SEYBOLD Report
ISSN: 1533 - 9211
https://seyboldreport.net/

A STUDY ON BEARING LOADS AND FATIGUE FAILURE IN WIND TURBINE SYSTEMS

Kollibala Siva Rama Reddy S and Dr. Prashant Kumar Shrivastava

Department of Mechanical Engineering, Dr. A. P. J Abdul Kalam University, Indore (M.P), India.

Corresponding Author email: balasivaramareddy@gmail.com

Abstract:
The utilization of wind turbines as a reliable and sustainable source of energy has gained significant attention in recent years. Within the wind turbine generator system, bearings play a crucial role in ensuring efficient operation. However, the bearings employed in wind turbines face immense challenges, including heavy loads, high speeds, and harsh environmental conditions, which can result in fatigue failure. Accurate prediction of the fatigue life of wind turbine bearings is therefore vital for ensuring the reliable and long-term performance of wind turbines. This review article provides a comprehensive overview of the fatigue failure modes observed in wind turbine bearings. It explores various load measurement techniques employed to analyze bearing loads in wind turbine systems and discusses the mathematical models utilized for predicting the fatigue life of bearings. Additionally, the paper presents an examination of experimental investigations on load measurement in wind turbine bearings and highlights the importance of data acquisition systems and software used for analyzing bearing performance. Furthermore, the review discusses the current state of research in the field and identifies potential avenues for future investigations. The significance of accurate fatigue life prediction in wind turbine bearings is emphasized, as it enables proactive maintenance strategies and enhances the overall reliability and efficiency of wind turbine systems.

1. Introduction

Wind energy is rapidly emerging as a prominent source of renewable energy, and wind turbines are gaining widespread popularity for electricity generation. Wind turbines exhibit a wide range of sizes, from small-scale installations catering to individual homes or businesses, to expansive wind farms capable of supplying power to entire communities. The electricity production capacity of a wind turbine is contingent upon factors such as wind speed and turbine size. Higher wind speeds and larger turbine dimensions correspond to increased electricity generation potential [1]. Notably, wind turbines are highly regarded as a form of sustainable energy due to their negligible greenhouse gas emissions and minimal operational expenses once installed. Functioning as key components in wind turbines, bearings are pivotal for ensuring efficient operation. However, the demanding operational conditions of wind turbines, characterized by heavy loads, high speeds, and severe environmental exposures, render the bearings susceptible to fatigue failure. Consequently, accurate prediction of fatigue life in wind turbine bearings becomes imperative for ensuring reliable turbine performance [2]. The integral role of bearings in wind turbines is to facilitate smooth and efficient rotation of the rotor blades. Various types of bearings are employed in wind turbines, encompassing main bearings, pitch bearings, and yaw bearings, as illustrated in Figure 2. Main bearings, positioned at the turbine base, bear the weight of the rotor and nacelle. Typically, these bearings assume the form of large-scale, double-row, or four-row tapered roller bearings designed to accommodate both radial and axial loads. Pitch bearings, on the other hand, enable adjustment of the rotor blade angle to optimize performance in response to changing wind conditions. These bearings are typically smaller in size and may adopt either cylindrical roller bearings or angular contact ball bearings. Yaw bearings, responsible for rotating the nacelle and rotor assembly to align the blades with the wind direction, are critical components subjected to substantial loads and vibrations inherent in wind turbines. Typically, they comprise large-scale, double-row ball or roller bearings engineered to handle both radial and axial loads.

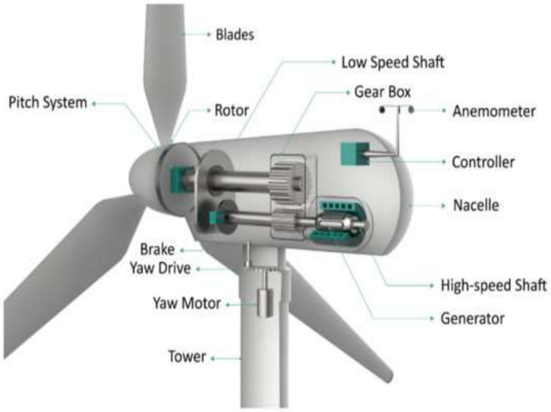


Fig 1 : Components of wind turbine [2]

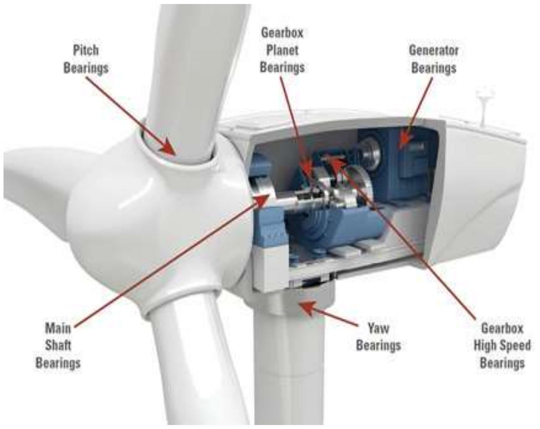


Fig 2 : Types of bearings in wind turbine [3]

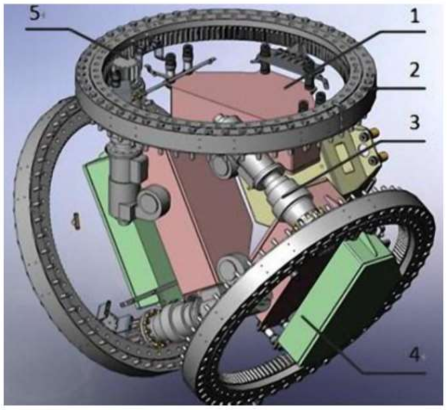


Fig 3. Pitch system [4] (1) Pitch controller. (2) Slewing bearing. (3) Pitch motor. (4) Battery cabinet. (5) Gearbox.

