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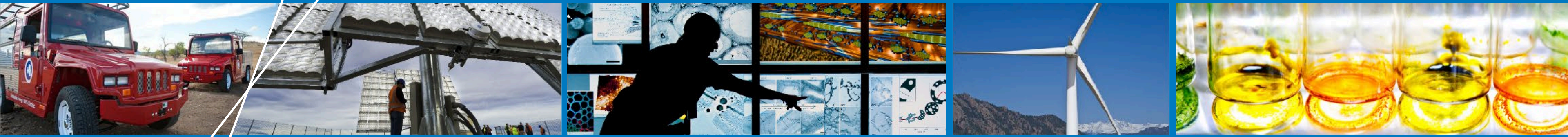
Main Bearing Dynamics in Three-Point Suspension Drivetrains for Wind Turbines



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National Renewable Energy Laboratory

American Wind Energy Association WINDPOWER

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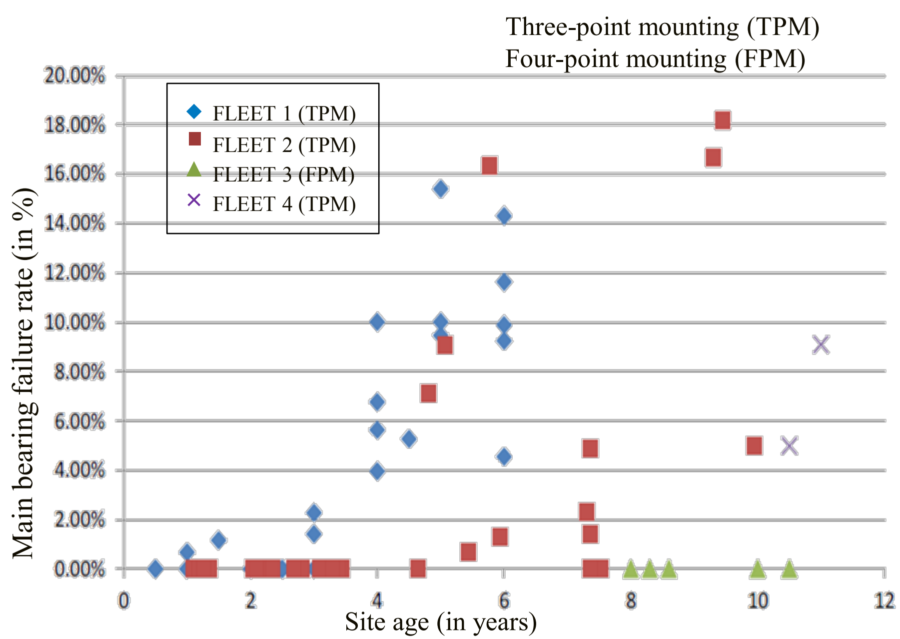
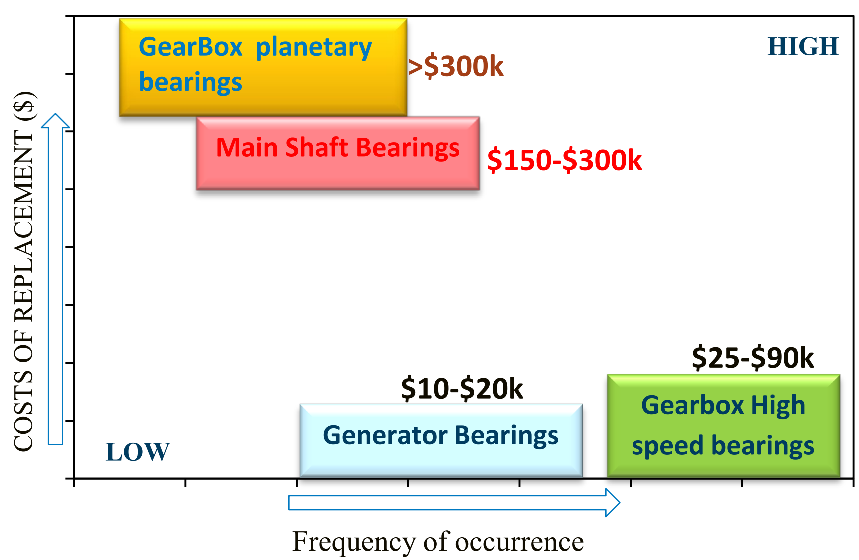
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Motivation

- Main bearing health affects the reliability of wind turbine drivetrain
- Increasing evidence of failures and repair costs associated with main bearings from existing fleets of wind turbines
- Many of the main bearings in three-point mounting (TPM) have failed to survive beyond 6 years.

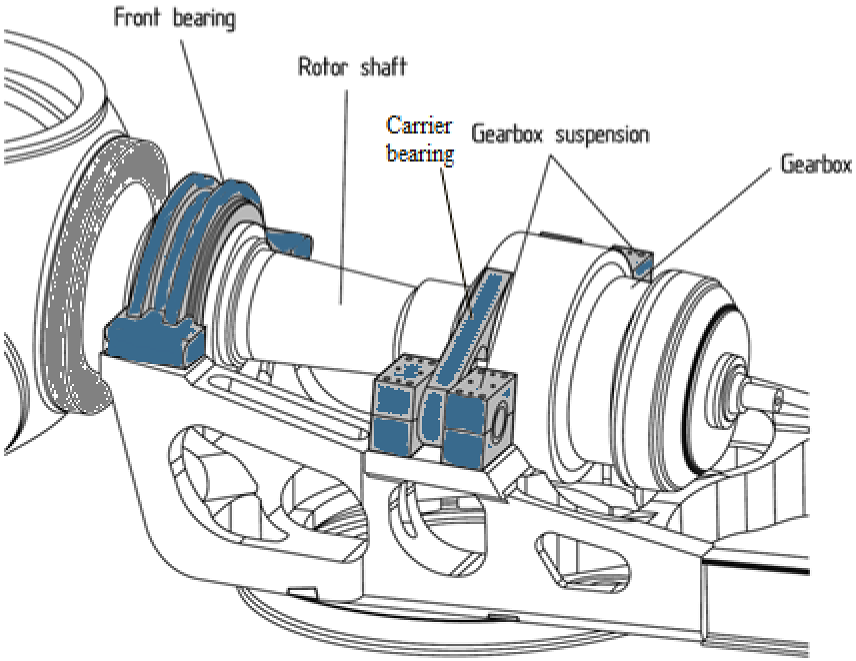


(Brake 2013)



***Failure-Data** based on* (Brooks 2014)
Costs- source (Hornemann 2013)

TPM



TPM drivetrain (Hau 2013)

Spherical roller bearings: most main bearings fail to achieve design life of 20 years

- Chosen with adequate C/P margin
- Withstand rolling contact fatigue
- Low value of '*e*' (axial/radial load ratio) up to 20%–35%.
- Some reports suggest actual values of '*e*' can be up to **60%** (Ionescu and Pontius 2009).
- Field life of most bearings **< 6 years**
- Load limit → contact design *e* =1.5 tan□ (□is the contact angle)(ISO 281).

C- Dynamic load rating

P-Dynamic equivalent load

TPM

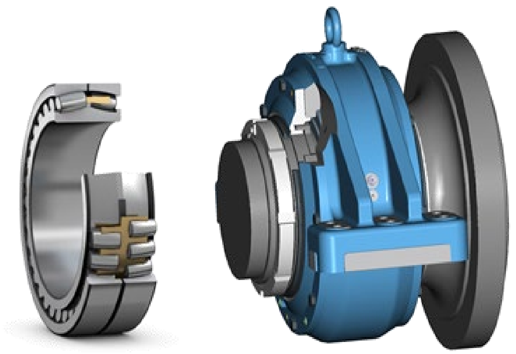


Image courtesy(SKF product catalogue)

Loading beyond this limit results in:

- Unloaded upwind row
- Roller unseating effects/skewing, retainer distress, and excessive heat generation (Ionescu and Pontius 2009)

Large raceway axial displacements further exacerbate these problems

- Rollers tend to roll and slide excessively
- Low lambda conditions →Micropitting

Spherical roller bearings: most main bearings fail to achieve design life of 20 years

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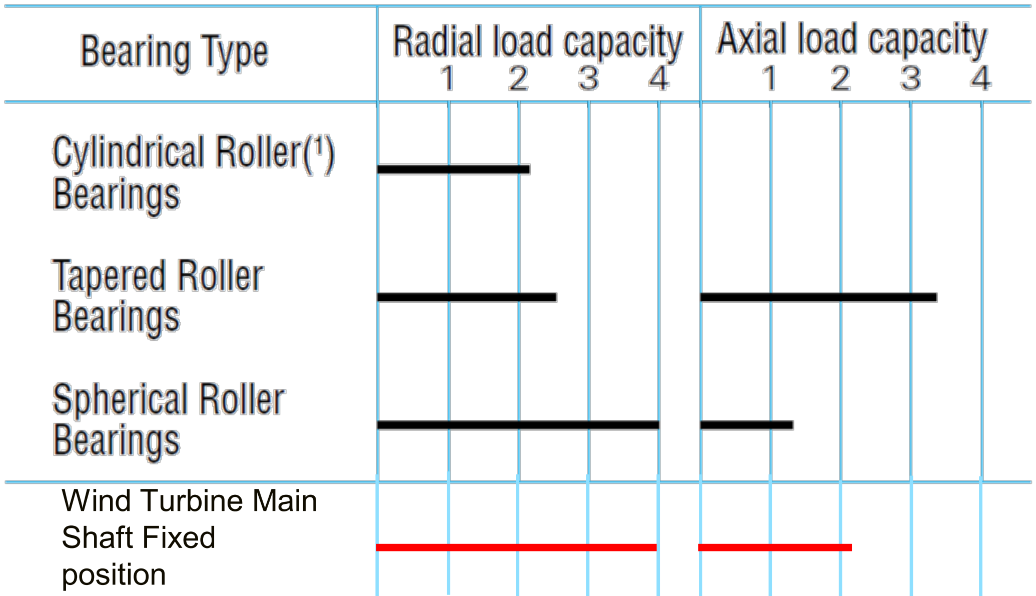
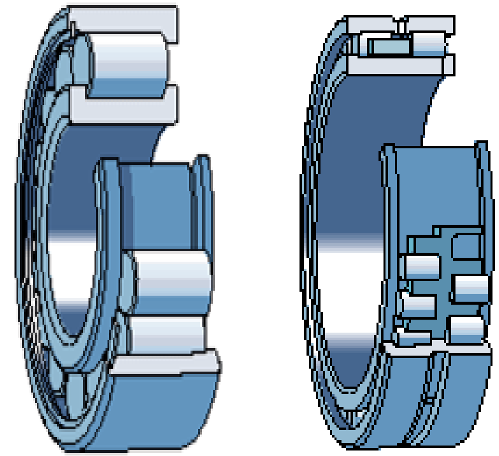
Roller Bearing Types – Load Capacity



Note(1) The bearings with ribs can take some axial loads.

