TIMKEN

Technical Article

Improving Bearing Life
in Wind Turbine Main Shafts and Gearboxes

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Improving Bearing Life
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- The need for larger megawatt (MW) class turbines has increased, but scaling up traditional turbine designs is not the answer.
- Wind operators can select upgraded spherical roller bearings (SRB) to improve bearing life.
- Another option is a conversion upgrade using a tapered double inner (TDI) roller bearing.

Abstract

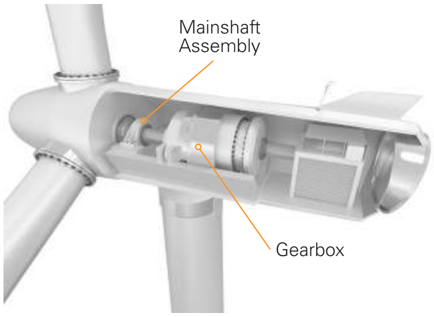
During the early days of wind turbine development, the sub-megawatt class turbines typically used Spherical Roller Bearings (SRBs) in the mainshaft position with significant success. As the development need for larger megawatt (MW) class turbines increased, our competitors' SRB mainshaft bearing was "scaled up" in size and design. However, documented field failures in mainshaft SRBs for multi-MW class underscored its limitations for this application.

With a mature supply chain of large bore Tapered Roller Bearings (TRBs), the industry trend is the conversion of SRBs to TRBs in turbines greater than 1MW. The table below highlights typical mainshaft design configurations.

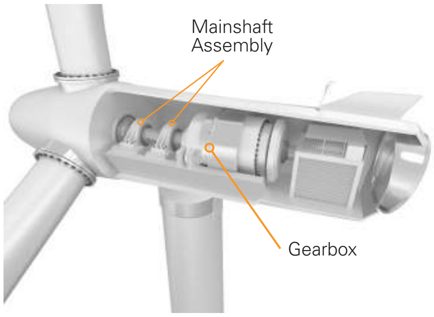
Design Firms:	< 1.5MW	2 - 5MW	5MW+
Vestas	SRB	SRB	2TS
GE Wind	SRB	SRB/TRB	
Gamesa	SRB	SRB	2TS
Enercon	TDI + CRB	TDI + CRB	TDO
Mingyang	SRB	TDO	
Suzlon	SRB	SRB	
Guodian	SRB	SRB	TDO
Siemens	SRB	SRB/TDO	TDO
Acciona (Nordex)	SRB	SRB	
Goldwind	TDI + CRB	TDO	TDO
Dongfang	SRB	2TS	2TS
CSIC	SRB	SRB	TDO
RePower (Senvion)	SRB	SRB	
Alstom Power	2TS	2TS	
Northern Power Systems	TDI + CRB	2TS	
Wind Tech	2TS		
Romax	TDI + CRB		
Aerodyn	TDO		

Tapered Roller Bearing: TS = Tapered Single; TDI = Tapered Double Inner;
TDO = Tapered Double Outer

Figure 1:



Three-Point Mount Mainshaft Arrangement



Four-Point Mount Mainshaft Arrangement

I. Current State: Turbine Design

As measured by total MW, modular wind turbine designs dominate the industry and commonly use SRBs to support and carry the mainshaft loads. Classified as three and four point designs, Figure 1 illustrates the nomenclature.

The three-point mount in the left hand illustration has a single support of the dynamic loading with a single 2-row SRB in front of the gearbox. There are two additional support points located at the gearbox torque arms, which yield three-support points. Advantages of the three-point mount arrangement utilizing SRBs include:

- Shorter nacelle package with reduced turbine mass
- High system deflection and misalignment capability
- Commercially economic and mature supply chain

These advantages are offset by distinct disadvantages. For example, during significant thrust loading from wind, the downwind (DW) row of the SRB is fully loaded while the upwind (UW) row is typically unloaded. When combined with an ever-dynamic wind regime, the load zone size and location changes with an increased and unintended load transmission into the gearbox. Due to the required radial internal clearance (RIC) within the SRB, the axial deflections and moment loads transfer to the gearbox planetary carrier bearings.

As the SRB wears during operation, this additional loading affects planetary gear meshes and planetary gears and bearing loads. The performance of the single SRB designs has experienced significant field failures much earlier than the intended design life of 20 to 25 years. These early failures have significantly increased field repair and lifetime operation cost.

Similarly, the four-point mount uses two gearbox torque arms to help support the mainshaft with two 2-row SRBs for the mainshaft support; which yield four-support points. Normally the UW floating SRB predominately carries radial loads while the DW fixed SRB carries the majority of the wind thrust loading. This is an improvement over the three-point mount design, but there is increasing field evidence of premature damage to the DW fixed SRB location similar to that of the three-point mount design.

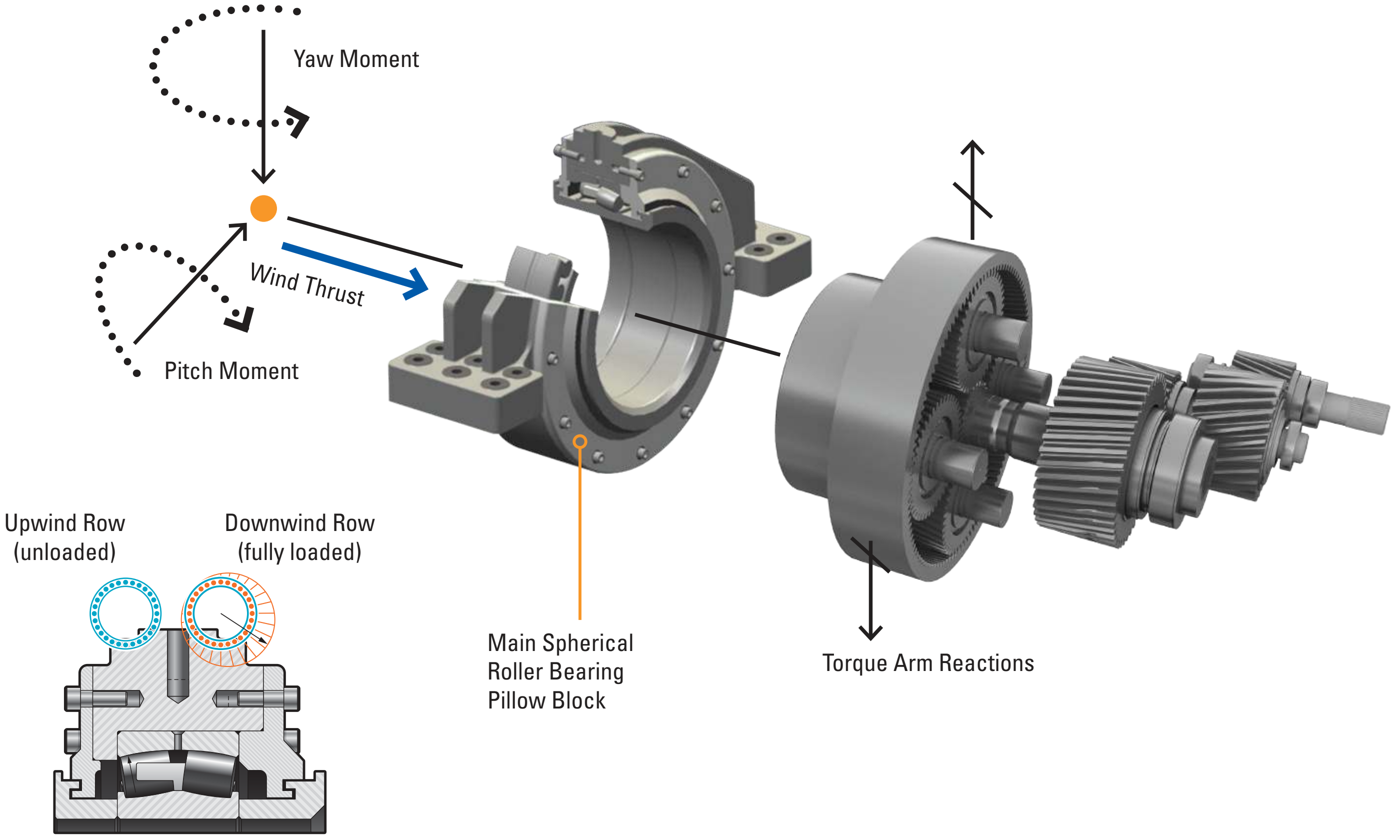
II. What is Driving the Change?

