing heat generation, reduction of lubricant film in the raceway contacts, reduction of bearing fatigue life, raceway surface galling and in advanced cases a bearing seizure. This is typically not the case because many pillow blocks are set with generous clearances to ensure this does not happen.

Typical Main Shaft Bearing Support Configuration

Figure 2 shows a schematic of a modular design. The pillow block is generally located adjacent the rotor and is bolted to the base frame of the nacelle. It supports the main shaft at the end adjacent the rotor. The opposite end of the main shaft is usually supported by the input shaft bearings in the gearbox.

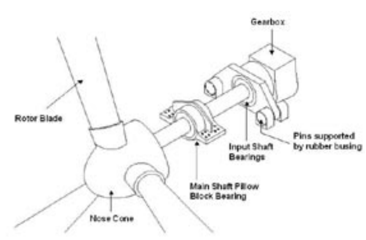

FIGURE 2 – MAIN SHAFT GENERAL ARRANGEMENT

The gearbox itself is most often mounted on 2 pins, one on each side of the gearbox, that are surrounded by hard rubber bushings which in turn are captured in cradle mountings affixed to the frame of the nacelle. This semi-flexible arrangement helps maintain alignment during operation when the main shaft deflects and the gearbox and nacelle frame deflect. But the ability of this cradle arrangement has limitations to how much it can compensate for the initial misalignment at assembly between the axes of the pillow block and transmission input shaft. Therefore, the SRB has become the popular bearing style over the years to insure that the remainder of misalignment can be accommodated by the bearing raceways.

Typical Main Shaft Free Body Diagram, Applied Forces and Bearing Reactions

Figure 3 shows a load schematic imposed by the rotor blades on a typical wind turbine. During operation, loads arrive in the form of a radial load from rotor mass, side loading from the wind, rotor thrust and over turning moments induced by the blades in 2 planes.

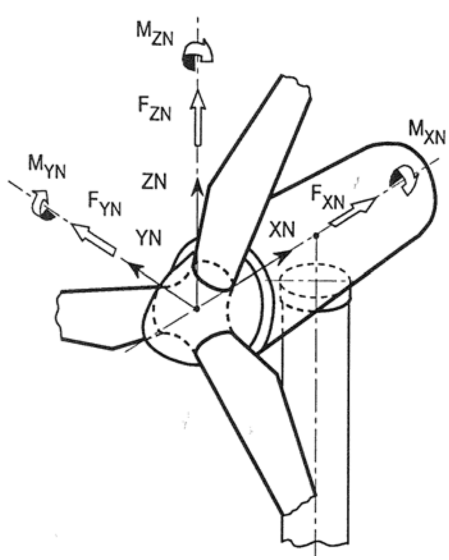

FIGURE 3 – ROTOR LOAD SCHEMATIC

Bearing support points are in the pillow block and on the input shaft of the gearbox. Resolving the bearing reactions becomes a statically indeterminent problem, since many points of support each with their own spring stiffness are involved. FEA techniques are often applied in an attempt to account for all the deflections that influence the load distribution among the bearing rows. It is generally recognized for most application conditions, that all the loading in the pillow block SRB is taken by the row closest to the gearbox. The SRB bearing row adjacent the rotor often carries little or no load. This is due to several factors including:

(1) Applying rubber bushings on the side of the gear box of sufficient compressive ability to allow the gearbox to shift axially along the main shaft axis without offering too much resistance

(2) By specifying axial clearance in the input shaft cylindrical roller bearings greater than the expected shift permitted by the pillow block SRB

(3) By specifying gearbox input shaft bearings that have sufficient thrust capacity to manage whatever thrust loads enter the input

This consideration can be avoided altogether if the pillow block bearing can be set with minimal clearance so that main shaft axial movement under load is substantially less than the gearbox input shaft bearing axial clearance. With proper consideration given to the design and assembly of the main shaft and gearbox, this can be accomplished readily when a preloaded two row TRB is used in the pillow block.

Advanced Main Shaft Pillow Block Design with Self Aligning Tapered Roller Bearing with Internal Preload

Application of the self-aligning, preloaded tapered roller bearing (TRB) in a main shaft pillow block represents a very sensible and sophisticated alternative to the SRB design. Especially as the Wind Energy Industry moves to larger and more demanding equipment, the designer should consider whatever options are available to mitigate potential failure modes.

Figures 4A and 4B show 2 variations of one such alternative. Both of these designs are unitized (cannot be disassembled) to protect the integrated seals during handling. The design in Figure 4A has full complements of rollers, and the design in figure 4B includes less rollers and bearing retainers. The selection of which design to use should be based upon required bearing L-10. Advantages using either of these designs include:

(1) Factory set - preloaded bearing setting for maximizing support stiffness.