Load capacity table reproduced from NSK

(a)

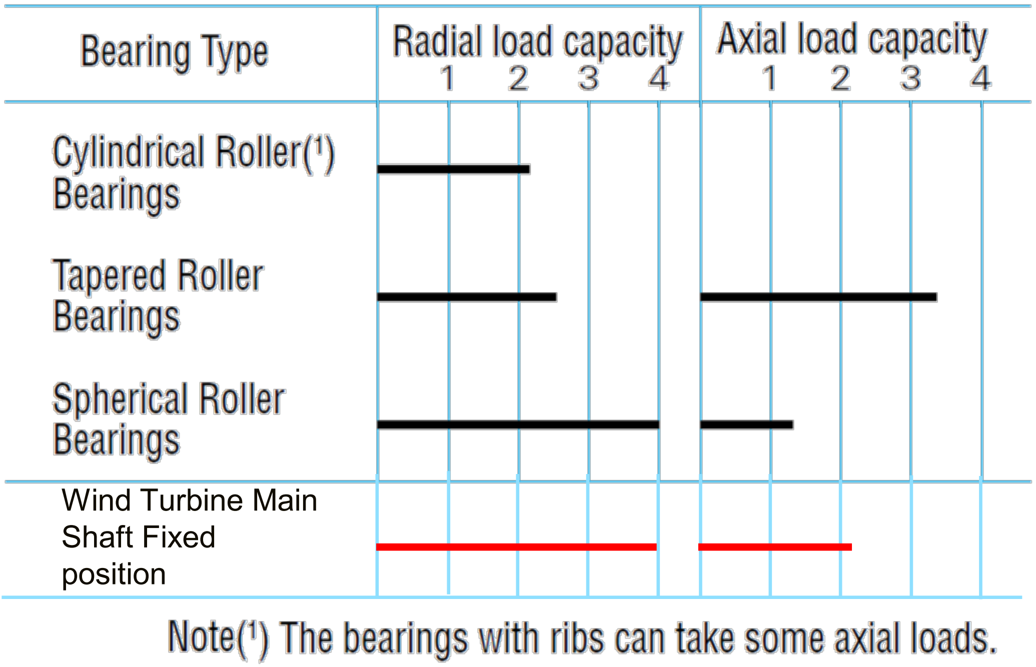


(b)

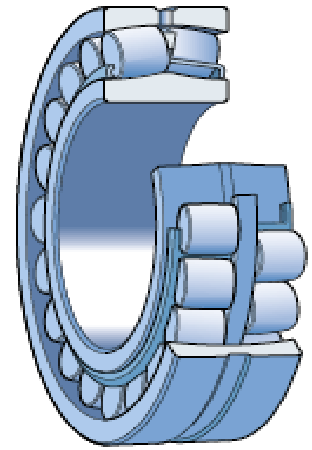
Cylindrical roller bearing
(a) Single row and (b) double row
(Illustration by SKF)

- ***Cylindrical roller bearings (CRBs):*** Clearance is a critical setting

Roller Bearing Types – Load Capacity



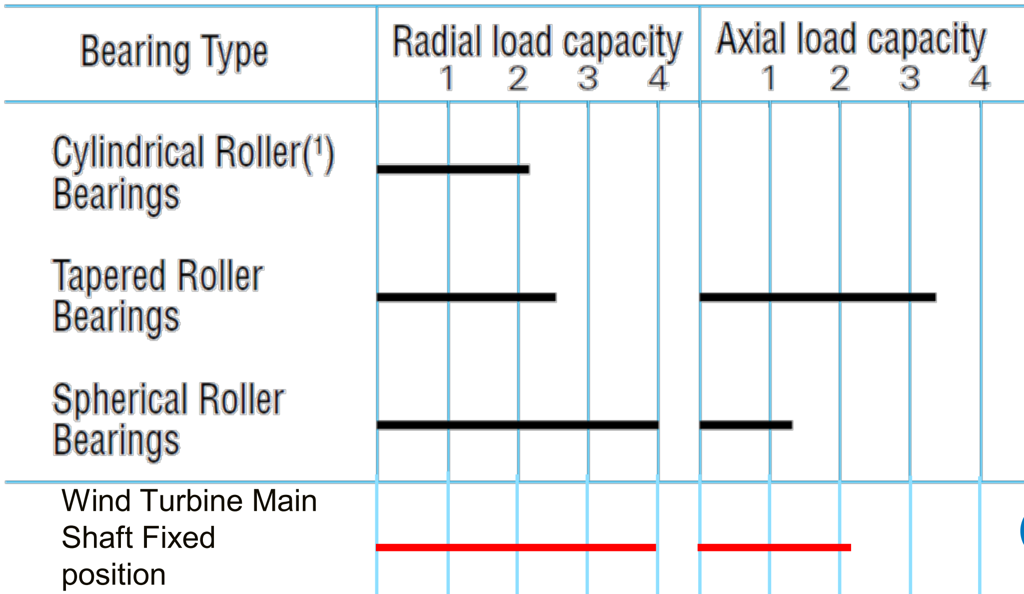
Load capacity table reproduced from NSK



Spherical roller bearing
(Illustration by SKF)

- ***Spherical roller bearings (SRBs) :*** Use barrel-shaped rollers; excellent tolerance to misalignment.

Roller Bearing Types – Load Capacity



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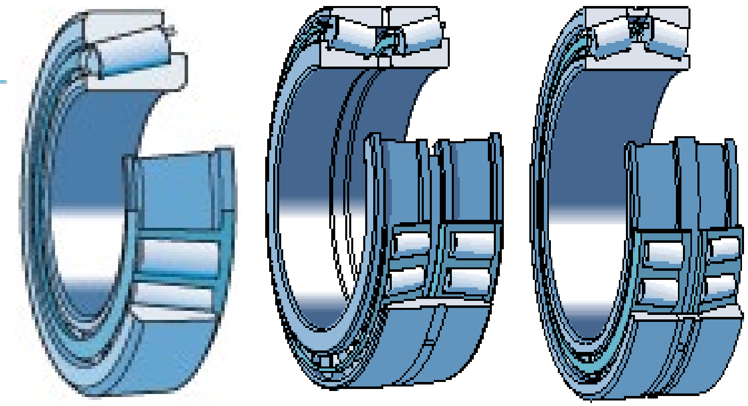

Tapered Roller Bearing

(a) Single row (b) Double row-Outer (c) Double row-Inner

(Illustration by SKF)

- ***Tapered roller bearings (TRBs):*** Low tolerance to misalignment, preload is a critical setting

SRB Failure Modes and Mitigation Strategies

- Micropitting – bearing race damage
- Single piece cage failure
- Roller edge loading
- Debris damage

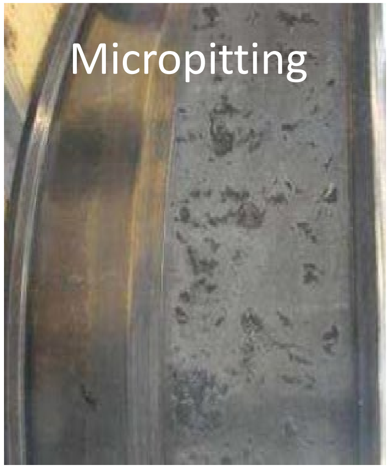

Photo from (Brooks 2013)

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Photo from (Brake 2013)

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SRB Failure Modes and Mitigation Strategies

Industry recommendations for mitigation include using:

- Wear-resistant SRBs: coated rollers
- Larger main bearing* with higher static/dynamic load rating
- Asymmetric roller profile*
- Tighter internal radial clearance.*

* Each of these may lead to a difference in the stiffness and bearing load response

The impact of these upgrades on the rest of the drivetrain and vice versa are unknown.

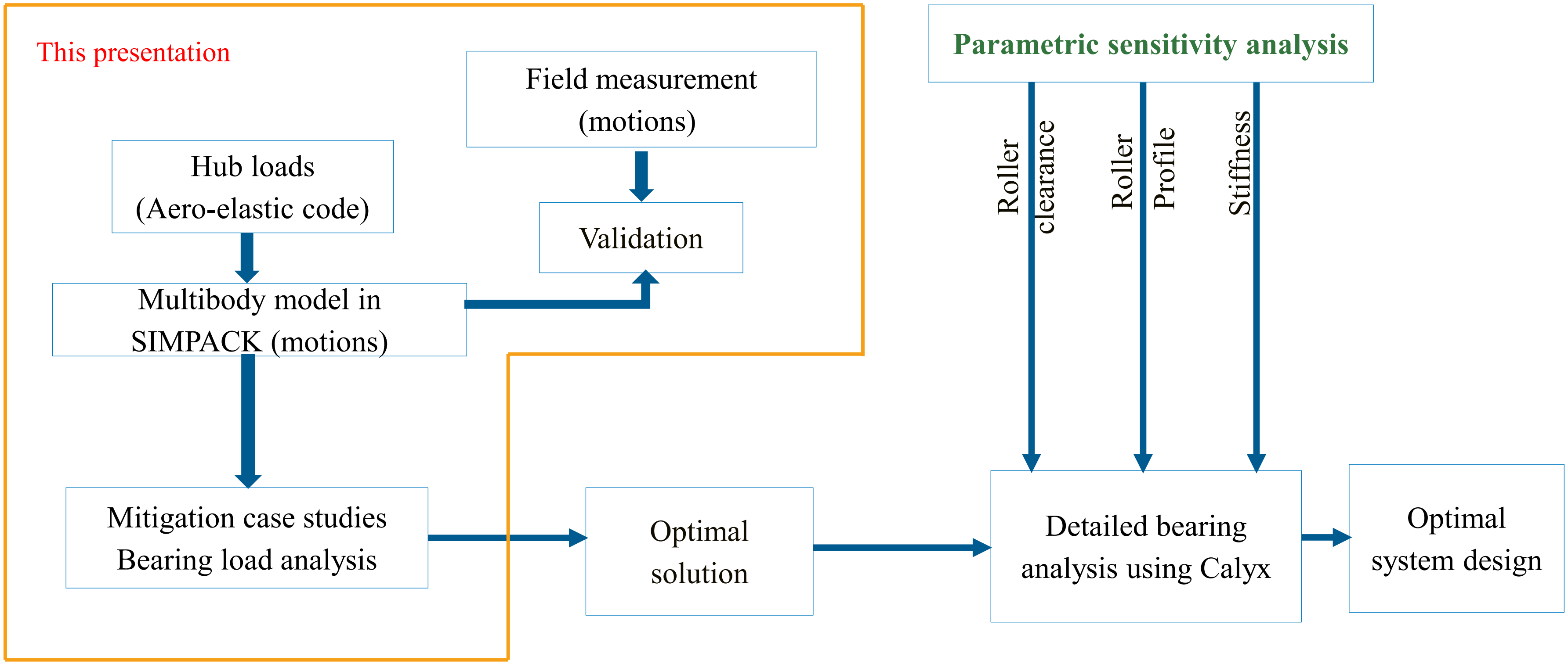
There is a need to:

- Revisit bearing operating conditions
- Investigate potential solutions to mitigate failure.