It is widely accepted that use of a single SRB in the mainshaft position in multi-MW class turbines is not the preferred design solution. The primary driver for a change in design philosophy is the premature damage of the SRBs seen in operation. The damage limiting the mainshaft SRB is not classic fatigue failure, but primarily micropitting leading to surface fatigue and wear.

The combination of dynamic loading and RIC results in these SRBs exhibiting unseating effects, abnormal load distribution between rows, roller skewing, high cage stress, excessive heat generation, low lambda conditions, Heathcoat slip, and roller smearing. An official maximum limit has not been established, but a conventional ratio of permissible thrust to radial loading deemed acceptable for 2-row SRB is approximately 25%.

Thrust loading in the application is many times significantly greater than this limit. With these high axial loads, only the DW row supports both the radial and thrust loading while the UW row is completely unloaded. This is a significant contributor to the micropitting damage and results in a less than ideal operating condition. Figure 2 depicts the unequal load sharing.

Figure 2: Applied Loads and Unequal Load Sharing



Field observations reveal that all three-point mount turbines are experiencing the same common damage modes, regardless of manufacturer. Although the damage takes longer to develop, many four-point mount arrangements are experiencing the same damage modes. These damage modes are the same and can include micropitting, edge loading, roller end thrust, single piece cage failures, cage and center guide ring wear, and debris damage. Images in Figure 3 below represent actual field damage from a variety of turbine models and MW-class. These unplanned main bearing replacements are costly and have significant impact on financial performance to the owner/operator.

1 MW **1.3 MW** **1.5 MW**

1.65 MW **2.1 MW** **2.3 MW**

Figure 3: Common Damage in SRB Mainshaft

Even when the wind turbine mainshaft is equipped with two SRBs utilizing a fixed/float arrangement, axial movement of the mainshaft still occurs due to bearing clearance. A fixed SRB carries the radial and axial load from the rotor while the floating SRB carries only the radial load. The mounted clearance plays a major role in permissible movement in both the radial and axial directions. Minimizing radial translation is beneficial on both the bearing and system performance, but a reduced mounted bearing clearance increases the risk of an operating preload and then the potential for thermal runaway.

III. Enhanced Solutions

Timken upgrade solutions are available for most multi-MW turbines. For Original Equipment Manufacturers and Aftermarket customers options are available to increase reliability and improve system performance. Divided between upgrade redesigns, and direct replacements, solutions have evolved from Wear Resistant (WR) SRBs to now a drop-in Timken® Tapered Double Inner (TDI) Roller Bearing.

SRB Upgrades for Existing Turbines

For a direct interchange to existing fleets, Timken offers a WR SRB using engineered surface technology combined with Timken enhanced design and manufacturing. The WR bearings protect raceways against micropitting by significantly reducing the contact surface shear stresses and asperity interactions. The engineered surface is a unique and durable tungsten carbide/amorphous hydrocarbon coating (WC/aC:H). It is two to three times harder than steel, 1-2 micrometers thick, and has low friction coefficients when sliding against steel. In steel bearings, the coating disables the adhesive wear mechanism that causes the failure.

With advanced engineered surfaces on the roller, the coating helps to polish and repair debris-damage to the raceways during operation. The enhanced surface finish increases the effective lubricant film thickness and becomes more efficient to separate the asperity contacts. These improvements reduce the shear stresses that cause wear and lead to increased bearing damage. Below, Table 1 shows a summary of the features and benefits.

Technology	Description	Benefits
Roller Finishing	Low Roughness, Isotropic Finish	Reduced Asperity Contact & Stress
Roller Coating	WC/aC:H Coating 1 µm thick	Increased Wear Resistance Increased Fatigue Life Increased Debris Resistance
Internal Geometry	Roller/IR Conformity	Decreases Roller Stress, Reduces Potential Roller Skew Creates Favorable Traction
Split Cage	Two-Piece Machined Brass Cage with no Guide Ring	Lowers Possible Operating Forces Removes source of debris generation

Table 1: Timken WR SRB Features and Benefits

The TDI bearing has a number of advantages. When following careful assembly and maintenance procedures the bearing can yield significantly improved system performance. The benefits include:

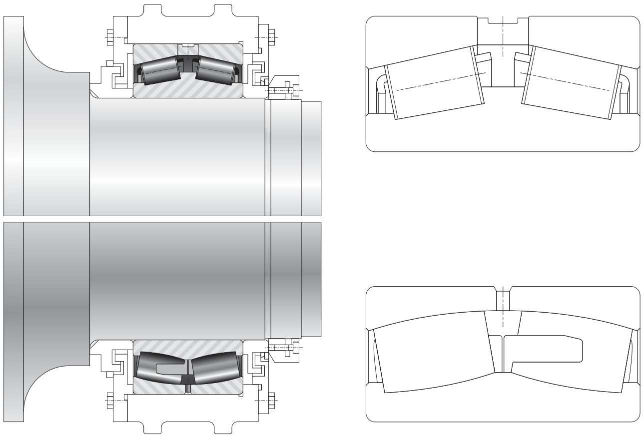
- Drop in replacement for SRB
- Preloaded system results in low risk of sliding, skidding and smearing
- Improved system stiffness
- Pure torque transmitted to gearbox without the additional load to torque arms.

TDI Conversion Upgrade for Existing Turbines

The benefits of a TDI bearing include reduced bearing wear, reduced deflection/load into the gearbox and increased system rigidity. A TDI mainshaft design can optimize the overall powertrain system due to its design and pre-load characteristics. The design characteristics help ensure excellent system stability/rigidity, load sharing between rows, and predicted roller-to-race interactions. For the case of SRB replacement, a single pre-loaded TDI also can manage the combination of radial and thrust loads much better than the SRB.

The TDI is an excellent choice to ensure load sharing across both bearing rows while being more flexible for system misalignment than a Tapered Double Outer (TDO) design. Having higher load capacity, the bearing preload helps mitigate smearing/skidding and micropitting. Designed as a direct drop-in, the TDI uses the existing OE pillow block housing and shaft without changing shaft and housing fits. Represented in Figure 4 below is a comparison of the TDI to the SRB in an identical housing.

Tapered Double Inner Roller Bearing (TDI)



- Limits misalignment through preload
- Accommodates some misalignment through internal geometry and roller profiles
- Absorbs thrust

- Accommodates some misalignment through clearance and shape
- Transmits thrust

Spherical Roller Bearing (SRB)

Figure 4: TDI Mainshaft Bearing Arrangement

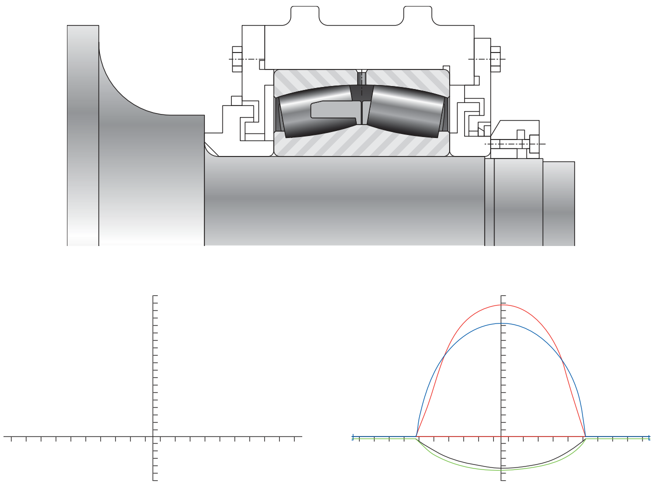
Analysis shows that a preloaded bearing system significantly improves load share between rows, reduces false brinelling, and reduces loads and deflections transmitted to the gearbox. The improved load share improves overall system dynamics and performance. The optimized preloaded system helps ensure excellent system stability in even the heaviest of wind conditions. The specially designed internal geometry controls roller-to-roller stress profiles and handles the initial system misalignment inherent in these turbine configurations. In uptower field-testing, a TDI mainshaft used in a 1.5MW three-point mount configuration continues to operate exceptionally well, and validates the predictions.