Fig 4. Cut section Four-point contact ball bearings single-row slewing bearing with internal gears [7]

Fig 5. Cut section of Double-row slewing bearing with internal gears [7]

Fig 6. Cut section of Double-row slewing bearing with External gears [7]

Fig 7. Cut section of Cross roller bearings [8]

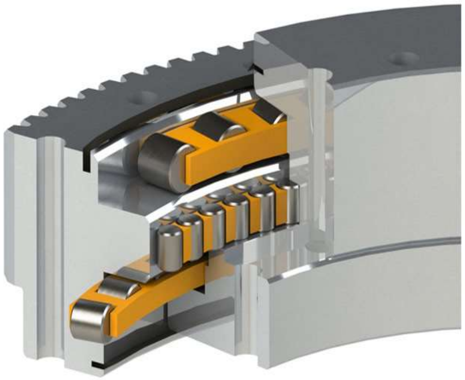


Fig 8. Cut section of Cross roller bearings [9]

A slewing bearing, specifically designed to accommodate both axial and radial loads while enabling rotational movement around a central axis, comprises two rings: an inner ring affixed to a stationary structure and an outer ring affixed to a rotating structure. These rings are connected by a series of rolling elements, such as balls or rollers, which facilitate relative rotation between the two rings. Slewing bearings find widespread utilization across diverse industrial sectors, including but not limited to cranes, excavators, wind turbines, and solar trackers. Their inherent design and engineering make them capable of withstanding substantial loads, high rotational speeds, and a broad spectrum of environmental conditions.

1.Types of Slewing Bearings in Wind Turbines

1.1 Four-Point Contact Ball Bearings

Four-point contact ball bearings are a specialized type of slewing bearing that feature a single row of balls arranged in a four-point contact configuration between the inner and outer rings. This unique design enables them to effectively handle both axial and radial loads while maintaining a low profile and high stiffness. The four-point contact arrangement facilitates a large contact angle between the balls and raceways, allowing the bearing to withstand loads from various directions. This makes them well-suited for applications requiring high load capacity and precise positioning, such as in cranes, excavators, and robotics. These bearings are typically constructed from high-quality, hardened steel to ensure durability, and they are available in a range of sizes and configurations to accommodate diverse applications.

1.2 Double-Row Ball Bearings

Double-row ball bearings, another variant of slewing bearings, feature two rows of balls arranged within a groove between the inner and outer rings. This design enables them to handle both high radial and axial loads while maintaining a relatively low profile. The presence of two ball rows provides a larger contact area between the balls and raceways, allowing for greater load capacity compared to single-row bearings. These bearings find utility in applications necessitating high load capacity, such as cranes, excavators, and wind turbines. They are available in various configurations, including open, sealed, or shielded, and are typically manufactured from high-quality steel. Different types of cages can be utilized based on the specific requirements of the application. Double-row ball bearings are favored for their ability to handle high loads while maintaining a compact design.

1.3 Cross Roller Bearings

Cross roller bearings are a specialized type of slewing bearing that employ cylindrical rollers arranged in a crossed pattern between the inner and outer rings. This configuration provides a substantial contact area between the rollers and raceways, enabling the bearings to effectively handle high radial loads, moment loads, and tilting moments while maintaining a compact profile. These bearings excel in applications demanding high precision and accuracy, such as machine tools, robotics, and medical equipment. Their crossed roller arrangement facilitates the handling of radial and axial loads, as well as tilting and torsional loads. Cross roller bearings are known for their versatility, reliability, and suitability for a wide range of industrial and commercial applications.

1.4 Three-Row Roller Bearings

Three-row roller bearings feature three rows of rollers aligned in a linear manner between the two rings. They are specifically designed to endure extremely high radial loads and are commonly employed in heavy-duty applications such as cranes and excavators. The presence of three roller rows ensures a significant contact area between the rollers and raceways, enabling them to withstand high radial loads and moment loads. Although they can handle some axial loads and tilting moments, their capacity in these regards is not as extensive as that of four-point contact ball bearings. These bearings are available in various sizes and configurations, including open, sealed, or shielded, and are typically constructed from high-quality steel. Different types of cages can be employed based on specific application requirements.

2. Performance and Applications of Slewing Bearings

2.1 Load Capacity and Stiffness

Load capacity and stiffness are crucial parameters to consider in wind turbine bearings. Load capacity refers to the maximum load that a bearing can sustain without failure. Wind turbines experience significant axial, radial, and moment loads, and the bearing must be able to withstand and distribute these loads effectively. By accurately determining the load capacity, engineers can ensure that the bearing can handle the forces imposed during normal operation and withstand any abnormal or extreme conditions.

Stiffness, on the other hand, refers to the ability of the bearing to resist deformation under load. A high stiffness bearing minimizes deflection and maintains precise alignment between the rotating components, allowing for smooth and efficient operation. It helps to prevent excessive vibration and misalignment, which can lead to premature wear, increased friction, and potential failure.

Optimizing the load capacity and stiffness of wind turbine bearings is crucial for ensuring their reliable and efficient performance. Through advanced analysis techniques such as finite element analysis (FEA) and experimental validation, engineers can design bearings with enhanced load-carrying capabilities and optimal stiffness characteristics. This ensures that the bearings can effectively support the loads experienced in wind turbine systems, minimize wear and fatigue, and contribute to the overall reliability and longevity of the turbine.

2.2 Application in Cranes, Excavators, and Robotics

Bearings find wide-ranging applications in cranes, excavators, and robotics. In cranes, bearings support the rotating structure and enable smooth movement of the boom, ensuring efficient lifting and positioning of heavy loads. Excavators rely on bearings for precise motion control of components like the boom, arm, and bucket, enabling effective digging and material handling operations. In robotics, bearings facilitate precise and smooth articulation of robot joints, contributing to accuracy and flexibility in various robotic applications. From withstanding heavy loads in cranes and excavators to providing precise motion control in robotics, bearings play a crucial role in enhancing the performance and reliability of these machines.

2.3 Utility in Wind Turbines

Bearings play a crucial role in wind turbines by supporting the main shaft, rotor, and other rotating components. They enable smooth rotation, proper alignment, and efficient transfer of mechanical energy from the blades to the generator. Wind turbine bearings are designed to withstand heavy loads, harsh environmental conditions, and cyclic loading, ensuring reliable operation and minimizing downtime. They contribute to the overall performance, longevity, and cost-effectiveness of wind turbines, making them an essential component in the generation of renewable wind energy.