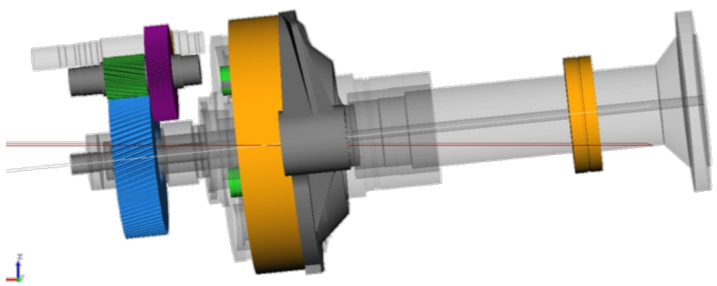
Study Objective and Methodology

The objective of this work is to identify an optimal system design solution that results in improved bearing life in TPM configuration by:

- Establishing a multibody simulation model for TPM configuration in SIMPACK
- Validating the model against field measurements
- Assessing bearing load mitigation strategies
- Evaluating bearing load sensitivities to roller clearance, stiffness, and roller geometry profiles.



TPM Model in SIMPACK

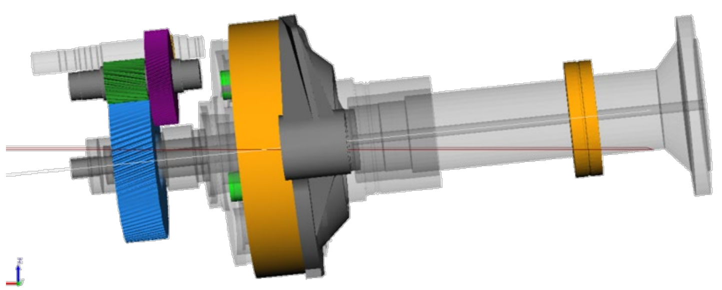


Multi-body model of TPM in SIMPACK

Turbine rating	1.5 megawatts
Rated speed	19 rpm
Main bearing	230/600 CAW33

- SIMPLIFIED model focused on key elements on nontorque load(NTL) path
  - Main shaft and main bearing, planet carrier, ring, torque arms and bed plate(Guo 2014)
  - Intermediate and high-speed stages are less influenced by NTL(Guo 2015)
- Structural flexibilities from housing, carrier not included
- Main shaft: flexible beam using node-based finite difference approach
- Eleven sets of load cases representing the turbine's normal operation at wind speeds from cut-in to cut-out
- For each simulation, SIMPACK yielded a time series of integrated bearing reactions (for e.g., forces/moments and displacements).

TPM Model in SIMPACK



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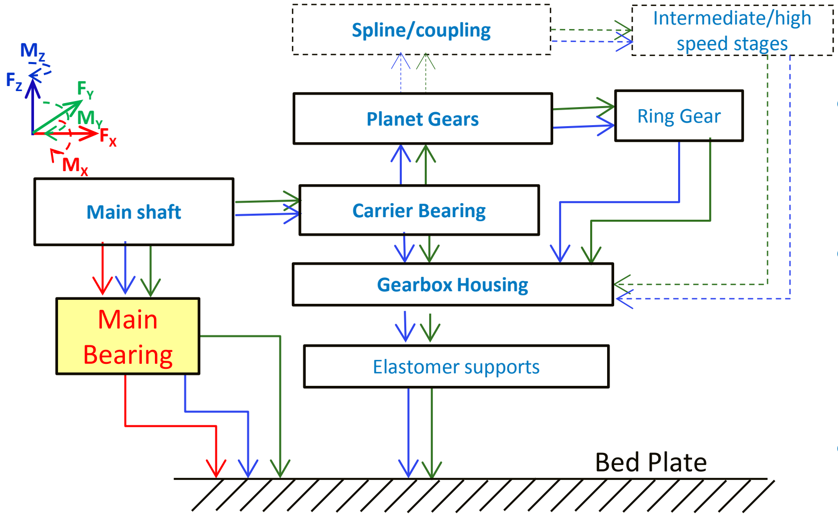

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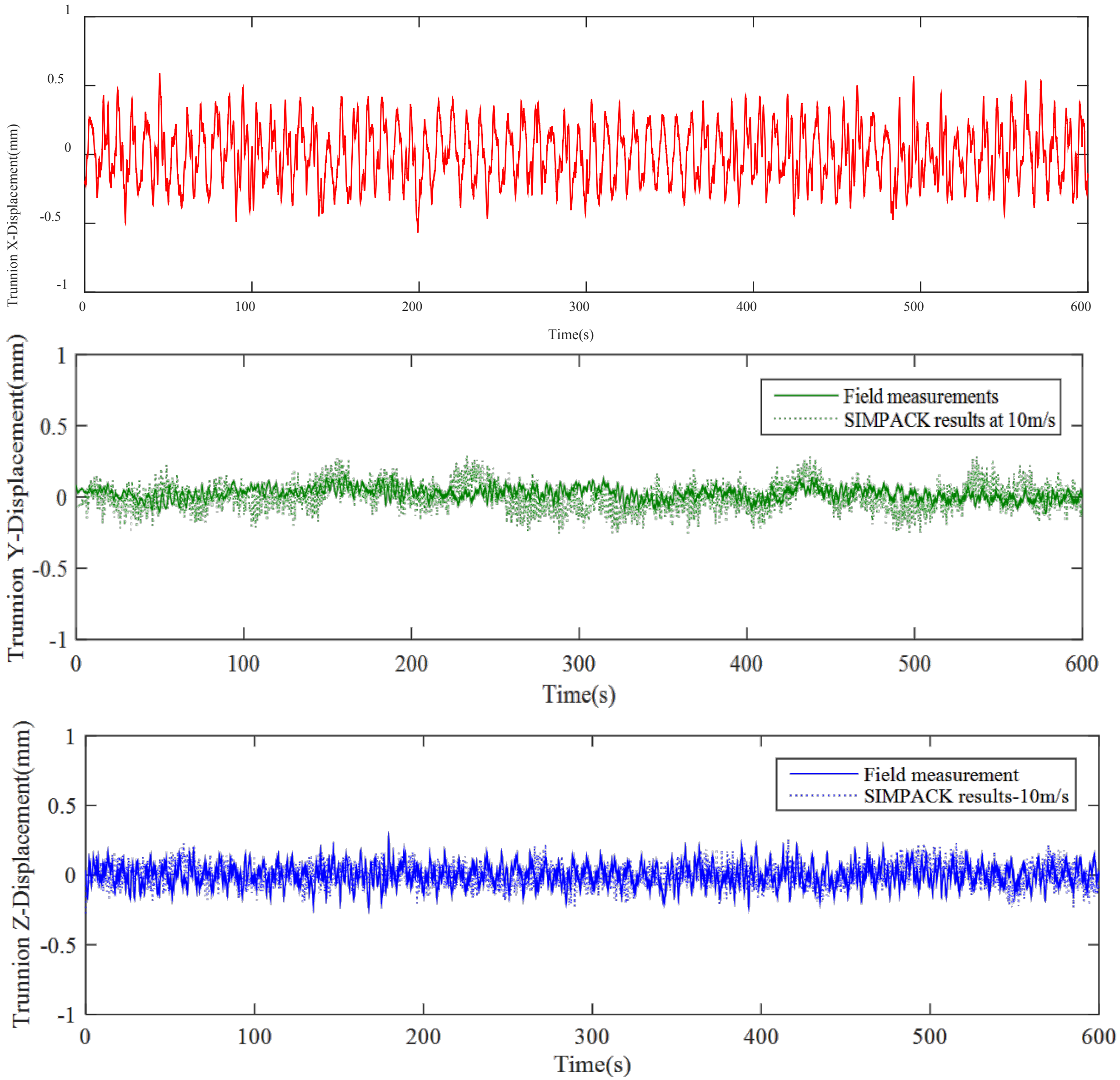
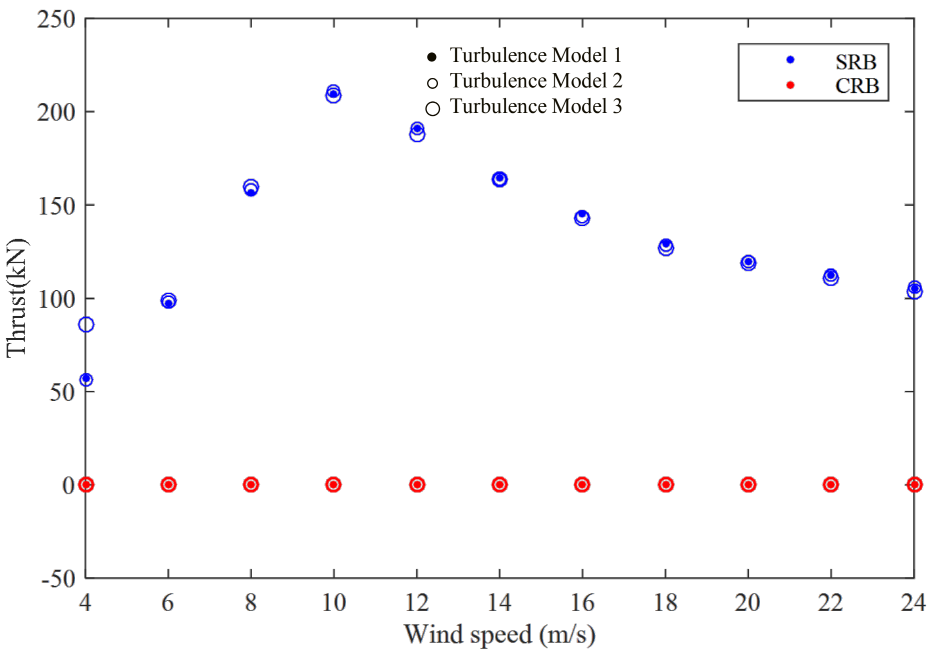
Field Measurements and Model Validation



- First set of results on motion validation are shown here
- Trunnion displacement measurements were taken from a 1.5-megawatt turbine
- Measurements taken at 10m/s average wind speed
- SIMPACK results showed good correlation
- Further measurements have been planned.