TDI Design and Predictive Modeling

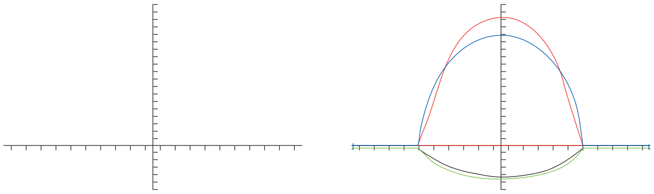
Bearing design criteria includes a 20-year or more fatigue life prediction, dynamic stress limits of 1650 MPa, extreme stress limits of 4000 MPa, and capability to handle a high degree of static and operating misalignment. Timken's proprietary and advanced modeling tool, Syber, considers overall system stiffness, initial imposed bearing misalignment, as well as dynamic misalignment for bearing development. To properly model the support arms, the gearbox connection included specific stiffness information for the axial, radial and tilting stiffness. Figures 5 and 6 demonstrate the comparison of load zone and load sharing when converting from a SRB to a TDI design.

Figure 5: Equivalent Load Cases:
Load zone calculations for the 240/600 SRB and NP822933-90WA1 TDI:

Spherical Roller Bearing (SRB)

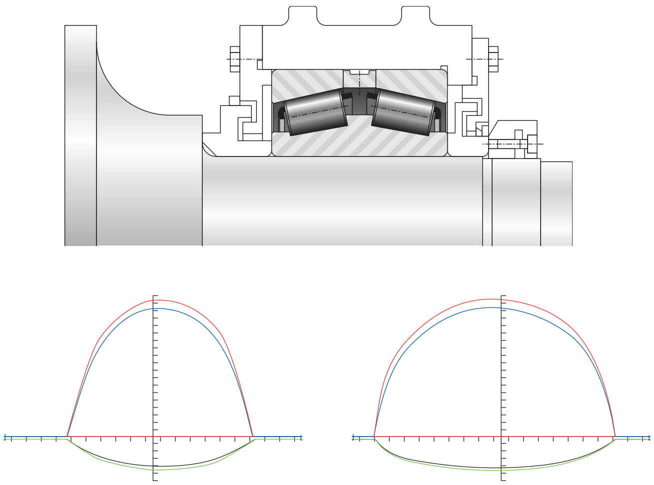


SRB Equivalent Stress Plot = Note, unloaded row which is typical in application; zero misalignment

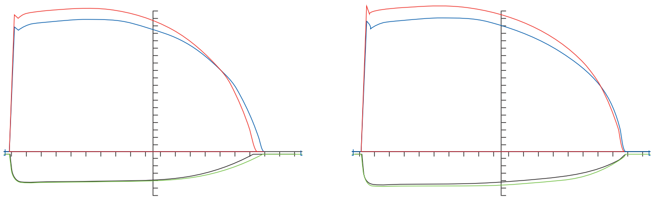


SRB Equivalent Stress Plot = Note, unloaded row which is typical in application; 1mrad misalignment

Tapered Double Inner Roller Bearing (TDI)



TDI Equivalent Stress Plot = Note, both rows loaded in all cases, zero misalignment



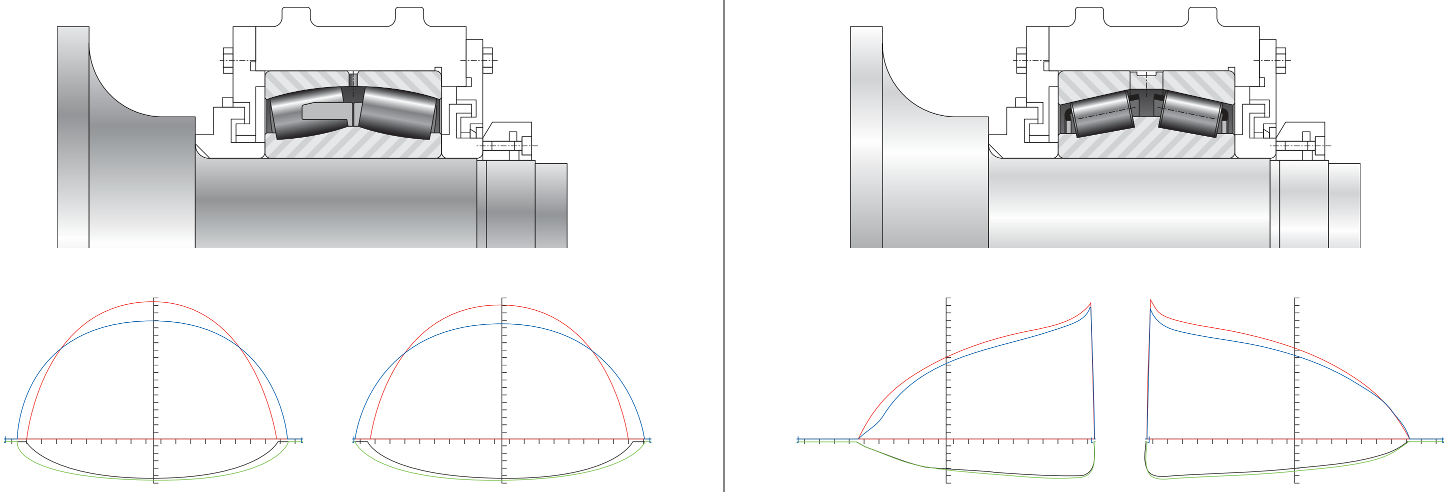
TDI Equivalent Stress Plot = Note, both rows loaded in all cases, 1mrad misalignment

The bearing could easily become misaligned in mounting due to the system tolerances stack up, or the coaxial relationship between shaft centerline at bearing position and gearbox connection centerline with the mainshaft. Optimized internal geometry, combined with proper uptower assembly procedures, mitigates the assembly concerns. Analysis included the angular system displacement as well as the induced misalignment under fatigue and extreme loading to determine impact on bearing and system performance.

Figure 6: Extreme Load Cases:
Load zone calculations for the 240/600 SRB and NP822933-90WA1 TDI:

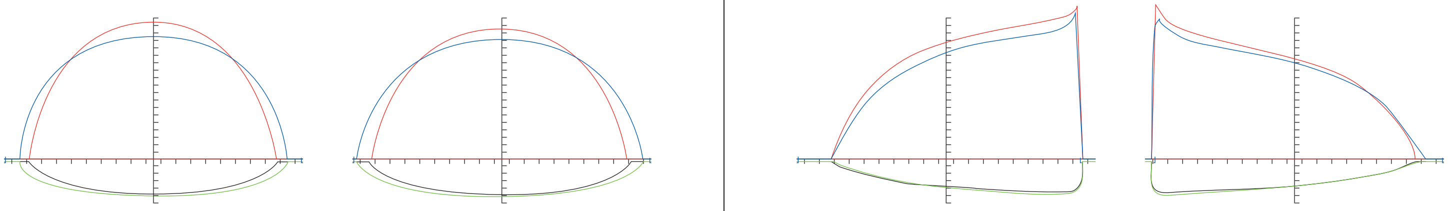
Spherical Roller Bearing (SRB)

Tapered Double Inner Roller Bearing (TDI)



SRB Extreme Stress Plot; zero misalignment

TDI Extreme Stress Plot; zero misalignment



SRB Extreme Stress Plot; 1mrad misalignment

TDI Extreme Stress Plot; 1mrad misalignment

Advanced Modeling

Moving beyond quasi-static bearing analysis, advanced finite element (FE) modeling predicts the directional impact of changing bearing types. Modeling techniques relate to defining linear elastic material properties in the solid models of the shaft and pillow block and defining the bolts as ABAQUS Pre-Tension beam elements. Figures 7 and 8 depict the overall system modeling.