3. Design Challenges and Considerations for Wind Turbine Bearings

3.1 Harsh Environmental Conditions

Wind turbines operate in challenging environments with exposure to wind, moisture, temperature variations, and contaminants. Bearings must be designed to withstand these conditions, preventing corrosion, wear, and damage. Proper sealing and lubrication systems are essential for protecting the bearings and ensuring their long-term reliability.

3.2 Material Selection and Durability

Material selection is a critical aspect of wind turbine bearing design to ensure durability and long-term performance. Bearings need to withstand heavy loads, corrosion, fatigue, and wear while operating in diverse temperature ranges. High-quality alloy steels are commonly chosen for their high load capacity and fatigue resistance. Corrosion-resistant materials, such as stainless steels or specialized coatings, are essential to combat environmental factors. Wear-resistant materials and heat-resistant steels maintain performance and minimize surface damage. Compatibility with lubricants and cost considerations are also important factors in material selection. By carefully considering these aspects, wind turbine bearings can be designed to deliver durability, reliability, and optimal performance in demanding operating conditions.

3.3 Lubrication and Maintenance Practices

Wind turbines are typically located in remote areas, making maintenance and servicing challenging. Bearing designs should consider ease of access for maintenance activities such as lubrication, inspection, and potential replacement. Simplified maintenance procedures and bearing designs that facilitate quick and efficient servicing contribute to minimizing downtime and associated costs.

4. Role of Slewing Bearings in Wind Turbines

4.1 Transferring Loads and Facilitating Rotor Rotation

Wind turbines are subjected to a wide range of loads during operation, including both radial and axial loads [25].

Radial loads in wind turbines are primarily due to the weight of the rotor and the aerodynamic forces acting on the blades. The weight of the rotor is transmitted through the main shaft and bearings, while the aerodynamic forces are transmitted through the blades and the rotor hub. In addition to these loads, wind turbines may also be subjected to side loads due to wind gusts or other environmental factors [26].

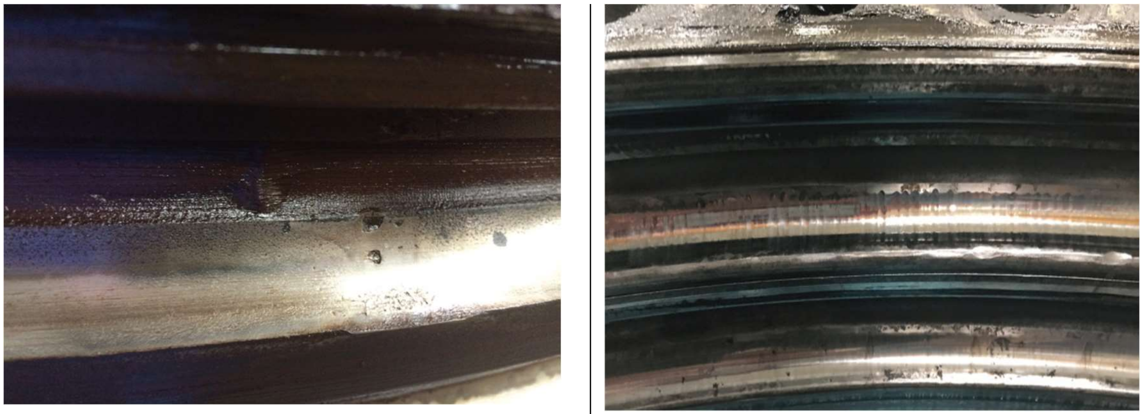
Axial loads in wind turbines are primarily due to the torque generated by the rotor. The torque is transmitted through the main shaft and thrust bearings and is used to drive the generator. Wind turbines may also be subjected to additional axial loads due to wind gusts or changes in wind direction [27].

4.2 Importance of Reliable and Efficient Operation

Corrosion-induced failure in slewing bearings due to pitting and corrosion of raceways or rolling elementsshown in Fig. 9. In addition to fatigue failure, slewing bearings are also susceptible to other failure modes such as wear and corrosion. Wear occurs when the bearing surfaces experience friction and material is gradually removed from the raceways or rolling elements. Over time, this wear can lead to increased clearance between components, causing the bearing to become loose or even seize up, ultimately resulting in failure. Corrosion is another significant factor that can contribute to the failure of slewing bearings. Exposure to moisture, chemicals, or other environmental factors can lead to the corrosion of raceways or rolling elements. Corrosion can cause pitting or deterioration of the bearing surfaces, compromising their structural integrity and leading to premature failure. It is important to note that proper design, adequate lubrication, and regular maintenance are crucial in mitigating the risks of wear, corrosion, and fatigue failure in slewing bearings. Appropriate material selection and surface treatments can also help enhance the bearing's resistance to these failure modes. Regular inspection and monitoring are necessary to detect any signs of wear, corrosion, or fatigue cracking early on, allowing for timely maintenance and replacement of affected components

(a) Corrosion pitting in ball

(b) Corrosion pitting in rings



(c) Denting and corrosion

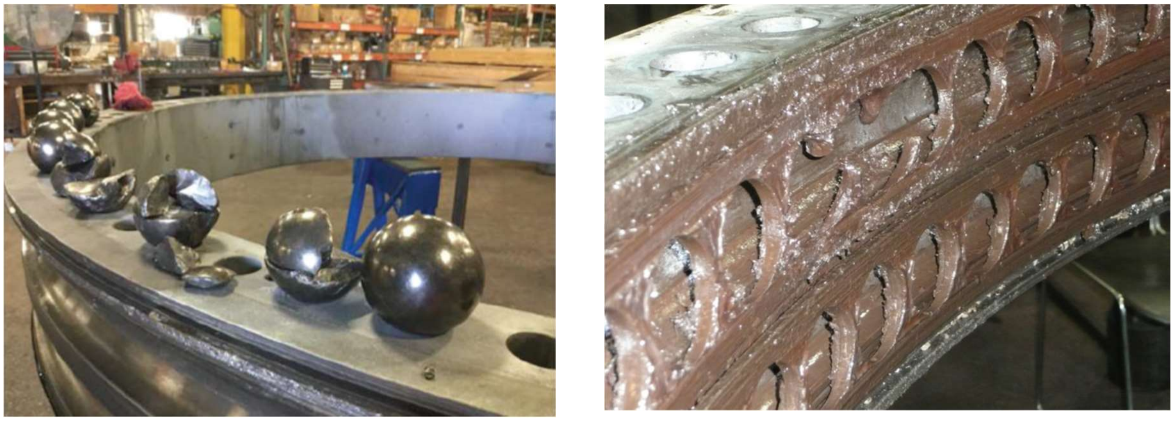
(d) False brinelling and corrosion

Fig 9 : Corrosion fatigue failure [5]