Loads at SRB and CRB

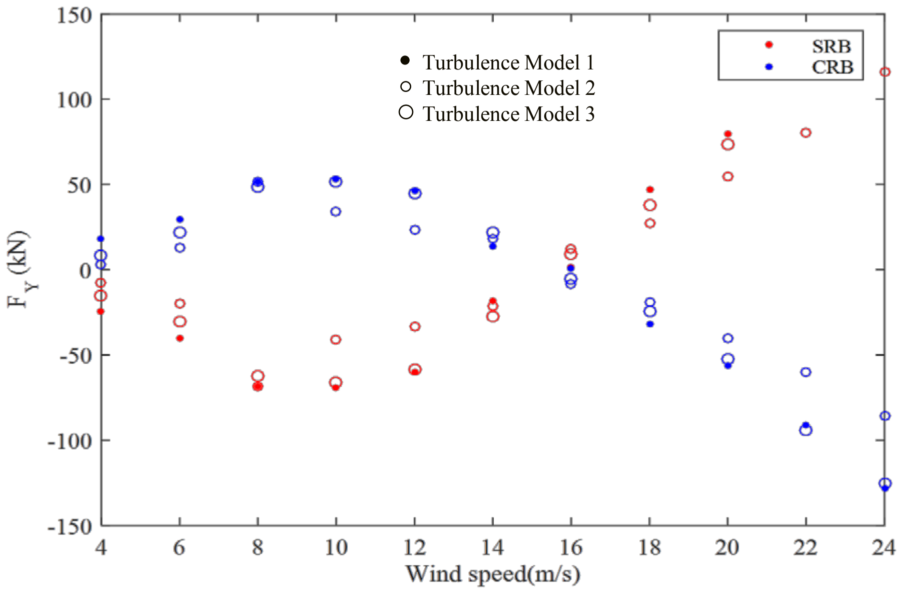


Results for three turbulence models are shown here

SIMPACK simulations showed :

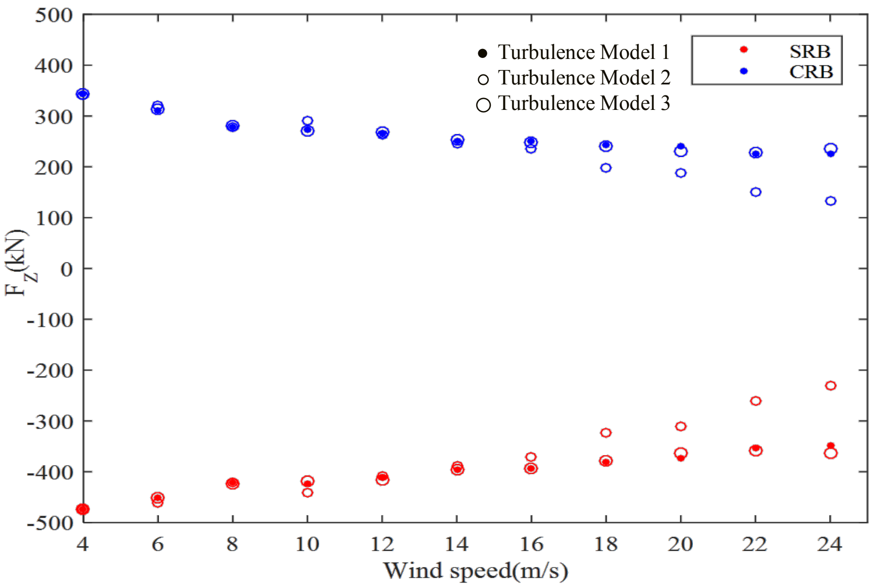
- Thrust loads followed the blade pitch action
- Main bearing carried all of the thrust loads
- CRB at the carrier did not support any thrust

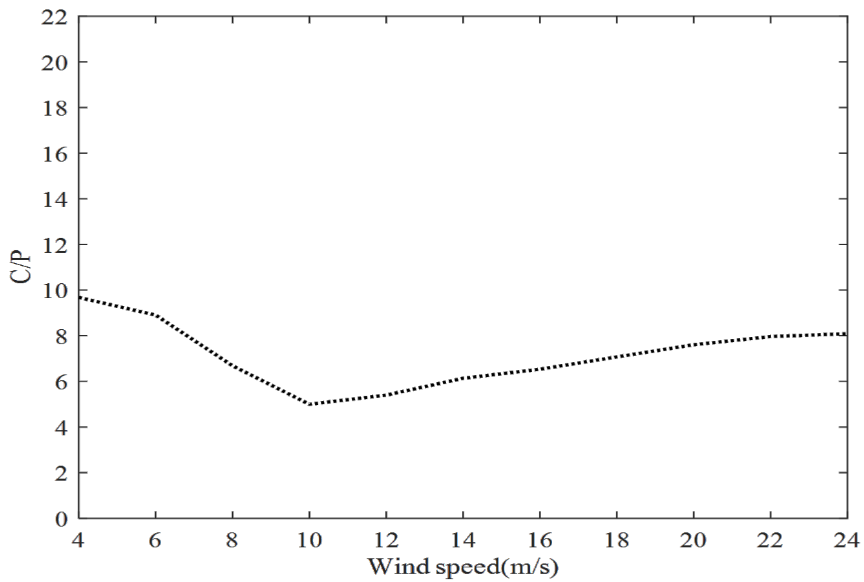
Loads at SRB and CRB



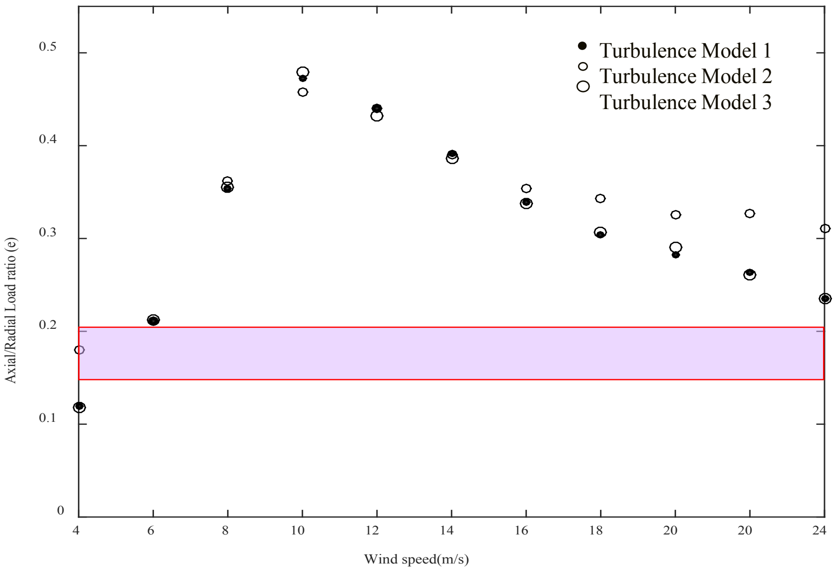
SIMPACK simulations showed :

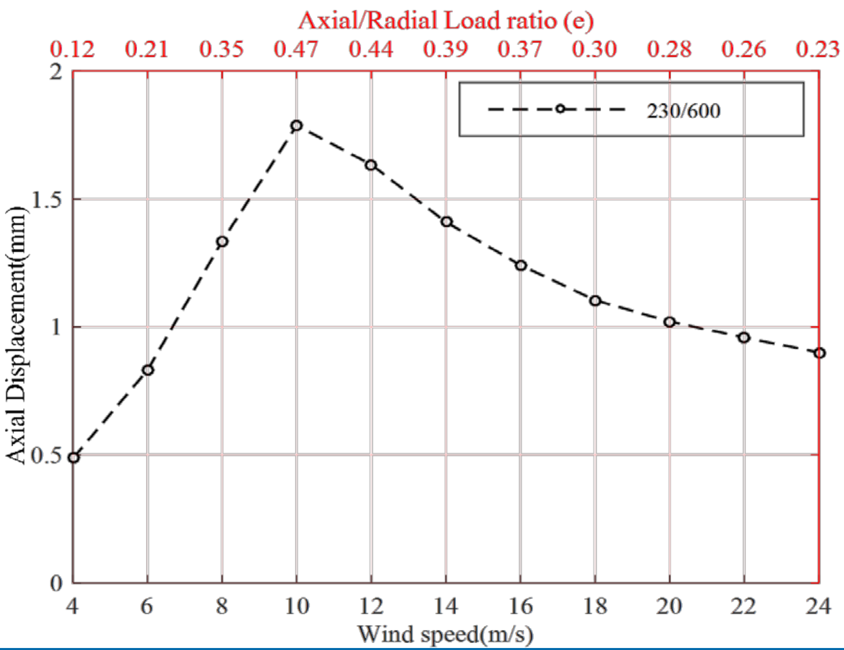
- Both SRB as well as CRB supported radial loads
- The reactions were opposite in sense
- **4< C/P < 10** suggests high loads and reduced grease service life (Klueber Lubrication)





Loads at SRB and CRB





SIMPACK simulations showed :

- Axial/radial load ratio, *e* followed the thrust loads
- Actual value of *e* > 22% for a majority of the operating span of the wind turbine
- Maximum value of *e* was up to 47%