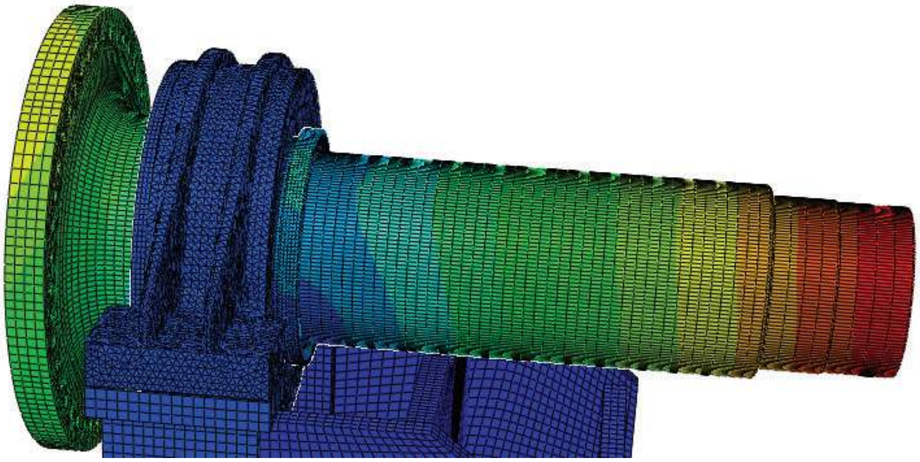


Figure 7: FE Model Set-Up

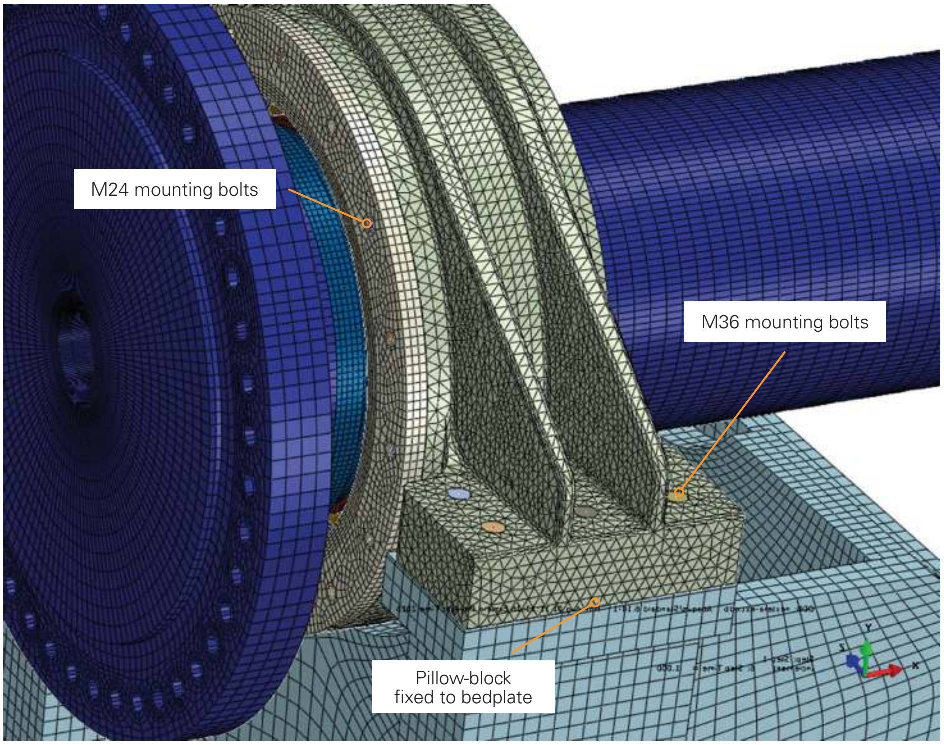


Figure 8: FE Model Bolted Connections

Analyzing both the SRB and TDI housed unit, the max stress in the pillow block occurs in the lower radius of the support. The highest stress location in the shaft is located at the UW shoulder fillet radius. The bedplate support exhibits highest stress at the interface of the pillow block to the bedplate. Figures 9 and 10 highlight max stress location with Table 2 (next page) summarizing the results for both equivalent and extreme load cases. Table 3 (next page) summarizes the bolt stress analysis.

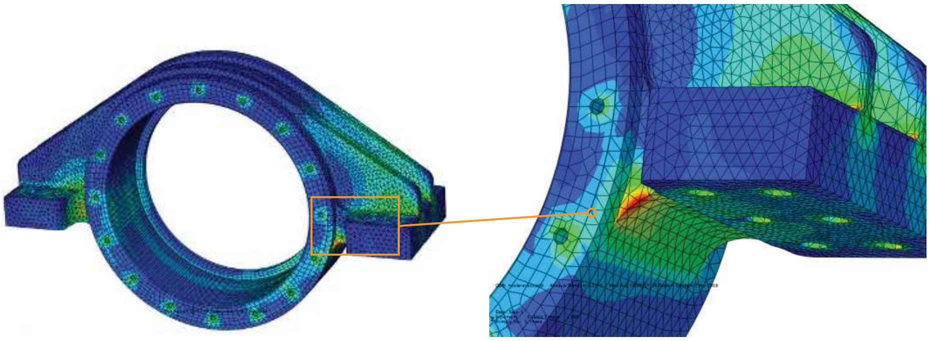


Figure 9: Pillow-Block Max Stress Location

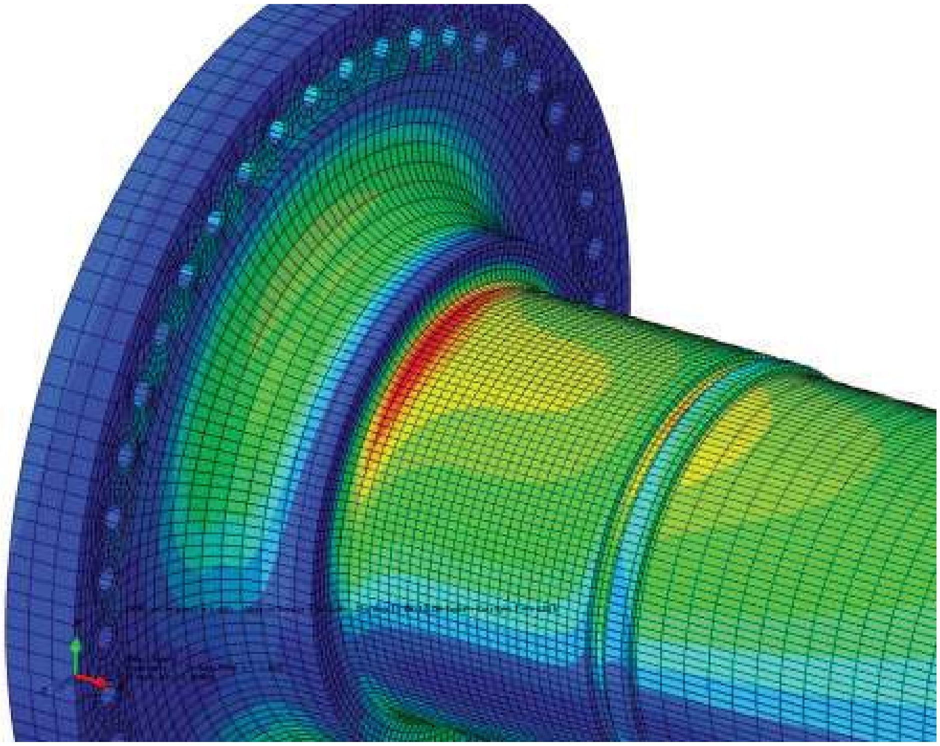


Figure 10: Shaft Max Stress Location

The stress levels and safety factors indicate very similar performance between the SRB and TDI. Finite Element Analysis (FEA) predicted minimal changes to stress levels in all components when comparing results of the TDI to the SRB. This shows that converting from one bearing type to the other imparts negligible effect on the system.