(2) Significantly improved load distribution to both bearing rows during operation.

(3) Increased bearing fatigue life.

(4) Substantially reduced thrust loading to the gearbox input shaft bearings.

(5) Elimination of false brinelling and subsequent failure modes.

(6) Improved alignment of sealing elements and sealing surfaces.

(7) Alignment capability equal to a pillow block equipped with a spherical roller bearing.

(8) Unitized construction for simplifying assembly.

(9) Matched component construction achieving a solid interface on the spherical alignment and support surface.

(10) Factory supplied, high durability seals.

(11) Engineered surfaces on rolling elements available to improve L-10 and resistance to false brinelling.

FIGURE 4A – PILLOW BLOCK WITH FULL COMPLEMENT PRE-LOADED TAPERED ROLLER BEARING

FIGURE 4B – PILLOW BLOCK WITH STANDARD PRELOADED TAPERED ROLLER BEARING

Installation Procedures for the TRB Pillow Block

Unlike the SRB pillow block design that is generally assembled onto the main shaft as individual components, the TRB pillow block is pressed onto the main shaft as a pre-assembled unit. Once the TRB pillow block and main shaft are assembled together, the following procedure would follow:

(1) Install the pillowblock onto the mainshaft completely against the shaft shoulder and clamp the bearing races tightly with a suitable device to

ensure all axial clearance between the bearing faces and shoulder is removed, thereby establishing the pre-set preload on the bearing.

(2) This sub-assembly is then inserted into the input of the transmission. The weight of the main shaft will tend to push the gearbox input shaft towards the rear of the gearbox by whatever the input shaft bearing clearance will permit.

(3) Bolt the pillow block to the nacelle frame, aligning main shaft and gearbox axes within specifications. At this stage, the spherical socket inside the pillow block has compensated for the mounting misalignment, so that bearing reactions are not affected by it.

(4) The final stage is to tighten the tapered locking collar on the input of the transmission taking care to insure that the axial clearance is shared between the input shaft bearings somewhat evenly. Following this procedure, the preloaded tapered roller bearing in the pillow block will reduce axial movement of the main shaft significantly enough to prevent wind thrust from loading the gearbox input shaft bearings (oftentimes NCF cylindrical roller bearings are suitable for moderate, but not heavy thrust loading.)

Analytical Comparison During Operation of Main Shaft Pillows Blocks Equipped with Spherical and Tapered Roller Bearings

In making this comparison, a 27 condition-loading schedule for a 1.5 MW WTG was derived from a more comprehensive schedule. This schedule describes the radial loads in two planes Fy and Fz, moments in two planes My and Mz and wind thrust Fx. See Fig. 5.

CONDITION NUMBER	FX (NEWTONS)	FY (NEWTONS)	FZ (NEWTONS)	MY (NEWTON – METERS)	MZ (NEWTON – METERS)	PERCENT OF TIME	SUM % TIME
1	161,000	-351,000	-12,000	-330,000	-434,000	7.09	
4	161,000	-351,000	-12,000	0	-434,000	2.77	
7	161,000	-351,000	-12,000	344,000	-434,000	11.72	
10	161,000	-351,000	0	-330,000	-434,000	1.68	
13	161,000	-351,000	0	0	-434,000	0.65	56.41
16	161,000	-351,000	0	344,000	-434,000	2.77	
19	161,000	-351,000	15,000	-330,000	-434,000	9.77	
22	161,000	-351,000	15,000	0	-434,000	3.81	
25	161,000	-351,000	15,000	344,000	-434,000	16.15	
2	161,000	-351,000	-12,0000	-330,000	0	0.21	
5	161,000	-351,000	-12,0000	0	0	0.08	
8	161,000	-351,000	-12,0000	344,000	0	0.34	
11	161,000	-351,000	0	-330,000	0	0.05	
14	161,000	-351,000	0	0	0	0.02	1.65
17	161,000	-351,000	0	344,000	0	0.08	
20	161,000	-351,000	15,000	-330,000	0	0.29	
23	161,000	-351,000	15,000	0	0	0.11	
26	161,000	-351,000	15,000	344,000	0	0.47	
3	161,000	-351,000	-12,000	-330,000	228,000	5.27	
6	161,000	-351,000	-12,000	0	228,000	2.05	
9	161,000	-351,000	-12,000	344,000	228,000	8.7	
12	161,000	-351,000	0	-330,000	228,000	1.24	
15	161,000	-351,000	0	0	228,000	0.49	41.88
18	161,000	-351,000	0	344,000	228,000	2.06	
21	161,000	-351,000	15,000	-330,000	228,000	7.25	
24	161,000	-351,000	15,000	0	228,000	2.83	
27	161,000	-351,000	15,000	344,000	228,000	11.99	
						100	100