Results for three turbulence models are shown here

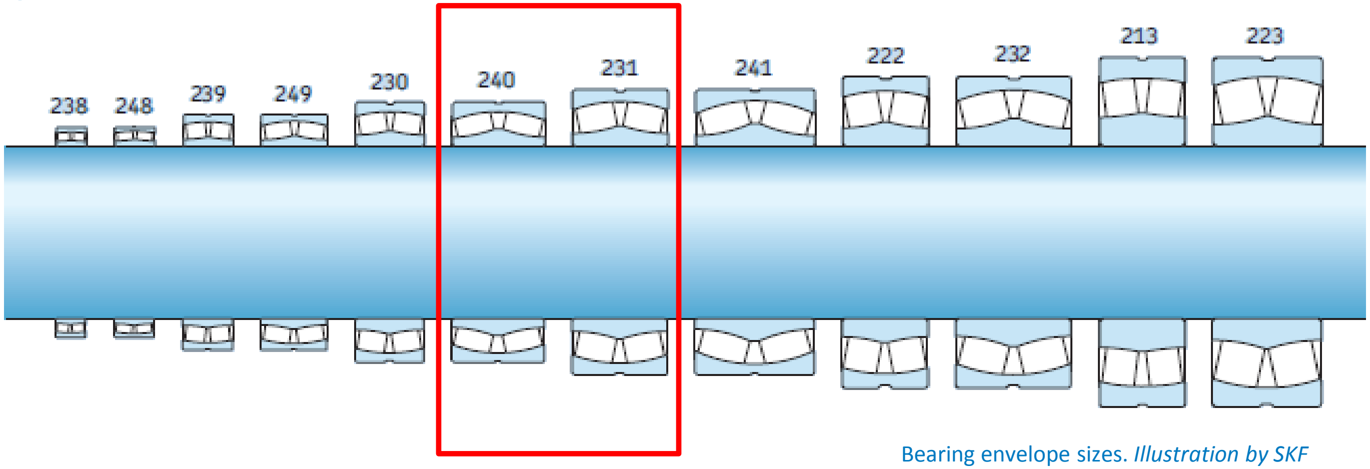
- Raceway displacement also followed the thrust loads
- Maximum displacement up to 1.78mm was observed
- Combination of large load ratio and raceway displacement
- Rollers→ excessive sliding with rolling.

Mitigation Case Studies for TPM

- Solutions to mitigate the damage from large thrust load and roller displacements were investigated in the following case studies:
  - Case Study I: Use of larger envelope bearings
  - Case Study II: Variation of internal radial clearance
  - Case Study III: Use of TRB as a carrier bearing.

Case Study I: Use of Larger Envelope Bearings

The TPM configuration had a main shaft bore diameter of 600 mm, a 230/600/ CA W33 bearing



Bearing envelope sizes. *Illustration by SKF*

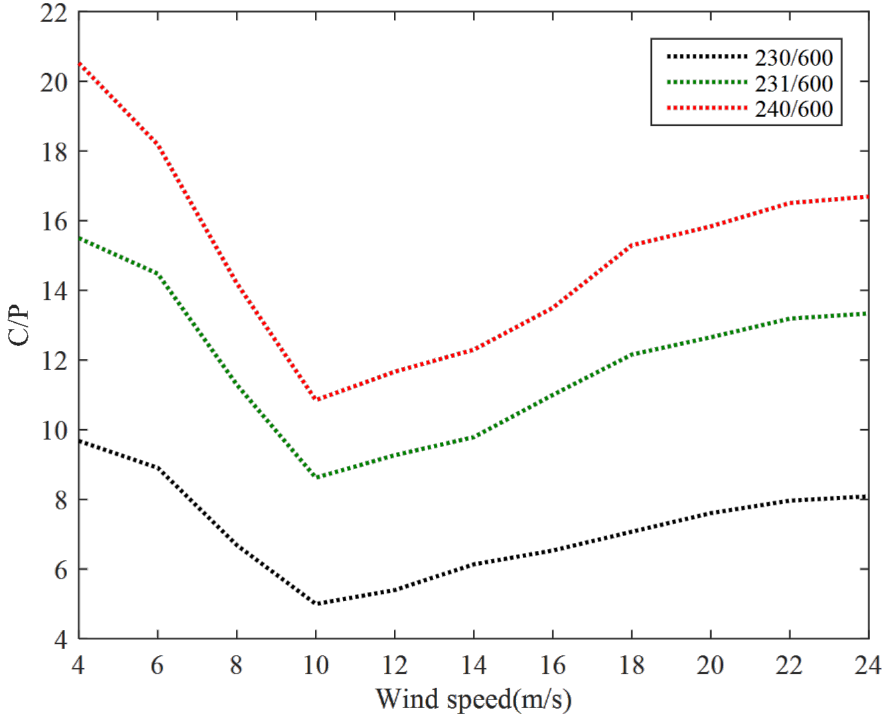
In this case study, the larger bearing envelope series 240 and 231 were chosen.

Properties included:

- Increase in face width/ outer bore diameter
- Increase in stiffness.

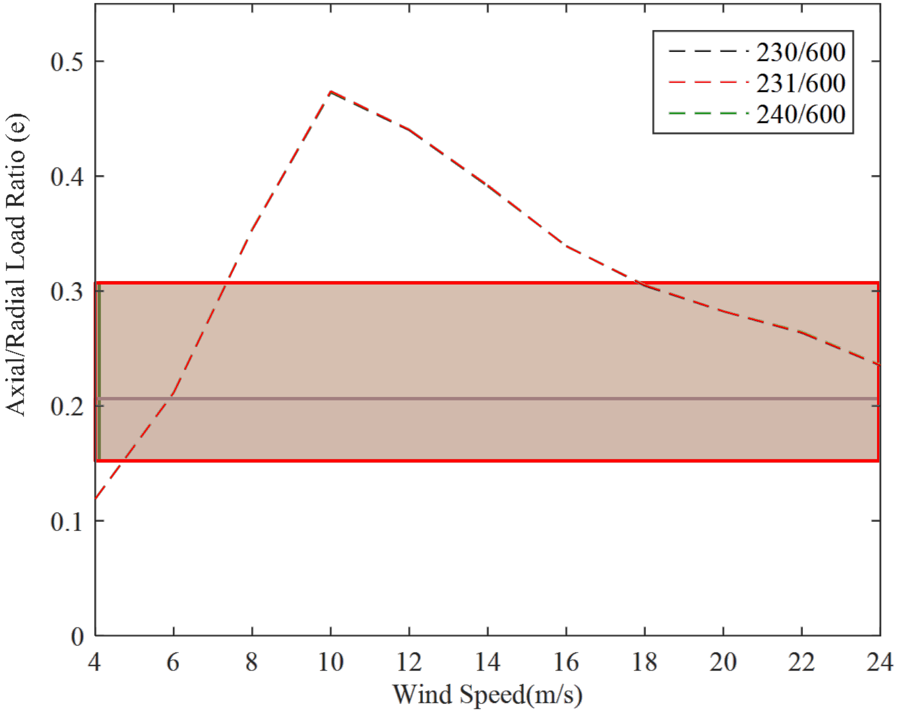
Item	230/600	231/600	240/600
Rollers	28	29	22
Dynamic load rating (kN)	6,252	8,580	10,738
Static load rating (kN)	11,400	17,000	18,000
Load limit	0.22	0.3	0.3

Results: Loads and Displacements



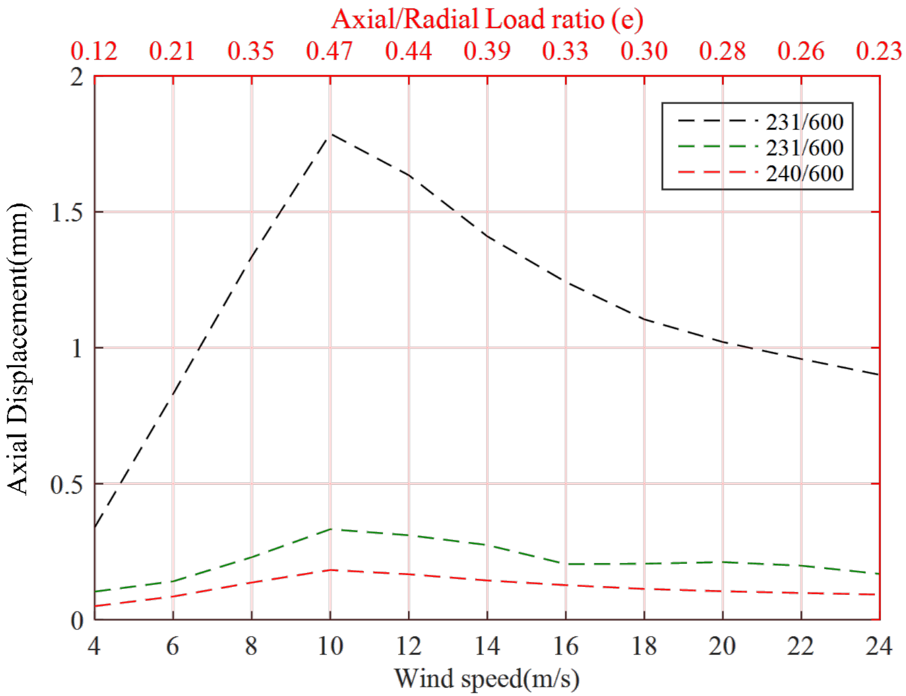
The results of SIMPACK simulations found:

- Larger bearings provided larger C/P ratio→ substantial load margin



- Yet, axial/radial load ratios did not necessarily improve with larger bearings

Results: Loads and Displacements



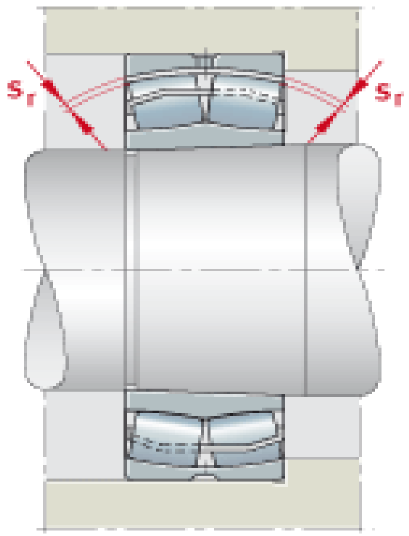
The results of SIMPACK simulations found:

- Raceway displacements could be significantly reduced with 240/600.