Table 2: 240/600 SRB and NP822933-90WA1 TDI Housed Unit Stress and Shaft Stress Summary

	SRB	**TDI**
Equivalent Load		
Pillow Block Stress (MPa)	67	62
Extreme Load		
Pillow Block Stress (MPa)	280	326
Shaft Stress (MPa)	274	259

Table 3: 240/600 SRB and NP822933-90WA1 TDI Housed Unit Bolt Analysis Summary

	SRB Assembly		**TDI Assembly**	
	M-24 Clamp Bolts	M-36 Mounting Bolts	M-24 Clamp Bolts	M-36 Mounting Bolts
Equivalent Load				
Max Stressed Bolt (MPa)	119	96	110	69
Min Stressed Bolt (MPa)	100	90	99	62
Fatigue Life (Cycles*)	2,300,000	>1E7	>1E7	>1E7
Extreme Load				
Max Stressed Bolt (MPa)	166	83	148	79
Min Stressed Bolt (MPa)	100	75	103	66
Fatigue Life (Cycles*)	50,000	>1E7	200,000	>1E7

IV. Mainshaft Assembly: Field Turbine Installation

Timken service engineers supported the installation of three prototype TDI mainshaft bearings. These three installs took place in 2015. Working closely with the end-user in their repair facility, Timken service engineering led the prototype bearing assembly. To make uptower inspection easier, modifications to the housing included additional ports for temperature sensor and shock pulse monitoring.

The holes for the temperature probes are located in the 6:00 position and intended to contact the small end (thinnest section) of each cup. This also would be nearest the roller to rib interface. Additionally, a shock pulse port was added at the 9:00 position when looking UW. Detailed assembly instructions were used.

Figure 11: Pillow-Block Install over TDI

Figure 12: Completed Assembly

Figures 11 and 12 show a successfully installed bearing.

The uptower assembly occurred with the continued assistance of Timken service engineering and followed procedures developed in unison with the customer. One key aspect is to ensure the main bearing assembly is properly oriented to the gearbox prior to final install of the housing to the bedplate. Rotating the mainshaft 360° in each direction after installing the assembly, but before installing the gearbox mount caps, allows the housing assembly to orient itself with respect to the gearbox connection.

This is possible by turning the gearbox output-shaft brake rotor/locking gear. Once rotation is complete and the housing assembly is "centered", final assembly of the mainshaft mounting bolts occurs per the turbine manufacturer's torque specifications. The procedure for mounting and aligning the mainshaft assembly uptower is depicted in figures 13-16.

Figure 13: Bed Plate / Pillow Block Interface

Figure 14: Torque Arm Alignment Measurement

Figure 15: MS Assembly Movement

Figure 16: MS Assembly Measurement

TDI Monitoring & Performance

As part of the test protocol, frequent inspection involved uptower inspection including borescope, Shock Pulse Measurements (SPM™ Spectrum), temperature readings, grease inspection/sampling and displacement monitoring.

Physical Inspection and Boroscope

The inspection pictures shown in Figures 17 through 20 represent the condition of the rollers and race after two years of runtime. With no early indications of damage relating to peeling, micropitting, etc., the images show the excellent running condition of the TDI bearing.

Figure 17: Bearing cup raceway

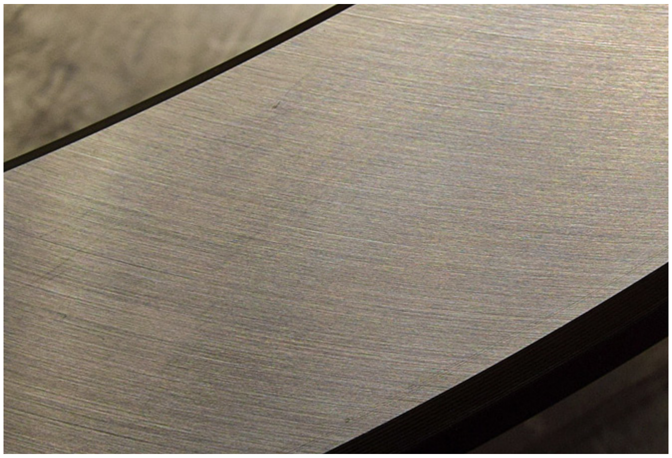


Figure 18: Bearing cup

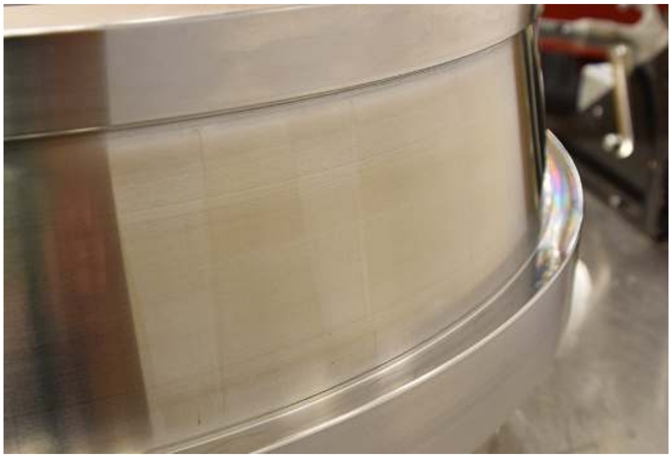


Figure 19: Bearing cone raceway

Figure 20: Bearing cone raceway

Shock Pulse Monitoring

Shock Pulse Technology is a variant of vibration analysis using an enveloping technique acquired through a tuned transducer. It allows for condition monitoring of slow rotating components and is well suited for mainshaft bearing applications. Shock Pulse levels also reflect the amount of metal-to-metal contact in a bearing as it relates to adhesion, micropitting, and early spall detection.

For perspective, Figure 21 represents the shock pulse measurement of a standard OE 240/600 SRB, Timken's WR 240/600YMDWEW919 SRB, and NP822933-90WA1 TDI; respectively. This carpet plot displays the significantly lower shock pulse level of the WR SRB. Comparatively, Timken TDI bearings run at lower shock pulse levels than a standard OE SRB, but higher level than Timken® Wear-Resistant SRB. Figure 21 represent bearings with six months to one year of run time.