FIGURE 5 – LOADING SCHEDULE FOR A TYPICAL 1.5 MW WIND TURBINE ROTOR (VALUES ROUNDED)

Free body diagrams are shown for both configurations in Figs. 6A and 6B. A quick observation can be made that the bearing centers are substantially different between the 2 arrangements, changing therefore the distribution of reactions among the bearing rows. Spread between the 2 tapered roller bearing rows is substantially wide and places one of the load centers closer to the rotor which tends to decrease the maximum bending stress in the main shaft.

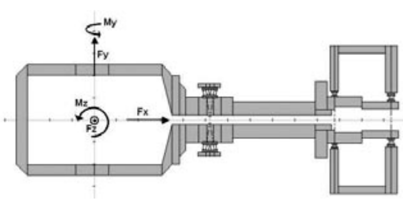

FIGURE 6A – GENERAL ARRANGEMENT USING THE SRB PILLOW BLOCK

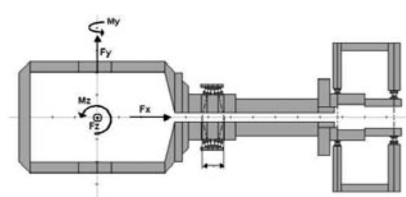

FIGURE 6B – GENERAL ARRANGEMENT USING THE TRB PILLOW BLOCK

Table 1 shows a comparison of the SRB and TRB specifications.

A review of this table shows that effort was made to compare fairly equivalent and similar sized bearings that can fit within the pillow block housings.

Lines 2 and 3 of the table show sizes and bearing capacities respectively. On line 4, C1 is the bearing rating for 1 million revolutions. These rating values are so close that one might expect the bearing performances would compare closely. In fact though, the bearing performance can be significantly different when more precise advanced life calculation methods are applied.

	SPHERICAL ROLLER BEARING	TAPERED ROLLER BEARING
SERIES IDENTIFICATION	230 / 600 CAW33	LM280200
BORE X OD X WIDTH	600 X 870 X 200	600 X 870 X 300
DYNAMIC RATING C1	5770 KN	5,335 KN
SPECIFIED CLEARANCE	0.20 – 0.35 MM	PRELOAD
AVG. MOUNTED SETTING	0.16 MM RADIAL CLEARANCE	.2 MM PRELOAD
ADVANCED BRG. L-10	640,000 HOURS	12,044,000 HOURS

TABLE 1

While the SRB is mounted with an average of 0.16 mm radial clearance, the average mounted setting for the tapered roller bearing can be optimized conveniently and safely at .20 mm axial preload. Preload refers to initial setting of the bearing in which the elastic contacts between rolling elements and raceways are pre-stressed to remove all initial clearance inside the TRB. The end result of using preload is to stiffen the bearing supports and maintain more rollers in contact during operation, reducing the bearing stresses.

Using an advanced bearing system & life analysis tool called SYSX (proprietary software developed by the authors' company), different and more accurate bearing lives are calculated and graphed in Figure 7. The results indicate that the TRB calculates more life in all conditions, and using Miner's rule to combine these results, the SRB now calculates 640,000 hours L-10 and the TRB now calculates 12,044,000 hours, shown in Table 1.

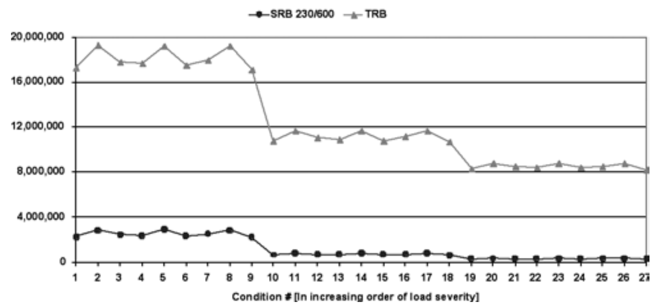

FIGURE 7 – ADVANCED BEARING LIFE RESULTS. LOADING CONDITIONS ALONG THE HORIZONTAL AXIS ARE LIGHTEST AT THE LEFT AND HEAVIEST AT THE RIGHT.