Case Study II: Adjusting Internal Clearance

Diametrical clearance is defined as the maximum diametrical distance that one race can move freely relative to other

- Influences bearing load distribution and fatigue life (Oswald 2012)



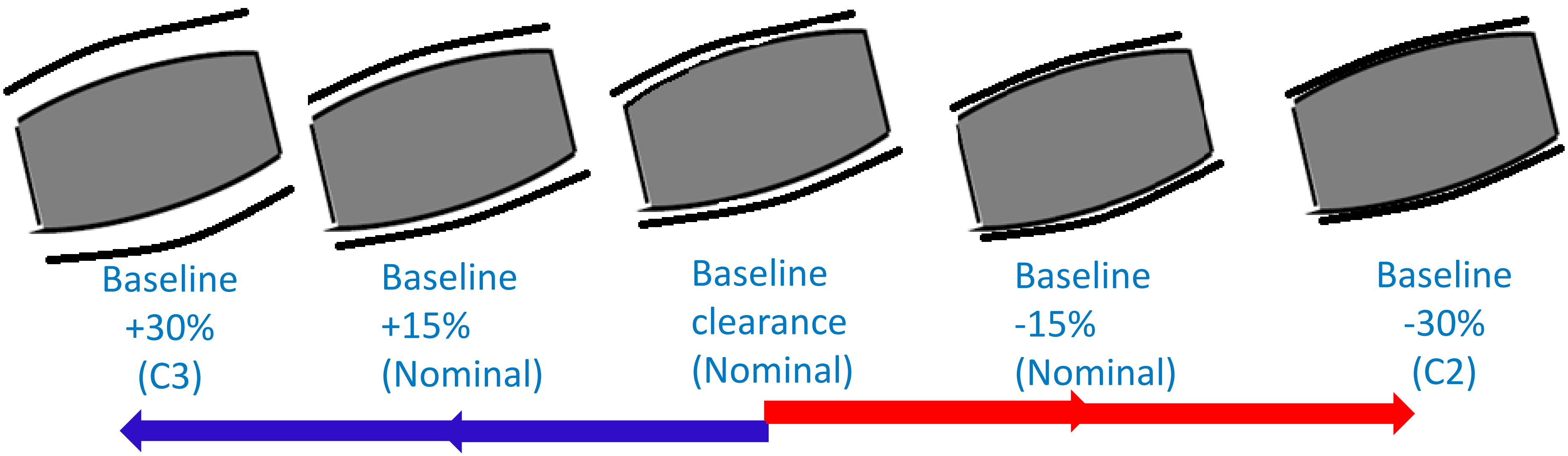
Diametric Clearance
Illustration by Schaeffler Group

Case Study II: Adjusting Internal Clearance

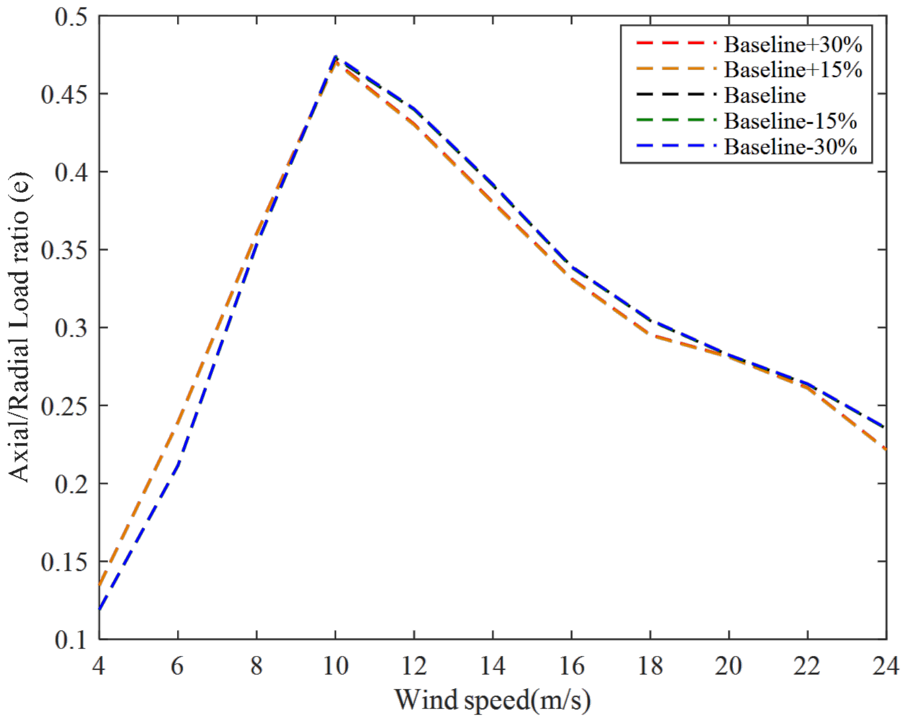
The goal of this work was to analyze sensitivity to radial internal clearance:

- The bearing was tested with five sets of radial internal clearance values with specifications of the class as laid out in ISO 5753-1:2009
- Clearances studied : Baseline,

Baseline +15% to +30%, and Baseline -15% to -30%



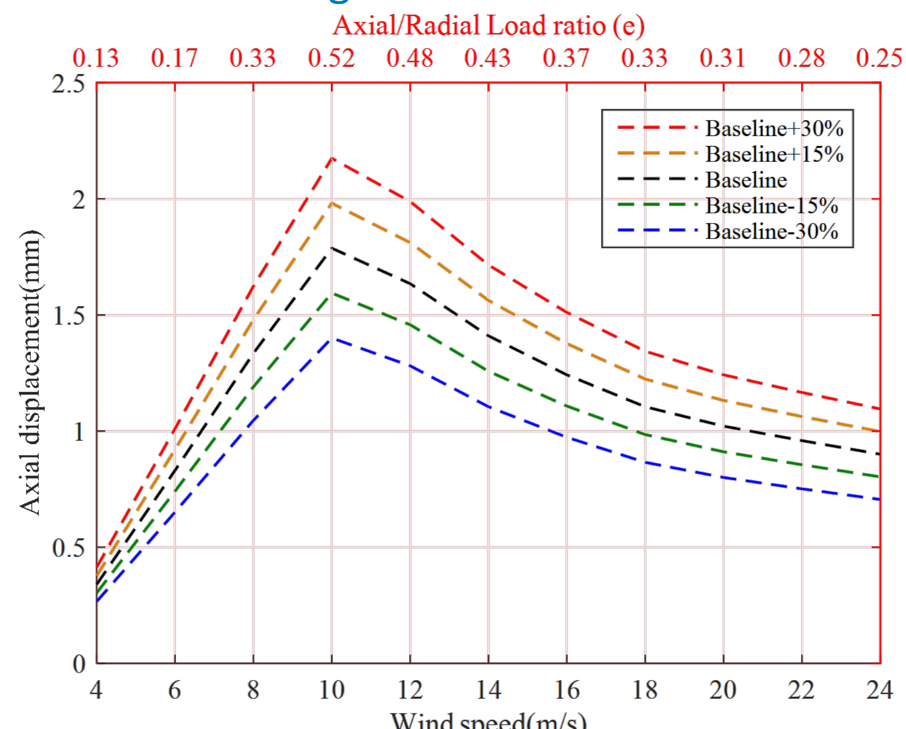
Loads and Raceway Motion



SIMPACK simulations found:

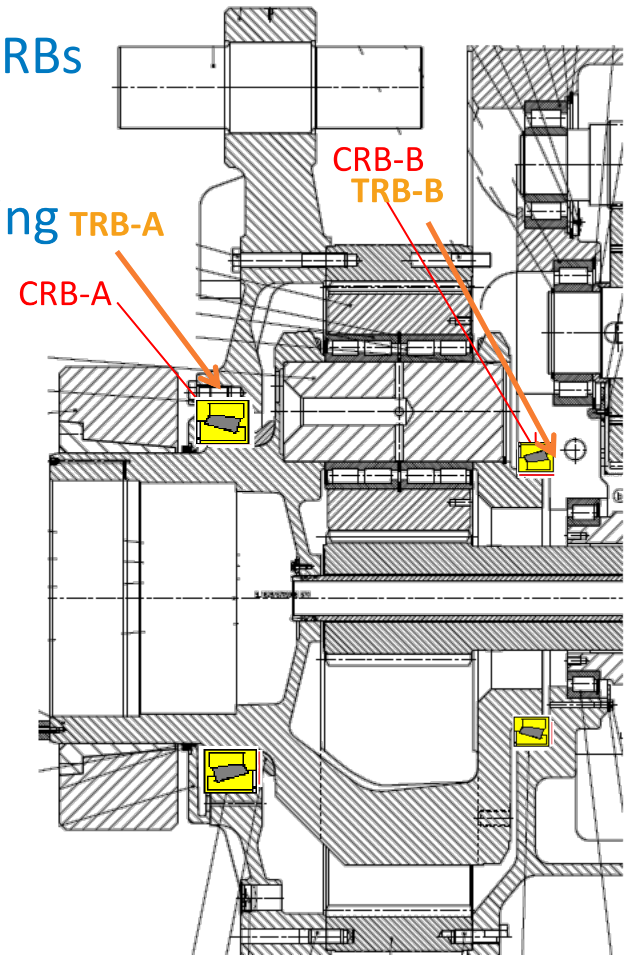
- Raceway axial displacements were reduced with tighter clearance.
- Every 15% change in clearance changed the displacement values by approximately 11%
- The peak value of displacements was still greater than 1 mm.

- Thrust loads and hence load ratios did not improve with clearance (the results overlap)



Case Study III: Using TRB as Planet Carrier Bearing

- Most TPM designs employ CRB/full-complement CRBs
- CRBs inherently support only radial loads
- All of the thrust loads supported by the main bearing
- Clearance is a critical factor.



Gearbox carrier model

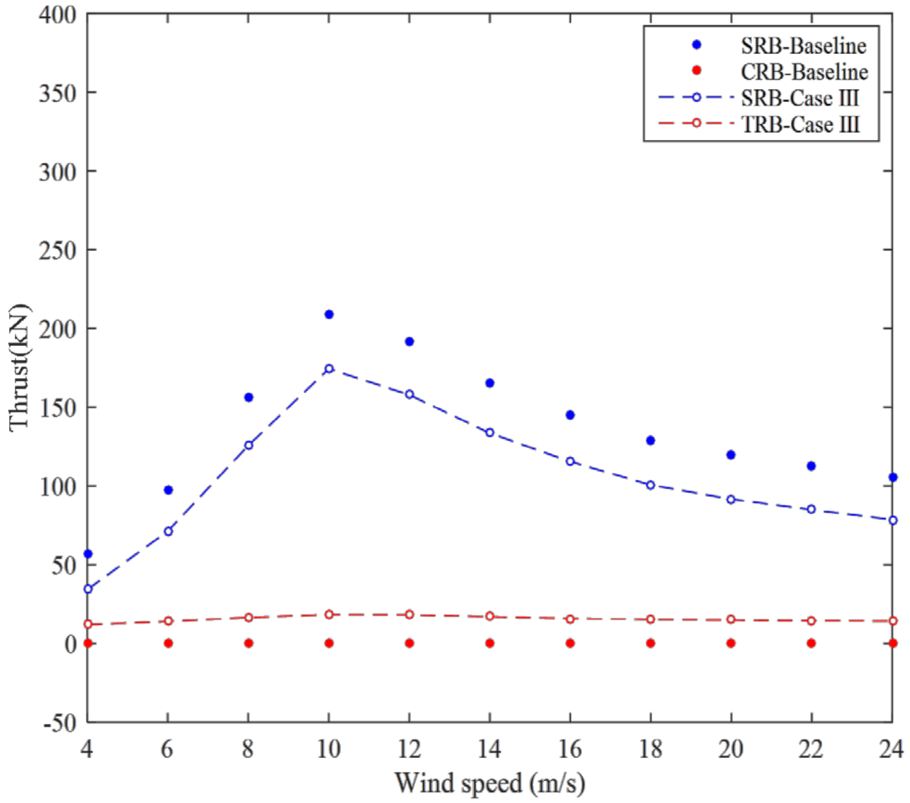
NREL is currently investigating a redesigned gearbox with preloaded TRB at carrier (Halse 2012).