Fig. 10: Failure modes associated with overloading in slewing bearings, including contact truncation, core crushing and cold working, fractured balls, and separator fracture. In addition to fatigue, wear, and corrosion, overloading failure is another significant failure mode that can occur in slewing bearings. Overloading failure happens when the bearing is subjected to loads that exceed its design capacity, resulting in deformation, increased wear, or even catastrophic failure. Several failure modes can be associated with overloading in slewing bearings, including contact truncation, core crushing and cold working, fractured balls, and separator fracture as depicted in Fig. 10. Contact truncation occurs when the bearing is subjected to excessive loads, leading to localized contact stress concentrations and potential damage to the raceway surfaces. Core crushing and cold working can occur when the bearing experiences high compressive loads, causing deformation and plastic flow in the bearing components. Fractured balls and

separator fracture can result from the bearing being subjected to excessive forces, leading to the failure of individual components within the bearing assembly. Overloading failure can be attributed to various factors, including improper installation, misalignment, or the application of loads that exceed the bearing's intended capacity. For instance, in wind turbines, overloading can occur if the turbine is operated in high wind speeds or if the rotor is not properly aligned with the wind direction, causing excessive loads on the slewing bearing. To prevent overloading failure in slewing bearings, it is crucial to ensure proper installation and alignment of the bearing and to ensure that the applied loads are within the designed capacity of the bearing. In the case of wind turbines, monitoring wind conditions and optimizing the position of the rotor can help mitigate the risk of overloading, ensuring the reliable performance and longevity of the slewing bearing.

(a) Contact truncation (b) Core crushing and cold working



(c) Fractured balls (d) Separator fracture

Fig 10 : Overloading failure [5]

4.3 Maintenance and Inspection Requirements

Improper installation or maintenance is a significant factor that can contribute to the failure of slewing bearings. This can encompass a range of issues, including misalignment, insufficient lubrication, or contamination of the bearing. These problems can have detrimental effects on the performance and longevity of the bearing, leading to premature wear or failure. Misalignment occurs when the bearing is not properly aligned with the mating components or when there is a deviation from the specified tolerances. Misalignment can result in uneven distribution of loads, increased friction, and accelerated wear of the bearing components. It is crucial to ensure proper alignment during the installation of slewing bearings to minimize the risk of failure. Insufficient lubrication is another common issue that can lead to bearing failure. Inadequate lubrication can result in increased friction and heat generation, leading to wear, corrosion, and eventually, failure of the bearing. It is essential to use the appropriate lubricant and ensure proper lubrication intervals to maintain optimal performance and prolong the lifespan of the bearing. Contamination of the bearing, such as the ingress of dirt, dust, or moisture, can also have detrimental effects on the bearing's performance. Contaminants can cause abrasive wear, corrosion, or the formation of particles that can disrupt the smooth operation of the bearing. Proper sealing, regular cleaning, and protection from environmental factors are necessary to prevent contamination and maintain the integrity of the bearing. To prevent these failure modes, it is essential to establish and follow a comprehensive maintenance and inspection program for slewing bearings. Regular inspections can help identify early signs of wear, misalignment, or contamination, allowing for timely corrective actions. Adequate lubrication and proper installation techniques should be employed to ensure optimal performance and maximize the service life of the slewing bearings.

5. Future Trends and Advances in Wind Turbine Bearing Technology

5.1 Enhanced Load Capacity and Performance

Pitch bearings are typically large, slewing bearings that can support the weight of the entire blade assembly, as well as the loads generated by wind and other external factors. They must be designed to withstand these loads while providing smooth and reliable operation under a range of operating conditions.

The design of pitch bearings can vary depending on the specific turbine design and manufacturer, but they generally consist of a set of inner and outer rings with rolling elements, such as balls or rollers, between them. The rolling elements allow for smooth rotation of the blades and help to distribute the loads evenly across the bearing surfaces. Pitch bearings are a critical component of wind turbines, enabling the blades to rotate and adjust their angle to optimize energy output. They must be designed to withstand the loads generated by wind and other external factors and maintained properly to ensure reliable and efficient operation of the turbine [39 - 41].

A pitch bearing test rig is a specialized testing setup designed to evaluate the performance and durability of pitch bearings under various operating conditions as shown in figure 13. These rigs are typically used by manufacturers and researchers to validate the design and quality of pitch bearings before they are installed in wind turbines.

A pitch bearing test rig typically consists of a rotating test platform that simulates the movement of the wind turbine blade, and a set of sensors and data acquisition systems that measure various parameters, such as bearing load, torque, and temperature. The test platform is typically driven by an electric motor, which can be programmed to simulate a range of operating conditions, including wind speed and direction as shown in figure 14.

Fig 13: Pitch bearing test rig [42]

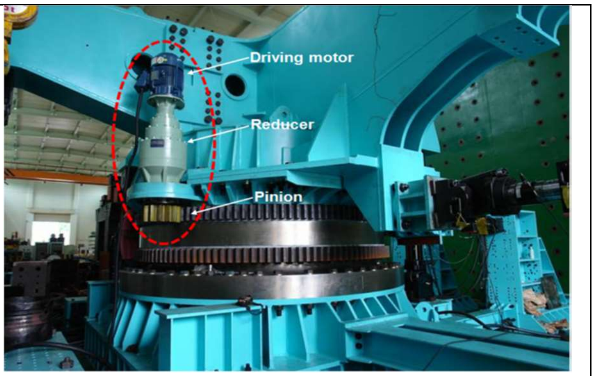


Fig 14:Arrangement of the drive system [42].