Figure 8 shows that the outboardinboard row of the SRB is virtually unloaded throughout all the loading conditions; whereas, each row of the TRB carries loading in all conditions. Radial loading on the outboard TRB row is higher because the slope of the deflected main shaft creates cross contact load zones in the TRB. In essence, the TRB resists shaft bending at the expense of inducing more radial loading on the inboard outboard row.

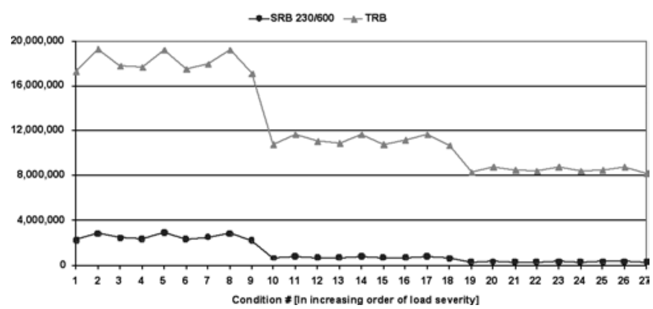

FIGURE 8 – BEARING RADIAL REACTIONS

However, Fig. 9 shows that a very sufficient load zone is maintained on this row under these loading conditions.

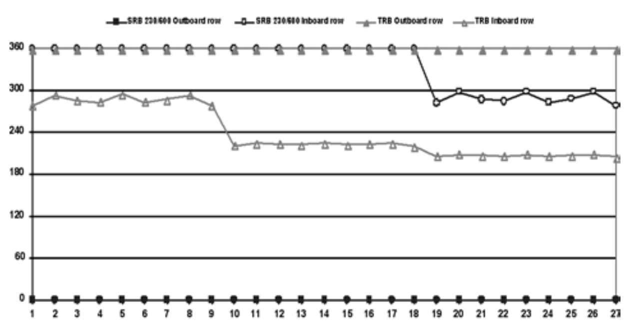

FIGURE 9 – COMPARISON OF LOAD ZONES

By maintaining better load zones, it can be noted in Fig. 10 that the contact stresses are typically lower for the TRB in the conditions that dominate the life calculation using Miner's rule.

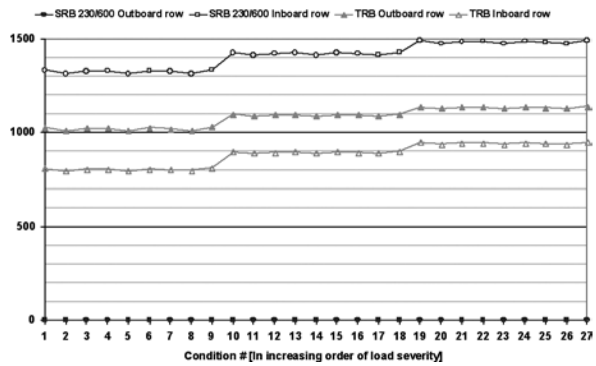

FIGURE 10 – INNER RACEWAY CENTER STRESS

Most importantly, Fig. 11 shows that the TRB will substantially reduce axial shaft movement, roughly from 1.4 mm using the SRB, to only 0.2 mm using the preloaded TRB design. This greatly reduces the opportunity for wind thrust to load the gearbox input shaft bearings.

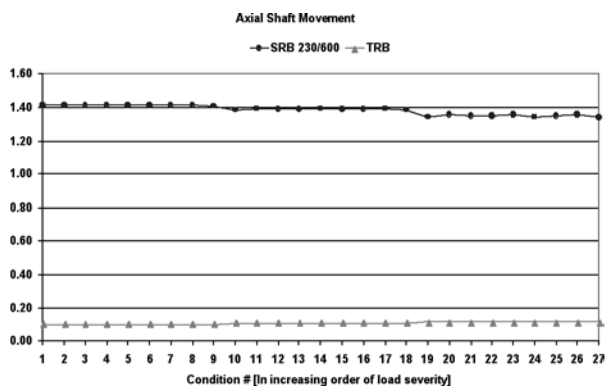

FIGURE 11 – AXIAL SHAFT MOVEMENT

So in summary, a substantial list of performance improvements can be generated that favor the use of a self-aligning tapered roller bearing equipped pillow block.

Analytical Comparison During Shutdown Of Main Shaft Pillow Blocks Equipped With Spherical And Tapered Roller Bearings

When the WTG is not in operation, the rotor is often brought to a complete stand still and locked in position with the parking brake. Common circumstances include shutdown for maintenance and shutdown during high-speed wind conditions. During this time, the rotor blades continue to react with the wind forces and produce static bearing reactions. The rotor blades will also tremor and transmit vibrations downstream through the remainder of the drivetrain. Such vibration can induce a mode of bearing raceway damage called false brinelling. See Fig. 12.