Pros: TRBs can support large axial and radial loads, thus potentially relieving the main bearing loads.

Cons: Accurate setting of preload, costs, mounting adjustments, and trunnion redesign.

Needs systematic validation/field evaluation

Results: Loads and Displacement

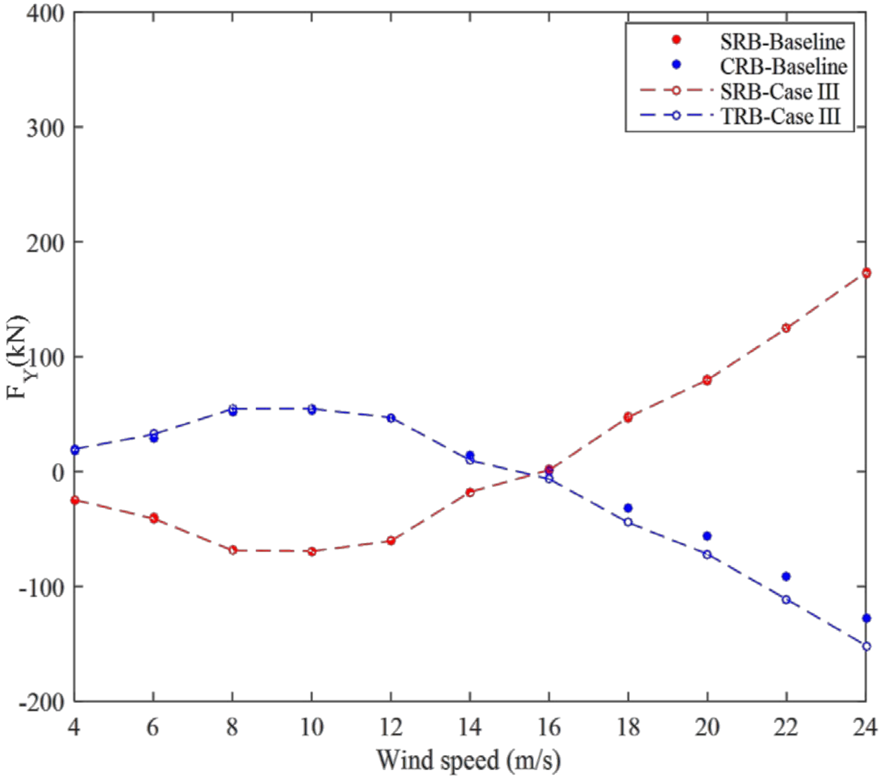


Simulation results of the redesigned carrier bearing showed that:

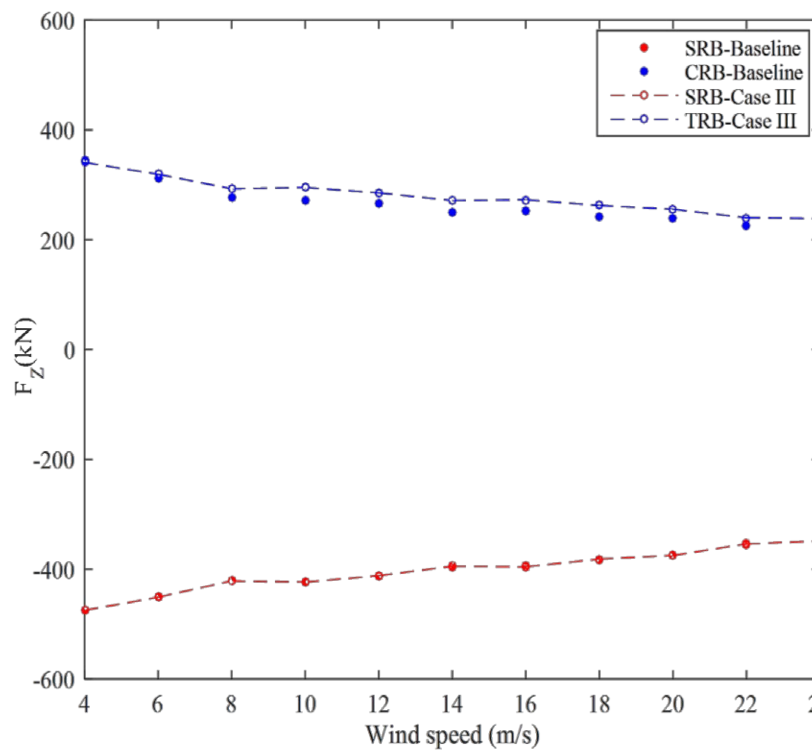
- Thrust loads on the SRB were reduced by up to 23%** compared to baseline configuration
- Baseline – CRB carried no thrust

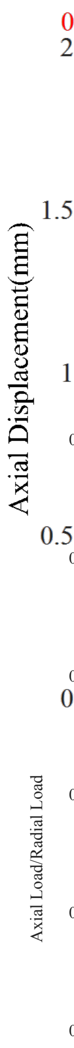
** Results are based on preliminary simulations, and are subject to change depending on axial stiffness of trunnion mounts, operating axial clearance on SRB and axial play on trunnion.