During testing, the pitch bearing is mounted on the test platform and subjected to a series of loading and unloading cycles, simulating the conditions it will experience during actual operation. The sensors and data acquisition systems record the performance of the bearing, including its load capacity, fatigue life, and overall durability.

Pitch bearing test rigs can also be used to evaluate the effect of different lubricants and operating conditions on the performance of the bearings. This can help manufacturers and researchers to optimize the design of the bearings and identify potential issues before they occur in the field. [42 – 44]

The experimental setup for load measurement may involve a test rig or a scaled-down model of the wind turbine, which can be used to simulate the loads and operating conditions experienced by the bearing in a real wind turbine. The test rig may include a motor or other device to simulate the rotation of the wind turbine, as well as sensors to measure the bearing loads and other relevant parameters.

During the experimental testing, the sensor data is typically recorded using a data acquisition system, which can collect and process the data in real-time. The data can then be analysed to determine the bearing loads and other relevant parameters, such as vibration, temperature, and noise levels.

The results of the experimental testing can be used to validate and calibrate mathematical models and simulations of the bearing's operation, as well as to identify areas of high stress or strain that may require further attention or optimization. The experimental data can also be used to optimize the design and materials of the bearing, and to develop more accurate and reliable life models for predicting the bearing's expected lifespan.

Overall, experimental investigation of load measurement in wind turbine bearings is an important tool for ensuring the reliability and efficiency of wind turbines, and can help to optimize the design and performance of wind turbine bearings over their expected lifespan

5.2 Integration of Condition Monitoring Systems

Measurement of bearing loads in wind turbines is an important aspect of monitoring and maintaining the health of the system. Several methods are used to measure bearing loads, including the use of load cells. Load cells are devices that are installed between the bearing and the support structure to measure the force transmitted through the bearing. They work based on the principle of strain gauges, where changes in deformation of a material result in a change in its electrical resistance. Load cells consist of a sensing element, typically a strain gauge or a group of strain gauges, bonded to a metal or other material. The sensing element is arranged in a specific pattern or configuration that allows it to measure the force applied to it. When a load is applied to the load cell, it deforms, causing a change in the electrical resistance of the sensing element. This change in resistance is proportional to the force applied to the load cell and can be measured using an electrical circuit. Load cells can be designed to measure either compression or tension forces or are available in various sizes, capacities, and types to suit different applications. In wind turbines, load cells are commonly used to measure the loads on the bearings, both radial and axial, and to monitor the performance of the system. The data obtained from load cells can be used to assess the health of the system, identify potential problems before they lead to failure, and optimize the performance of the wind turbine. Overall, load cells provide accurate and reliable measurements of bearing loads in wind turbines, helping to ensure the safe and efficient operation of the system.

Strain gauges are sensors that are bonded to the surface of the bearing and measure changes in strain caused by external loads. The strain gauges are wired to a data acquisition system that records the strain readings and calculates the corresponding load [28].

Strain gauges are sensors that are used to measure changes in strain or deformation in a material. They work on the principle that when a material is subjected to an external load, it undergoes a change in shape, which in turn results in a change in its electrical resistance.

A strain gauge consists of a thin strip of conductive material, such as a thin film of metal that is bonded to the surface of the material being measured. When the material is subjected to a load, it undergoes a deformation, which causes a change in the length and cross-sectional area of the conductive strip. This change in dimensions results in a change in the electrical resistance of the strip, which can be measured using a Wheatstone bridge or other electrical circuit.

The magnitude of the strain can be calculated from the change in resistance of the strain gauge using the formula:

$\varepsilon = \Delta L / L$

Where ε is the strain, ΔL is the change in length of the conductive strip, and L is the original length of the strip.

Strain gauges are commonly used in a variety of applications, including monitoring the deformation of structures, measuring the stress in materials, and measuring the loads on bearings, such as in wind turbines. They are highly sensitive and can provide accurate and reliable measurements of strain over a wide range of loads and temperatures [28 - 31].

Accelerometers are sensors that measure the acceleration of the bearing or other components of the wind turbine. Changes in acceleration can be used to infer the presence and magnitude of external loads.

Accelerometers are sensors that measure the acceleration of a body or structure. They work on the principle of the inertia of a mass, where changes in the motion of the mass due to external forces result in a change in the electrical signal output of the sensor.

An accelerometer typically consists of a mass that is suspended by springs or other means, and a sensing element that detects the motion of the mass. When the body or structure to which the accelerometer is attached undergoes acceleration, the mass moves in response to the external force. This movement causes a change in the distance between the mass and the sensing element, which in turn results in a change in the electrical signal output of the accelerometer.

Accelerometers are available in a wide range of types, including piezoelectric, piezo resistive, and capacitive accelerometers. They can be designed to measure acceleration in one, two, or three dimensions, and can provide accurate and reliable measurements over a wide range of frequencies and amplitudes [32 – 33].

In wind turbines, accelerometers are commonly used to monitor the vibration and motion of the blades, tower, and other components, and to detect any abnormal conditions that may lead to failure or reduced performance. They can also be used to measure the loads on the bearings indirectly, by measuring the acceleration of the components connected to the bearings. The data obtained from accelerometers can be used to assess the health of the system, identify potential problems before they lead to failure, and optimize the performance of the wind turbine [34 - 35].