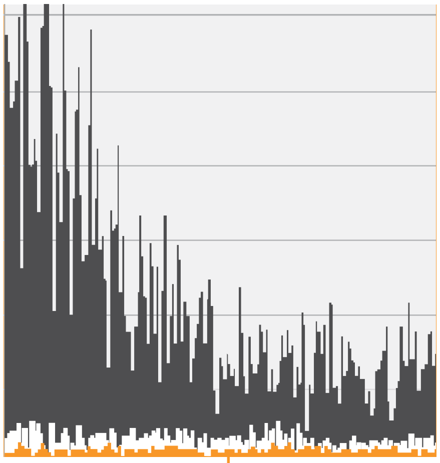
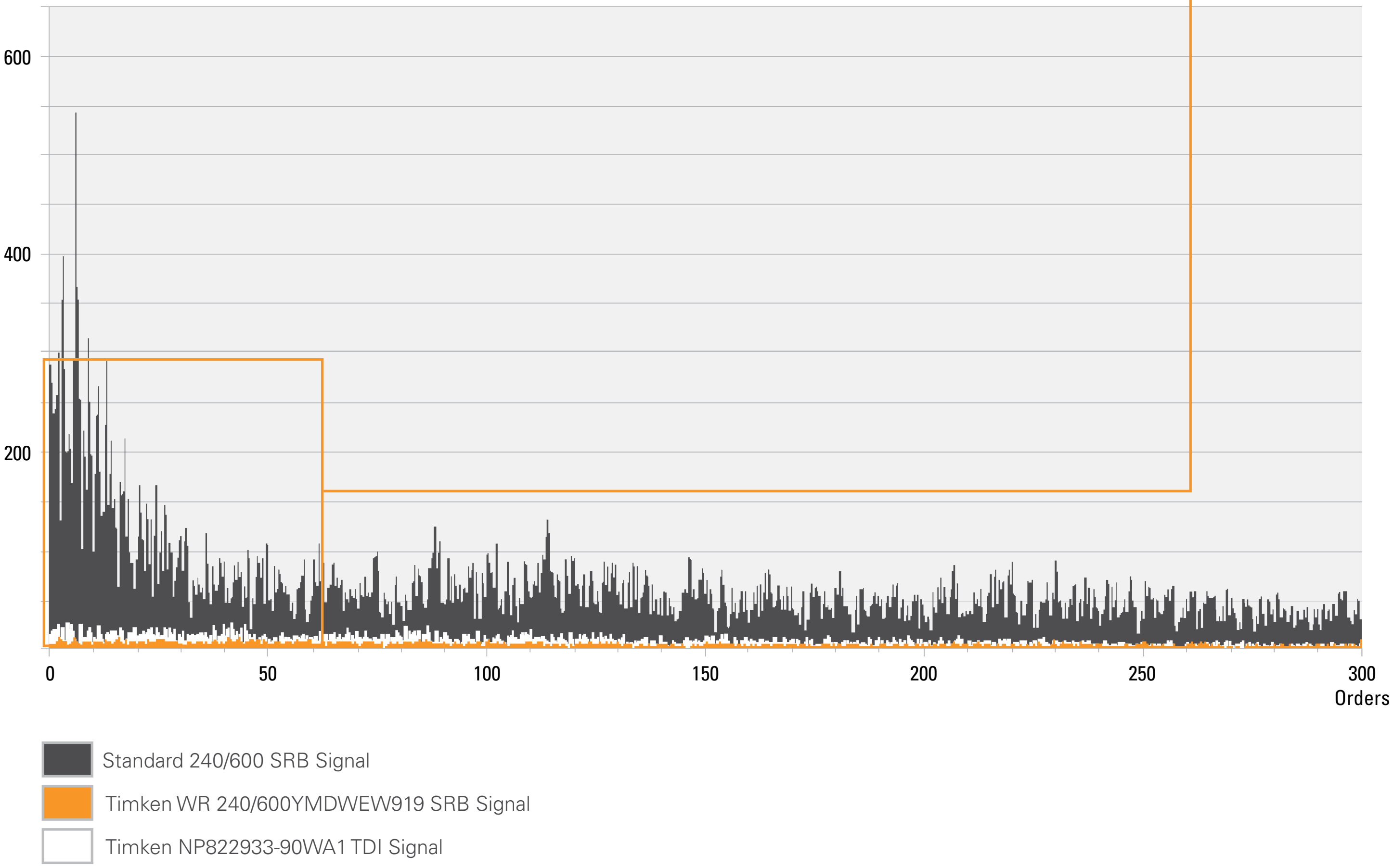


Figure 21: Shock Pulse Values



Temperature Readings

The operating temperature of TDI bearings is comparable to an OE SRB as shown in Figure 22 where the SRB data originates from a neighboring turbine and offers the best comparison point within the wind farm. Depending on ambient condition and nacelle temperature conditions, temperature readings for the TDI ranged from 38° to 46°C as compared to 36° to 40°C for an OE SRB.

As expected, the preloaded TDI is operating slightly warmer which is attributed to the bearing preload as well as the previously discussed temperature sensor location being more in the center of the load zone.

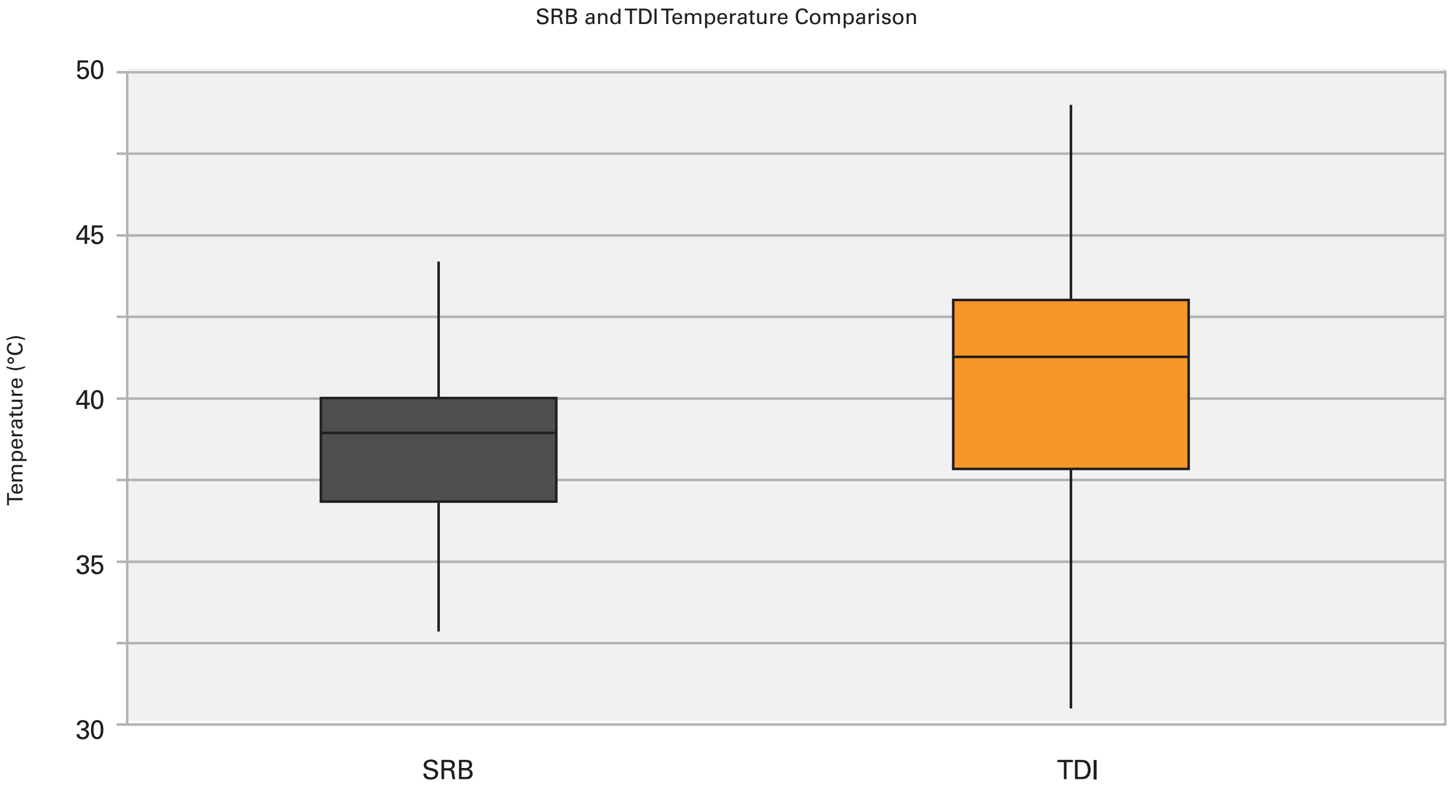


Figure 22: Main Bearing Temperature

Grease Sampling and Test

In addition to the above measurements and inspections, grease sampling and analysis conducted at an independent lab evaluated the working condition of the grease with results shown in Figure 23 and Table 4. The periodic grease analysis included:

1. Chemical composition (PPM) using ICP analysis per ASTM D1976
2. Iron content (PPM) per ASTM D7690
3. Cone Penetration per ASTM D217-10
4. Grease oxidation using Fourier Transform Infrared (FTIR) Spectrometry per ASTM E2412-10

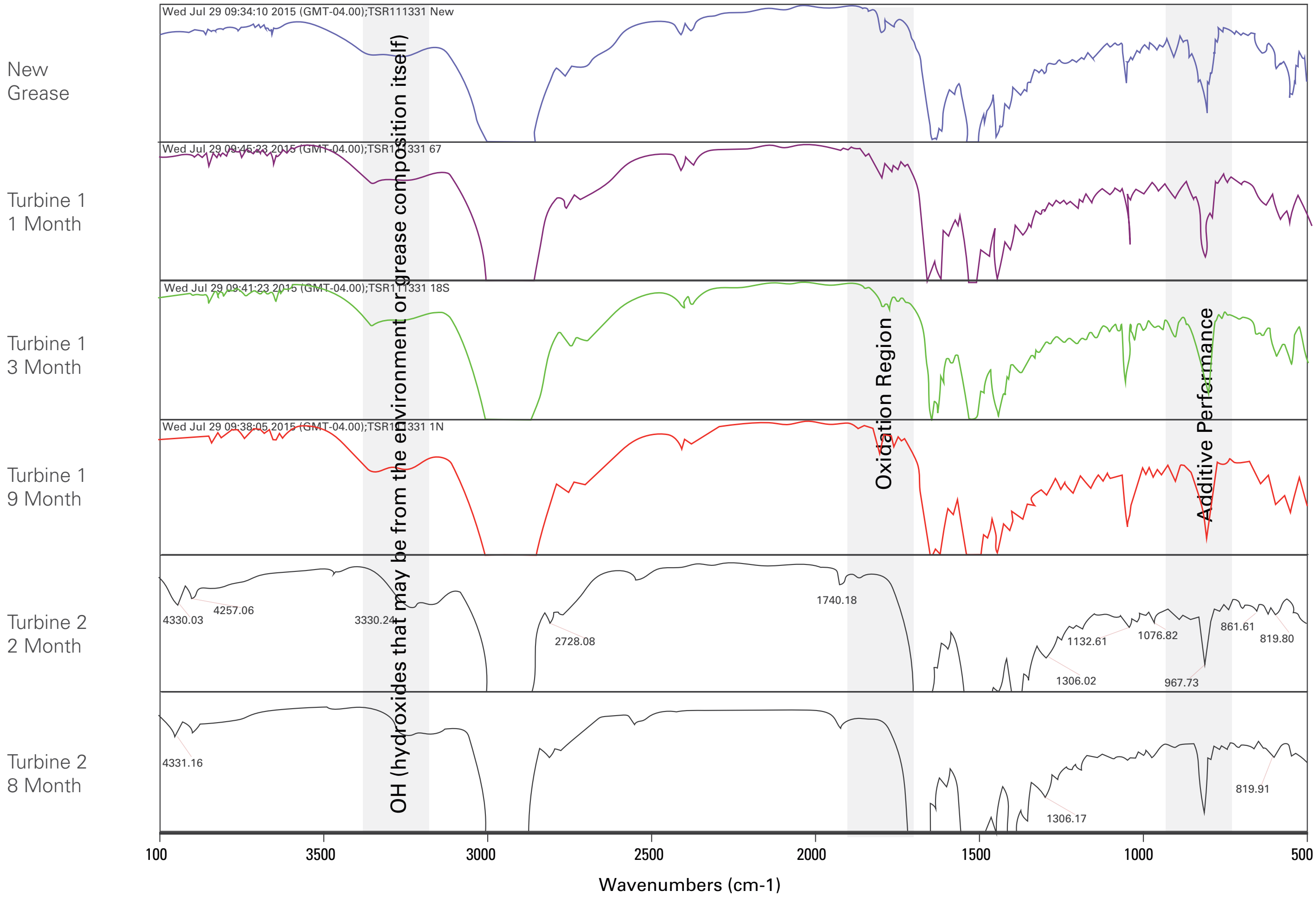


Figure 23: FTIR Spectrum

Table 4: Grease Analysis Results Summary

		Turbine 1			Turbine 2	
Sample ->	New	1 Month	3 Months	9 Months	2 Months	8 Months
Cone Bleed (%)	5.6	8	8	NA	7	NA
PEN 60x	321	365	365	360	399	360
NLGI Grade	1	0	0	0	00	0
Fe	0	20	15	10	20	40
Ca	62	40	80	200	20	30
P	80	110	110	350	100	110
Zn	700	700	700	700	750	1050
Mo	2500	2500	2500	1300	2700	3400
Li	900	900	900	1000	900	1000

Lubrication analysis of the various grease samples include a sample of new grease and show no significant change in chemical composition. With observed marginal wear and oxidation, the grease appears to have a slight change in penetration going to lower consistency.

The grease before test is typically 320 but the field grease had penetration of 365 – 399; with the penetration after 60 strokes showing borderline NLGI 1 range and roll stability test borderline NLGI 1 to NGLI 0. In discussions with the customer as well as the grease manufacturer/supplier, the grease is performing as expected. A desired amount of bleed and relative shear instability properly lubricates and protects against false brinelling.

FTIR Spectrometry shows promising results when comparing the new grease hydroxides, oxidation and additive performance to that of the turbine grease samples. For hydroxides, a percent change greater than 15% indicates a significant change with the hydroxides coming from the environment or the grease composition itself.

The additives region indicates the degradation of the various additives with primary emphasis on comparison of peaks; with the depletion of the additives, the peaks would decrease. Overall, FTIR analysis confirms acceptable grease performance.

Deflection Measurements

Displacement measurements were taken directly on the mainshaft using sensors mounted with a magnetic base directly on the bedplate. To understand the axial displacement of the shaft on the main bearing and gearbox connection, the results in Figure 24 clearly demonstrate the displacement of the TDI being approximately one third that of an SRB.

Directly attributed to the running internal clearance of an SRB versus the mounted preload of the TDI, the preloaded tapered bearing minimizes the transmittal of additional shaft deflection to the gearbox, through the carrier bearings, and to the torque arms. This ultimately should yield improved gearbox performance and reliability.