Results: Loads and Displacement

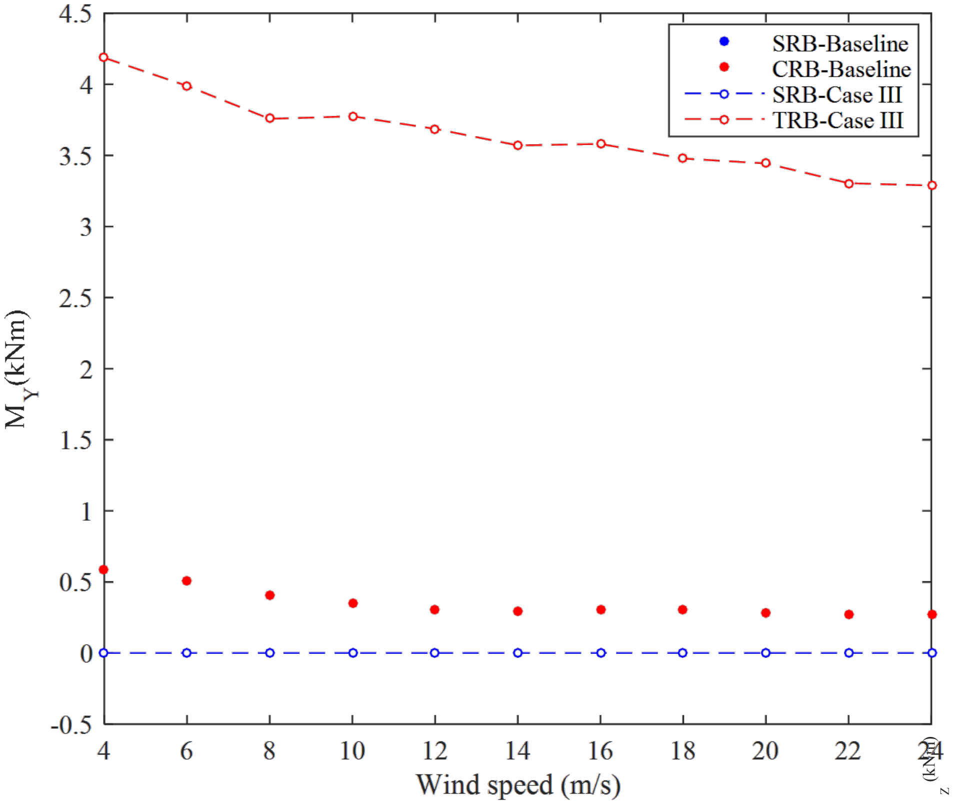


- Radial loads remained unchanged

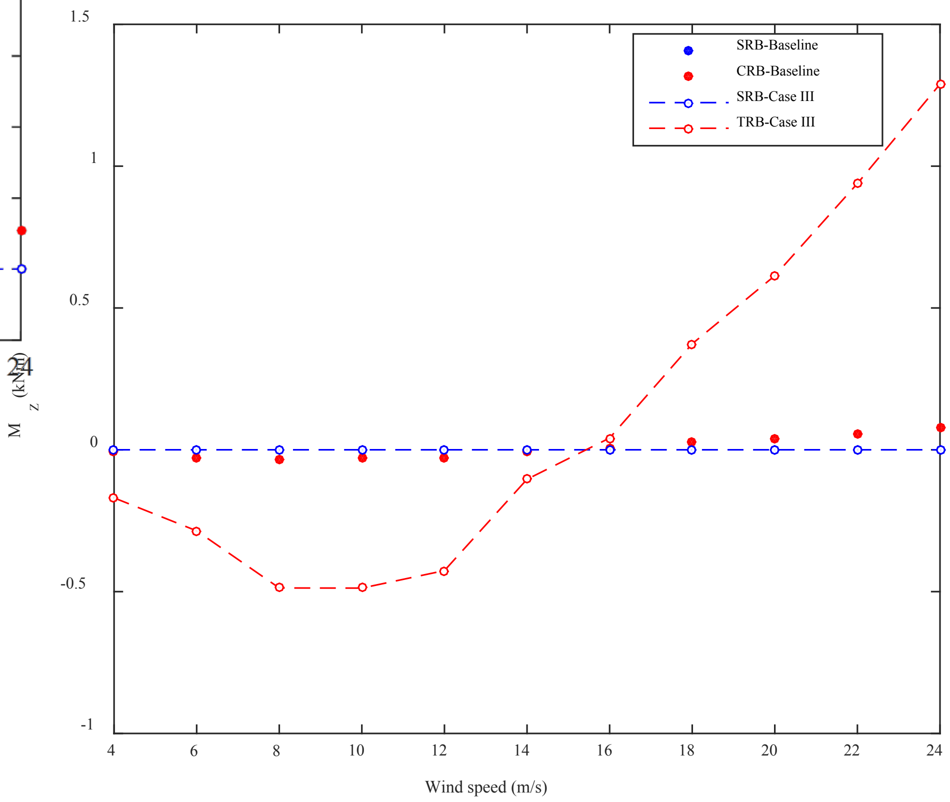




Results: Loads and Displacement

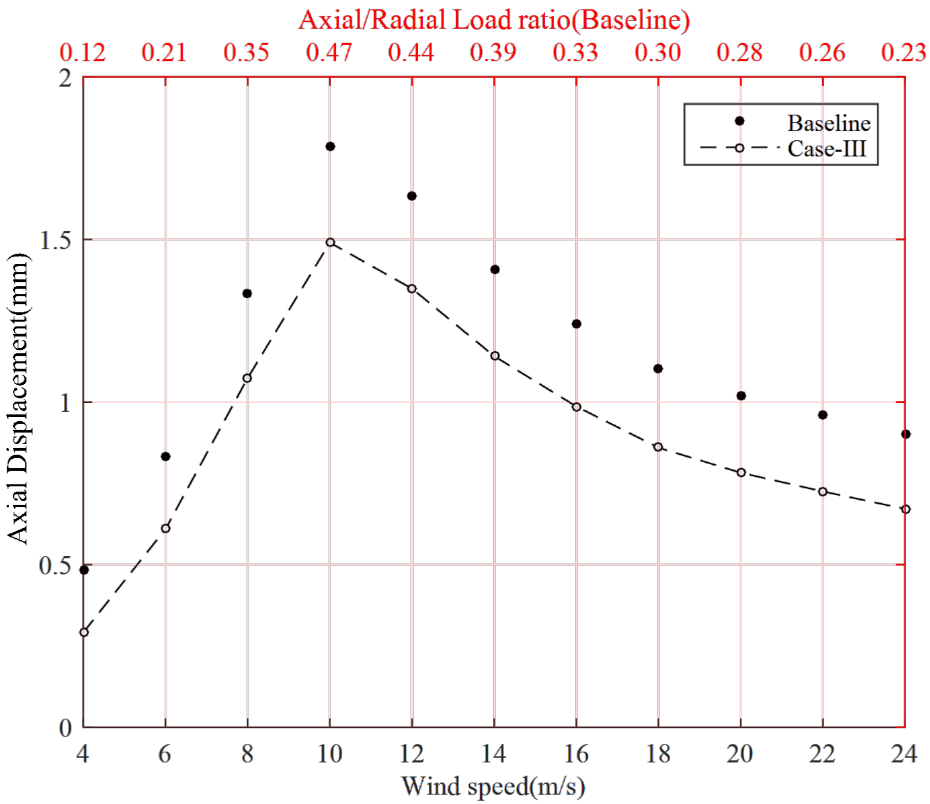


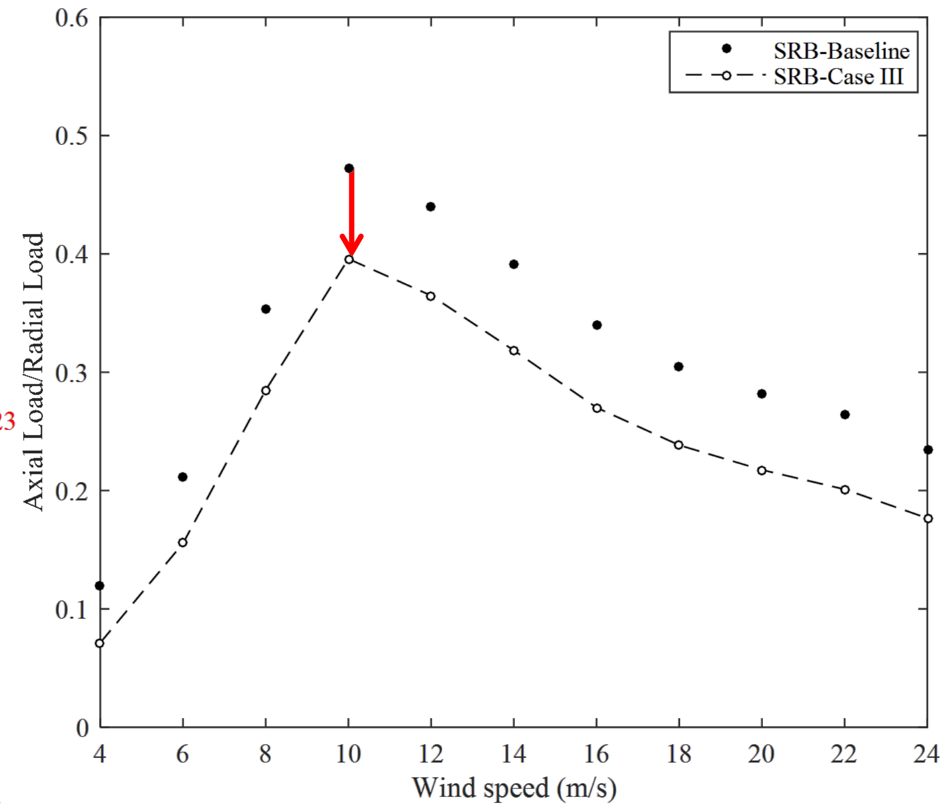
- Baseline – CRB carried no moments
- TRB – beneficial to gearbox as it supported nontorque loads



Results: Loads and Displacement

- Raceway displacements reduced by an average of 23%.





- Maximum load ratio reduced to 40%

Preliminary Findings

- This study validated the presence of excessive thrust loading and raceway displacement in SRBs in TPM
- Preliminary investigation on mitigation approaches contingent upon normal operation are summarized in the following table.

Study case	Load ratio	Raceway displacement	Pros	Cons
Larger bearings	No appreciable change	Significant reduction	Larger C/P margin	-
Tighter clearance	No appreciable change	Moderate reduction	-	-
TRB as a carrier bearing	Up to 20% reduction	Moderate reduction	Can help improve load distribution	May require system redesign, esp. trunnion

- Further load cases can provide detailed insight to main bearing behavior.

Further Work

- Investigate further design options, such as

  1) larger main bearing and TRB as carrier bearing

  2) bearing with tighter clearance and TRB as carrier bearing
- Identify the most optimal solution for TPM
- Evaluate bearing loading distribution sensitivity using Calyx
- Compare results against four-point mounting drivetrain configuration (subject to availability of data)
- Make recommendations for design improvements
- Publish results in a journal article.

References

- Brake, D. (April 2013). "WTG SRB Main Bearing Failures." Presented at the 2013 UVIG Wind Turbine/Plant Operations & Maintenance Users Group Meeting.
- Brooks, R. (April 2013). "Main Bearings." Presented at the 2013 UVIG Wind Turbine/Plant Operations & Maintenance Users Group Meeting. Portland, Oregon.
- Brooks, R. (2014). "Wind Drivetrain Bearing Reliability" (Webinar). Wind power Engineering & Development. Accessed April 21, 2015: http://www.windpowerengineering.com/design/mechanical /webinar-wind-drivetrain-bearing-reliability/.
- Guo,Y.; Bergua,R.; Van Dam,J.; Jove,J.; Campbell,J. (2014). "Improving wind turbine drivetrain designs to minimize the impacts of non-torque loads". Wind Energy., doi: 10.1002/we.1815.
- Guo, Y.; Keller, J.; La Cava, W. ; Austin, J. ; Nejad, A.R.; Halse, C.; Bastard, L.; Helsen, J. (2015). "Recommendations on Model Fidelity for Wind Turbine Gearbox Simulations." Presented at the 2nd Conference For Wind Power Drives, Aachen, March 3–4, 2015.
- Halse, C. (2012). *GRC Phase III Redesign Preliminary Design Review*. (internal only)
- Hau, E.; Renouard, H.V. (2013). *Wind Turbines: Fundamentals, Technologies, Application, Economics*. 3rd edition. Heidelberg: Springer Science & Business Media.
- Hornemann, M.; Crowther, A. (2013). *Establishing failure modes for bearings in wind turbines*. Accessed May 7, 2015: http://www.windpowerengineering.com/design/mechanical/bearings/establishing-failure-modes-for-bearings -in-wind-turbines/.
- Ionescu, L.; Pontius, T. (2009). "Main Shaft Support For Wind Turbine with a Fixed and Floating Bearing Configuration Tapered Double Inner Row Bearing Vs. Spherical Roller Bearing on The Fixed Position."
- ISO 281. (2007). Rolling Bearings - Dynamic Load Ratings and Rating Life. International Organization for Standardization. Switzerland.
- ISO 5753-1:2009-10. Rolling Bearings - Internal Clearance - Part 1: Radial Internal Clearance for Radial Bearings, International Organization for Standardization. Switzerland.

References (Continued)

- Klueber Lubrication. Tips and advice for the lubrication of rolling bearings. Accessed May 7, 2015: http://www.klueber.com/ecomaXL/files/Lubrication_of_rolling_bearings_tips_and_advice.pdf.
- NSK Rolling Bearings Catalogue CAT. No. E1102m. Accessed May 7, 2015: http://www.nskamericas.com/cps/rde/xbcr/na_en/E1102m.pdf.
- Oswald, F.B.; Zaretsky, E.V.; Poplawski, J.V. (2012). *Effect of Internal Clearance on Load Distribution and Life of Radially Loaded Ball and Roller Bearings*. NASA/TM—2012-217115. Cleveland, Ohio: National Aeronautics and Space Administration. Accessed May 7, 2015: http://ntrs.nasa.gov/archive/nasa/ casi.ntrs.nasa.gov/20120008398.pdf.
- SKF. (2007). "Spherical roller bearings." Accessed April 21, 2015: http://www.skf.com/binary/56-29536/6100_EN.pdf.
- Schaeffler Group. (2015). "Rolling bearings fitting and dismantling." Accessed May 7, 2015: http://medias.ina.com/medias/en! hp.tg.cat /tg_hr*ST4_102835979.

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The Gearbox Reliability Collaborative drivetrain installed in the dynamometer for testing. ***Photo by Mark McDade, NREL 32734***