5.3 FEA simulations with real-world measurements

Finite Element Analysis (FEA) is indeed a computer-based simulation technique that is widely used in engineering and manufacturing industries to model and analyze the behavior of structures and components under various loads and conditions. FEA involves dividing the structure into finite elements, representing discrete regions, and solving equations that describe the behavior of these elements. By considering the interactions between these elements, FEA can provide detailed information about the distribution of stresses, strains, and other physical quantities within the structure. In the context of bearing analysis, FEA can be utilized to simulate the behavior of bearings under different loads, such as radial and axial loads in wind turbines. By applying appropriate boundary conditions and loadings, FEA can predict the stresses, strains, and deformations experienced by the bearing components. This information can be valuable for assessing the performance and reliability of the bearing, identifying potential areas of concern, and optimizing the design to meet specific requirements. FEA has several advantages in bearing analysis, including its ability to handle complex geometries, nonlinear material behavior, and various loading conditions. It can provide insights into the structural integrity of the bearing, potential failure modes, and areas of high stress concentration. This information can guide engineers in making informed design decisions, such as selecting appropriate materials, optimizing bearing dimensions, or implementing design modifications to enhance performance and durability.

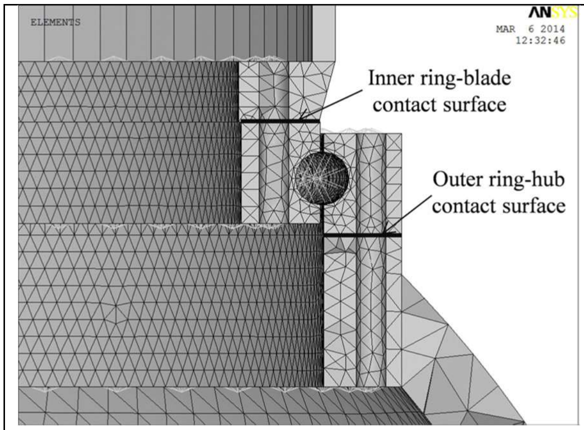


Fig 11: Part section of the FE model [37]

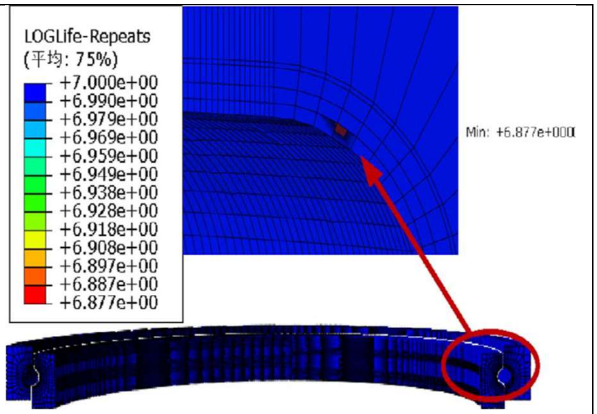


Fig 12 :Logarithmic plot of the lifetime cycles [12]

FEA involves dividing the structure or component into smaller elements, each with its own material and geometric properties as shown in fig 11. The behaviour of each element is analysed using mathematical equations and numerical methods to predict how the entire structure or component will behave under different loading conditions.A logarithmic plot of the lifetime cycles is a useful tool for visualizing and analysing the fatigue life of components and materials, helping engineers make informed decisions about design improvements, maintenance schedules, and replacement strategies as shown in fig 12.

In wind turbine design, FEA is commonly used to simulate the behaviour of the turbine blades, tower, and support structure under different wind and loading conditions. It can also be used to evaluate the performance of the bearings and other components, and to optimize the design of the entire system. FEA has become an essential tool in wind turbine design and engineering, allowing engineers to create more efficient and reliable turbines while reducing development time and costs [38].

5.4 Life Modelling for Estimating Wind Turbine Bearing Lifespan

Life modelling is an important tool used to estimate the expected lifespan of wind turbine bearings, which is essential for ensuring the reliable and efficient operation of wind turbines. There are several approaches to life modelling, but they generally involve the use of mathematical models and simulations to predict the fatigue life of the bearing under different operating conditions.[45-46]

Mathematical models and simulations are commonly used to predict the fatigue life of wind turbine bearings under different operating conditions. These models typically involve the use of fatigue analysis methods, such as the stress-life or strain-life approaches, which can be used to estimate the number of cycles to failure for a given stress or strain level.[47]

The stress-life approach is based on the assumption that the fatigue life of a component is primarily governed by the stress level and number of stress cycles it experiences. This approach involves the use of S-N curves, which describe the relationship between the applied stress level and the number of cycles to failure for a particular material or component.[48]

The strain-life approach, on the other hand, is based on the assumption that the fatigue life of a component is primarily governed by the strain level and number of strain cycles it experiences. This approach involves the use of e-N curves, which describe the relationship between the applied strain level and the number of cycles to failure for a particular material or component.

In both cases, mathematical models and simulations can be used to predict the expected fatigue life of wind turbine bearings under different operating conditions, including variations in load, speed, temperature, and other relevant factors. These models can also be used to optimize the design and materials of the bearings, and to identify potential failure modes and areas of high stress or strain that may require additional attention or testing.

Overall, mathematical models and simulations are an important tool for predicting the fatigue life of wind turbine bearings, and can help to ensure the reliability and efficiency of wind turbines over their expected lifespan.

One commonly used approach to life modelling is the use of the Weibull distribution, which is a statistical model used to describe the distribution of failure times for a particular population of objects. This approach involves collecting data on the operating conditions and loads experienced by the bearing, as well as information on its materials, manufacturing processes, and other relevant factors. This data is then used to estimate the parameters of the Weibull distribution, which can be used to predict the probability of failure for a given time interval.[49]

Another approach to life modelling is the use of finite element analysis (FEA) simulations, which involve the use of computer models to simulate the behaviour of the bearing under various loading conditions. FEA simulations can be used to predict the stress and strain distributions within the bearing, as well as the potential for fatigue damage and failure. This approach can be particularly useful for identifying potential failure modes and designing more durable bearings. [50]

Regardless of the approach used, life modelling is an important tool for optimizing the design and performance of wind turbine bearings, and can help to ensure the reliable and efficient operation of wind turbines over their expected lifespan.