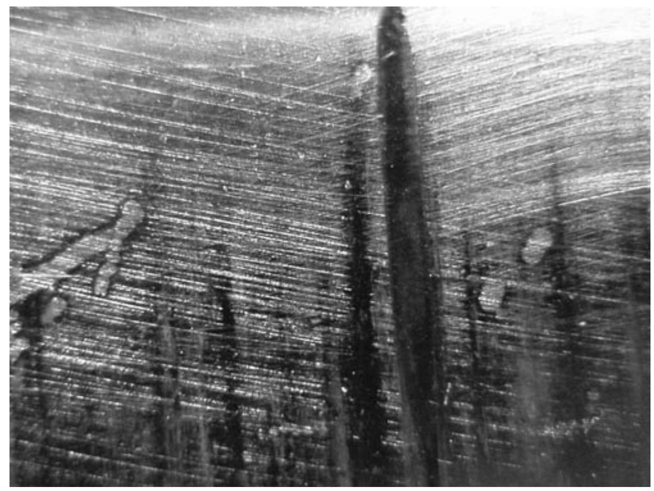

FIGURE 12 – BEARING RACEWAY WITH FALSE BRINELLING DAMAGE

False brinelling is generally associated with adhesive wear in the Hertizian contacts of bearing raceways and gears. In the case of a WTG pillow block, the blade vibration induces minute movements between the bearing rollers and raceways. This rubbing action quickly voids the contact of any protective lubricant, and creates dry Hertizian contact that intensifies the pressure between the contacting surface asperities. Quickly, adhesive wear between contacting asperities generates a series of roller spaced lines on the raceways. If left to propagate, extra main shaft vibration, audible noise and even early bearing fatigue can result.

Solutions to false brinelling in WTG's include keeping the rotor idling in slow speed wind conditions and specification of lubricants having the proper anti-wear and/or extreme pressure additives. Another solution is to reduce axial movement inside the bearing by reducing the bearing clearance. At the main shaft pillow block position, preload in the TRB pillow block will greatly reduce the axial shaft movement during shutdown as wind thrust is applied and then relieved.

The graph in Fig. 13 shows the magnitude of the axial movements for reversing thrust loads of varying magnitudes while the weight of the rotor is kept constant. For various magnitudes of reversing thrust, the graph shows that axial movement within the TRB TRB is significantly less than it is for the SRB, and therefore, the potential for false brinelling is greatly reduced.

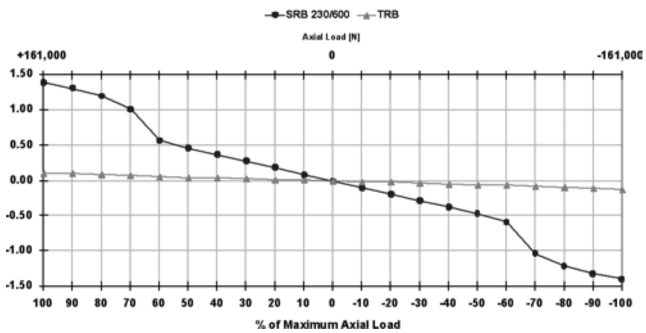

FIGURE 13 – AXIAL MOVEMENT INFLUENCING FALSE BRINELLING

For example, if thrust varies +/-40% of the nominal wind thrust, the SRB moves axially from positive 0.45 mm to negative 0.45 mm, for a total movement of 0.90 mm. For this same condition, the TRB moves axially from positive .05 mm to negative 0.05 mm, or for a total of 0.10 mm.

If the wind gusts high enough to produce the nominal thrust load of 160,000 N, then relaxes back to zero, total axial shaft movement permitted by the SRB design is 1.45 mm while the TRB TRB bearing design only permits .31 mm (a 4.7 to 1 decrease). Momentum effects would make the improvement even greater since the preload in the TRB design will halt axial shaft movement as the system returns to an equilibrium point, while the SRB clearance would permit the system more freedom to glide over a longer distance to a haltto return past the center position of the bearing.

Conclusion

While the SRB pillow block design has provided adequate performance in many small and intermediate sized wind turbine generators, there have been sporadic reports of damage leading to very expensive down time and repair. The concern grows over how much the designer can extrapolate from today's experience to much larger, more massive wind turbines. A number of criteria have been analyzed in this paper; and it has been demonstrated that a preloaded TRB solution can certainly provide improvement in all aspects considered.

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