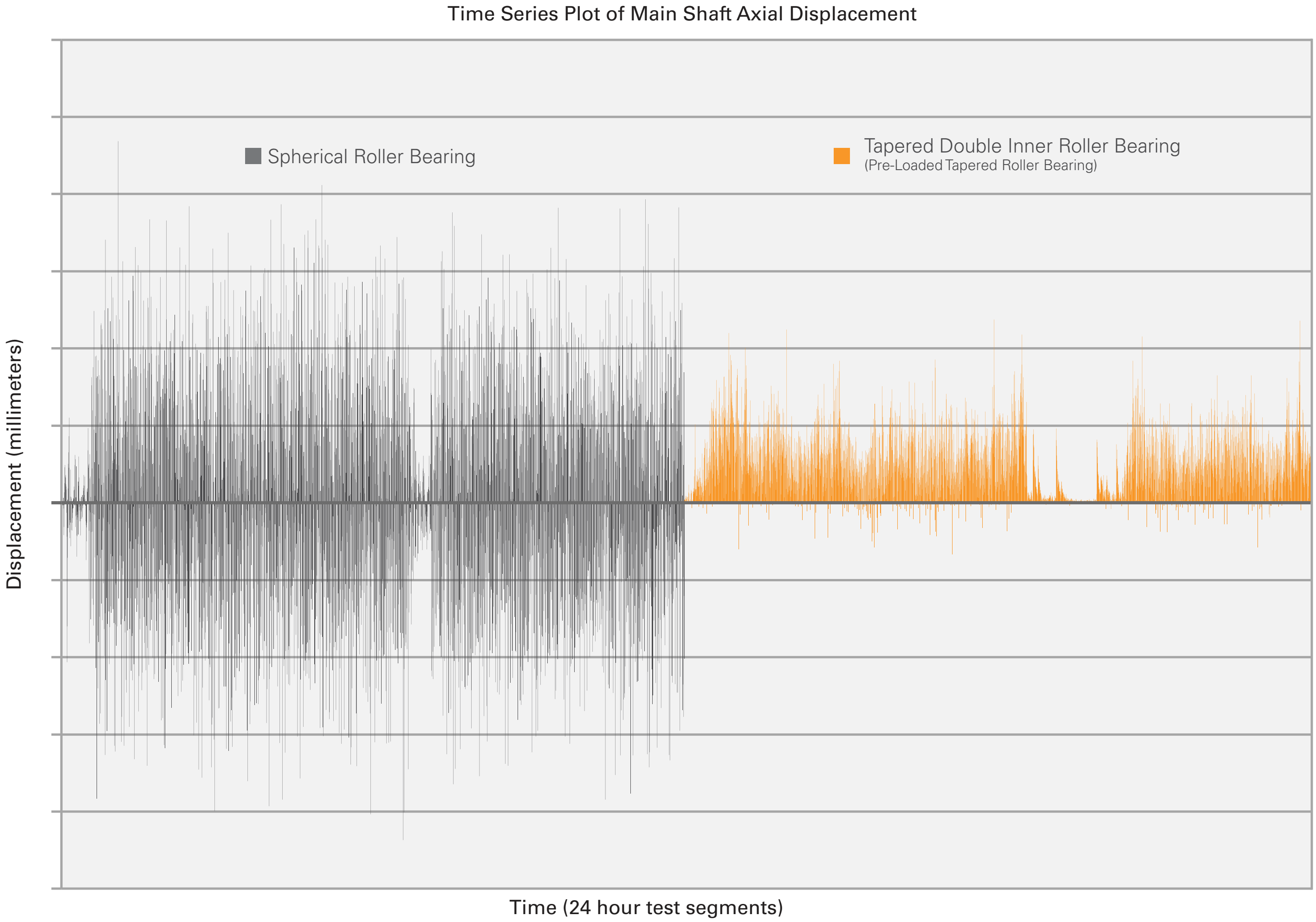
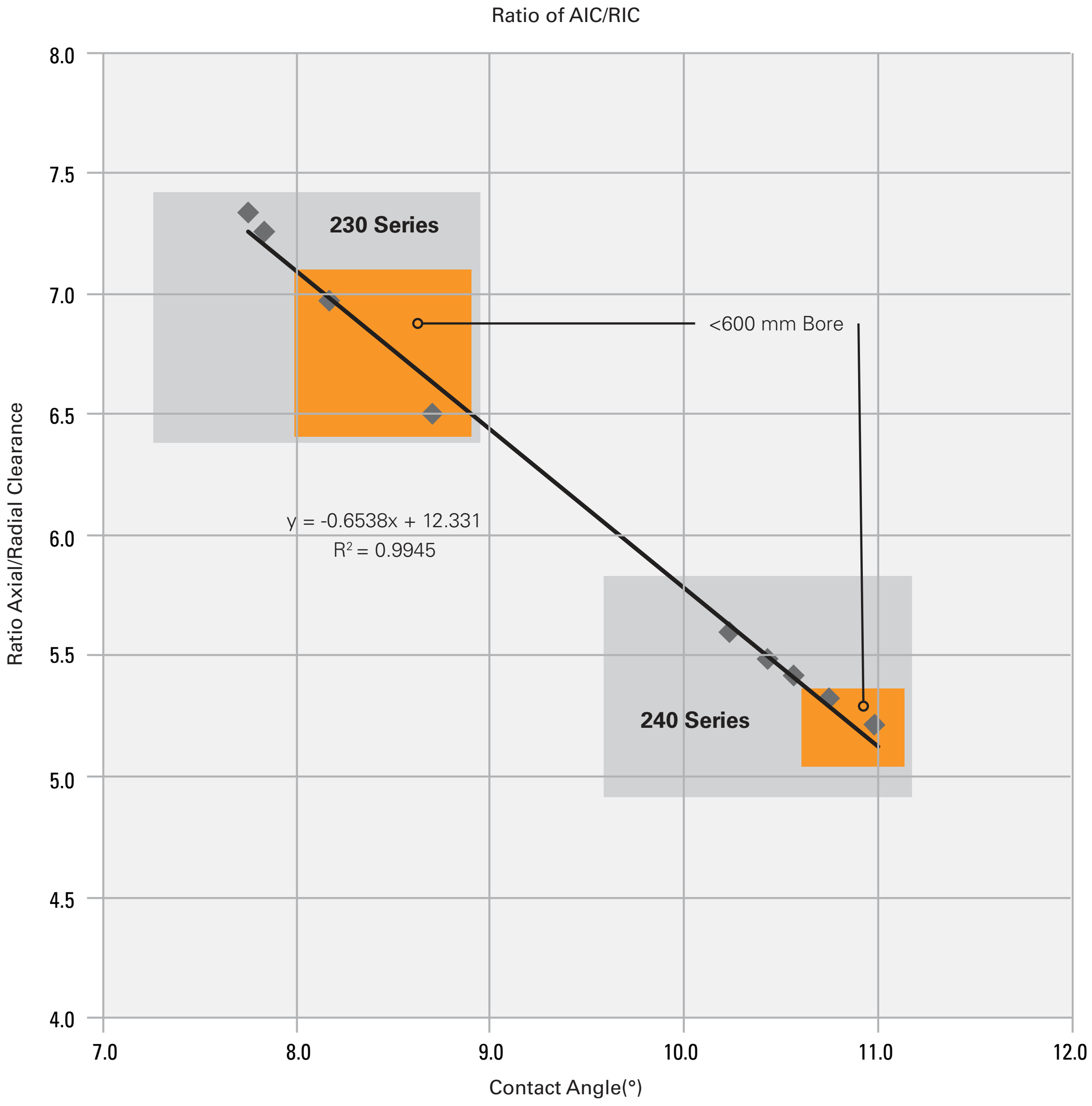


Figure 24: SRB and TDI Axial Displacement Comparison

A direct contributor to axial deflection into the gearbox relates to the influence of the bearing contact angle. With the relationship of RIC to axial internal clearance (AIC), higher bearing contact angles directly result in reduced axial play for a specific RIC. With a 230-series SRB having lower contact angle than an equal bore 240-series, the AIC is significantly more.

Typical axial clearance in a 240-series bearing is approximately 1.3 to 2.0 mm, as compared to 2.1 to 3.1 mm in a 230-series bearing. Looking within a specific series, a smaller bearing (e.g., <600mm bore) has less axial clearance due to the higher contact angle. Graph 1 highlights the clearance to contact angle influence.



Graph 1: Ratio of AIC to RIC for Specific Contact Angle

V. Conclusion

For the long-term financial sustainability of the wind turbine market, reliability of the mainshaft and gearbox design must improve. Advances in engineering and market demand have propelled upgrades in recent years utilizing Timken design solutions for existing SRB three-point mount turbines. The reliability requirement for offshore turbines has driven the use of preloaded TRBs. This same design direction is taking hold for onshore wind farms.

Improvements in mainshaft design will increase the reliability of the entire power train system, and lead to an overall lower total cost of ownership. Retrofitting the SRB in a three-point mount arrangement with a specially designed preloaded TDI improves the overall turbine reliability by reducing sliding, skidding and smearing, improving system stiffness, and significantly reducing axial movement of the gearbox.

VI. References

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