6. Conclusion and Outlook for Wind Turbine Bearings:

The review paper you described provides a comprehensive overview of the importance of analyzing bearing loads and addressing fatigue failure in wind turbine systems. It emphasizes the crucial role of bearings in supporting different loads and highlights the need for accurate load determination to ensure the design of bearings capable of withstanding the demanding conditions in wind turbines. The identification of failure modes, particularly fatigue failure, and the recognition of contributing factors like improper installation, overloading, and inadequate lubrication emphasize the significance of maintenance practices and improved design strategies to mitigate fatigue-related issues. The review also highlights the value of advanced techniques like finite element analysis (FEA) in predicting and analyzing bearing behavior under varying loads. FEA simulations enable engineers to assess stress distribution, strain patterns, and deformation characteristics, thereby aiding in the optimization of bearing designs and the identification of potential failure zones. Proactive maintenance strategies, material selection, lubrication methods, and bearing design optimization are all emphasized as crucial factors for enhancing the reliability, efficiency, and lifespan of wind turbines. The paper calls for continued research and development efforts in the field of wind turbine bearings, focusing on refining load calculations, exploring novel materials and lubrication solutions, and investigating innovative bearing designs to meet the rigorous demands of wind turbine operations. Overall, the findings presented in this review paper provide valuable insights for engineers, researchers, and stakeholders involved in the wind energy sector. By gaining a comprehensive understanding of bearing loads and fatigue failure mechanisms, advancements can be made in wind turbine technology, leading to more reliable and efficient renewable energy generation in the future.

References

[1] https://windexchange.energy.gov

[2] Ertek, Gürdal, and Lakshmi Kailas. 2021. "Analyzing a Decade of Wind Turbine Accident News with Topic Modeling" *Sustainability* 13, no. 22: 12757. https://doi.org/10.3390/su132212757

[3] Extending Bearing Life in Wind Turbine Mainshafts, https://www.power-eng.com/coal/extending-bearing-life-in-wind-turbine-mainshafts/

[4] Jian, K. Wind turbine pitch system. China Eletr. Equip. Ind. 2011, 7, 52–57.

[5] Yang, Cong, Zheng Qian, Yan Pei, and Lu Wei. 2018. "A Data-Driven Approach for Condition Monitoring of Wind Turbine Pitch Systems" Energies 11, no. 8: 2142. https://doi.org/10.3390/en11082142

[6] Kaydon white paper Extend wind turbine life with pitch bearing upgrades by Corey D. Bayles, senior engineer, renewable energy applications

[7] https://www.helinslewbearing.com/products-category.html

[8] https://medias.schaeffler.co.in/en/plp/CrossedRollerBearing

[9] Three-row roller slewing bearings ldbhttps://www.ldb-bearing.com/slewing-bearings/three-row-roller-slewing-bearings

[10] Chen, Yiming, Xin Jin, Yong Yue, Shuang Wang, Huali Han, Maoshi Wen, Qingfeng Wang, and Peng Cheng. "Investigation on 3D fatigue crack propagation in pitch bearing raceway of offshore wind turbines." Ocean Engineering 269 (2023): 113524.

[11] Gong, Yi, Jing-Lu Fei, Jie Tang, Zhen-Guo Yang, Yong-Ming Han, and Xiang Li. "Failure analysis on abnormal wear of roller bearings in gearbox for wind turbine." Engineering Failure Analysis 82 (2017): 26-38.

[12] He, Peiyu, Rongjing Hong, Hua Wang, and Cheng Lu. "Fatigue life analysis of slewing bearings in wind turbines." International Journal of Fatigue 111 (2018): 233-242.

[13] Kania, Ludwik, RafałPytlarz, and SzczepanŚpiewak. "Modification of the raceway profile of a single-row ball slewing bearing." Mechanism and Machine Theory 128 (2018): 1-15.

[14] Kania, Ludwik, Marek Krynke, and Eugeniusz Mazanek. "A catalogue capacity of slewing bearings." Mechanism and machine theory 58 (2012): 29-45.

[15] Amasorrain, Jose Ignacio, XabierSagartzazu, and Jorge Damian. "Load distribution in a

four contact-point slewing bearing." Mechanism and Machine Theory 38, no. 6 (2003): 479-496.

[16] Daidié, Alain, ZouhairChaib, and Antoine Ghosn. "3D simplified finite elements analysis of load and contact angle in a slewing ball bearing." (2008): 082601.

[17] Lu, Quan, Wanxing Ye, and Linfei Yin. "ResDenIncepNet-CBAM with principal component analysis for wind turbine blade cracking fault prediction with only short time scale SCADA data." Measurement 212 (2023): 112696.

[18] Skyba, Rudolf, SlavomírHrček, LukášSmetánka, and Maroš Majchrák. "Strength analysis of slewing bearings." Transportation Research Procedia 40 (2019): 891-897.

[19] Lacroix, Samy, Daniel Nélias, and Alexandre Leblanc. "Four-point contact ball bearing model with deformable rings." Journal of Tribology 135, no. 3 (2013).

[20] Heras, Iker, JosuAguirrebeitia, Mikel Abasolo, Ibai Coria, and IñigoEscanciano. "Load distribution and friction torque in four-point contact slewing bearings considering manufacturing errors and ring flexibility." Mechanism and Machine Theory 137 (2019): 23-36.

[21] Li, Yunfeng, and Di Jiang. "Dynamic carrying capacity analysis of double-row four-point contact ball slewing bearing." Mathematical Problems in Engineering 2015 (2015).

[22] Aguirrebeitia, Josu, Mikel Abasolo, Rafael Avilés, and Igor Fernandez De Bustos. "Theoretical calculation of general static load-carrying capacity for the design and selection of three row roller slewing bearings." Mechanism and Machine Theory 48 (2012): 52-61.

[23] Pan, Yubin, Rongjing Hong, Jie Chen, Zhongwei Qin, and Yang Feng. "Incipient fault detection of wind turbine large-size slewing bearing based on circular domain." Measurement 137 (2019): 130-142.

[24] Jin, Xin, Yiming Chen, Lei Wang, Huali Han, and Peng Chen. "Failure prediction, monitoring and diagnosis methods for slewing bearings of large-scale wind turbine: A review." Measurement 172 (2021): 108855.

[25] ISO 76:2006. Rolling bearing - Static load rating, 2006.

[26] Hart, Edward. "Developing a systematic approach to the analysis of time-varying main bearing loads for wind turbines." Wind Energy 23, no. 12 (2020): 2150-2165.

[27] Hart, Edward, Alan Turnbull, Julian Feuchtwang, David McMillan, EvgeniaGolysheva, and Robin Elliott. "Wind turbine main-bearing loading and wind field characteristics." Wind Energy 22, no. 11 (2019): 1534-1547.

[28] Ozbek, Muammer, and Daniel J. Rixen. "Operational modal analysis of a 2.5 MW wind turbine using optical measurement techniques and strain gauges." Wind Energy 16, no. 3 (2013): 367-381.

[29] Keil, Stefan. Technology and practical use of strain gages: with particular consideration of stress analysis using strain gages. John Wiley & Sons, 2017.

[30] "Load Cell and Strain Gauge Basics Load Cell Central". www.800loadcel.com. Retrieved 2019-07-29.

[31] Piskorowski, Jacek, and Tomasz Barcinski. "Dynamic compensation of load cell response: A time-varying approach." Mechanical Systems and Signal Processing 22, no. 7 (2008): 1694-1704.

[32] Lyden, Kate, Sarah L. Kozey, John W. Staudenmeyer, and Patty S. Freedson. "A comprehensive evaluation of commonly used accelerometer energy expenditure and MET prediction equations." European journal of applied physiology 111 (2011): 187-201.

[33]Murphy, Susan L. "Review of physical activity measurement using accelerometers in older adults: considerations for research design and conduct." Preventive medicine 48, no. 2 (2009): 108-114.

[34] Noppe, Nymfa, Konstantinos Tatsis, EleniChatzi, ChristofDevrient, and WoutWeijtjens. "Fatigue stress estimation of offshore wind turbine using a Kalman filter in combination with accelerometers." In Proceedings of International Conference on Noise and Vibration Engineering (ISMA 2018), International Conference on Uncertainty in Structural Dynamics (USD 2018), pp. 4693-6701. KU Leuven, Department of Mechanical Engineering, 2018.

[35] Kilic, Gokhan, and Mehmet S. Unluturk. "Testing of wind turbine towers using wireless sensor network and accelerometer." Renewable Energy 75 (2015): 318-325.

[36] Yu, Yong-Hun, Bo-Ra Lee, and Yong-Joo Cho. "New load distribution method for one-row slewing ball bearing considering retainer force." International Journal of Precision Engineering and Manufacturing 18 (2017): 49-56.

[37] Plaza, Jon, Mikel Abasolo, Ibai Coria, JosuAguirrebeitia, and Igor Fernández de Bustos. "A new finite element approach for the analysis of slewing bearings in wind turbine generators using superelement techniques." Meccanica 50 (2015): 1623-1633.

[38] Veers, Paul S., Thomas D. Ashwill, Herbert J. Sutherland, Daniel L. Laird, Donald W. Lobitz, Dayton A. Griffin, John F. Mandell et al. "Trends in the design, manufacture and evaluation of wind turbine blades." Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology 6, no. 3 (2003): 245-259.

[39] Stammler, Matthias, Fabian Schwack, Norbert Bader, Andreas Reuter, and Gerhard Poll. "Friction torque of wind-turbine pitch bearings–comparison of experimental results with available models." Wind Energy Science 3, no. 1 (2018): 97-105.

[40] Schwack, Fabian, Fabian Halmos, Matthias Stammler, Gerhard Poll, and Sergei Glavatskih. "Wear in wind turbine pitch bearings—A comparative design study." Wind Energy 25, no. 4 (2022): 700-718.

[41] Schwack, Fabian, Norbert Bader, Johan Leckner, Claire Demaille, and Gerhard Poll. "A study of grease lubricants under wind turbine pitch bearing conditions." Wear 454 (2020): 203335.

[42] Han, Jeong Woo, JuSeok Nam, Young Jun Park, GeunHo Lee, and Yong Yun Nam. "An experimental study on the performance and fatigue life of pitch bearing for wind turbine." Journal of Mechanical Science and Technology 29 (2015): 1963-1971.

[43] Leupold, S., R. Schelenz, and G. Jacobs. "Investigation of the individual load distribution of a blade bearing test rig by means of finite element simulation." In Journal of Physics: Conference Series, vol. 1618, no. 5, p. 052056. IOP Publishing, 2020.

[44] Nam, JuSeok, Jeong Woo Han, Young Jun Park, Yong Yun Nam, and GeunHo Lee. "Development of highly reproducible test rig for pitch and yaw bearings of wind turbine." Journal of Mechanical Science and Technology 28, no. 2 (2014): 705.

[45] Slot, H. M., E. R. M. Gelinck, C. Rentrop, and Emile Van Der Heide. "Leading edge erosion of coated wind turbine blades: Review of coating life models." Renewable energy 80 (2015): 837-848.

[46] Breslau, Georg, and Berthold Schlecht. "A Fatigue Life Model for Roller Bearings in Oscillatory Applications." Bear. World J. 5 (2020): 65-80.

[47] Kirke, B. K., and L. Lazauskas. "Experimental verification of a mathematical model for predicting the performance of a self-acting variable pitch vertical axis wind turbine." Wind engineering (1993): 58-66.

[48] Sakai, Tatsuo, Mitsuhiro Takeda, Kazuaki Shiozawa, Yasuo Ochi, Masaki Nakajima, Takashi Nakamura, and Noriyasu Oguma. "Experimental reconfirmation of characteristic SN property for high carbon chromium bearing steel in wide life region in rotating bending." Zairyo/Journal of the Society of Materials Science, Japan 49, no. 7 (2000): 779-785.

[49] Carrasco, Jalmar MF, Edwin MM Ortega, and Gauss M. Cordeiro. "A generalized modified Weibull distribution for lifetime modeling." Computational Statistics & Data Analysis 53, no. 2 (2008): 450-462.

[50] Xue, Yahong, Jigang Chen, SuminGuo, QingliangMeng, and Junting Luo. "Finite element simulation and experimental test of the wear behavior for self-lubricating spherical plain bearings." Friction 6 (2018): 297-306.