FAILURE ANALYSIS AND STRUCTURAL OPTIMIZATION OF CYLINDRICAL ROLLER BEARINGS IN CENTRIFUGAL PUMPS

[1]Devendra Kumar, [2]Prof. Abhilesh Dubey, [3]Prof. Girish Khare
[1]Department of Mechanical Engineering, Oriental Institute of Science and Technology - [OIST], Bhopal, India
[2]Department of Mechanical Engineering, Oriental Institute of Science and Technology - [OIST], Bhopal, India
[3]Department of Mechanical Engineering, Oriental Institute of Science and Technology - [OIST], Bhopal, India
Email [1]dgrahi28@gmail.com, [2]abhileshdubey@oriental.ac.in

* Corresponding Author: Devendra Kumar

Abstract: *Rolling bearings, including both roller and ball bearings, play a vital role in various engineering applications, offering a cost-effective and precise means of facilitating rotational movement. However, these bearings can experience failures, with contact fatigue spalling being a common issue. This research paper investigates the failure analysis of cylindrical roller bearings in centrifugal pumps, with a focus on load, vibration, and temperature factors. Finite Element Analysis (FEA) is employed to evaluate the bearing's performance under different conditions, including variations in load and material properties. The study also explores the impact of dimensional changes in bearing components. The findings reveal insights into the root causes of bearing failure and offer guidance for structural optimization to enhance bearing performance and longevity.*

Keywords: *Rolling bearings, Cylindrical roller bearings, Failure analysis, Finite Element Analysis (FEA), Contact fatigue spalling, Load distribution, Structural optimization, Centrifugal pumps.*

I. INTRODUCTION

The phrase "rolling bearing" encompasses a variety of bearings that facilitate the rotational movement of a shaft, including both roller and ball bearings. These bearings are characterized by their simple design and are extensively utilized across various engineering domains. Rolling bearings are not only low in cost and high in precision but are also commonplace in numerous types of rotary machinery. The primary mode of failure for these bearings is typically due to the contact fatigue spalling experienced by the rolling elements [1]. Contact finite element analysis is instrumental in revealing critical details about bearings under stress, such as contact pressure, deformation, degree of penetration, and the extent of sliding. This information is crucial for the advanced design of complex rolling bearings [2]. Addressing contact issues is pivotal in a multitude of engineering applications, including but not limited to ball bearings, gears, rollers, and attachments for pressure vessels. These engineering challenges often involve the interaction between surfaces that do not perfectly conform to one another and are subjected to forces that are both perpendicular and parallel to the contact surface. Roller bearings play a vital role when using applications that require extensive load supporting capacity. They are much stiffer and have a higher load capacity when compared to ball bearings of similar size. Nonetheless, the production costs for roller bearing assemblies tend to be higher compared to ball bearings of equivalent dimensions [3].

For those designing machinery, it is increasingly critical to evaluate the strength and stiffness of rolling bearings. Yet, conducting these analyses theoretically—especially assessments of stress and stiffness—presents considerable difficulties. Hertz theory [2] is commonly employed to examine the contact pressure and stiffness of ball bearings. However, this theory falls short in terms of accuracy when it comes to large deformations, as it only accounts for the deformation within the contact zones of the ball bearings and neglects the deformation of the bearing housings and the outer and inner rings. Similarly, the edge loads that are in the contact surface of roller bearings cannot be solved using Hertz contact theory. In order to solve these problems, author in, [4] proposed an approximate model that the rollerball is in contact with a surface of infinite length. The structural deformations of the inner and outer ring are also not considered using this approximate model, thus, rendering it not precise for roller bearing contact analysis. Rolling element bearings are one of the key components of many rotating machines. By implementing condition monitoring and vibration analysis for bearings, we can acquire essential insights into the machinery's operational health [5].

A. Raceway (inner ring and outer ring) or raceway washer

The track that the rolling elements traverse is known as the "raceway surface," which bears the load applied to the bearing. Typically, the inner ring is mounted on the axle or shaft, while the outer ring is affixed to the housing.

Rolling elements

There are two main categories of rolling elements: balls and rollers. Rollers are further differentiated into four varieties: cylindrical, needle, tapered, and spherical. Balls make geometric "point" contacts with the raceway surfaces of both the inner and outer rings, whereas rollers make "line" contact. In theory, rolling bearings are engineered to enable the rolling elements not only to orbit around the raceway but also to spin around their own axes simultaneously.

Cages

Cages serve to keep the rolling elements evenly spaced, ensuring that the load is distributed directly across the elements and not to the cage itself. They also keep the rolling elements in place, preventing them from dislodging during the handling of the bearing. The construction of cages varies, with different types including pressed, machined, and formed cages, each distinguished by its manufacturing process.

B. Classification of rolling bearings

Rolling bearings are categorized broadly into ball bearings and roller bearings. Ball bearings are differentiated by the design of their bearing rings: there are deep groove and angular contact varieties. Conversely, roller bearings are distinguished by the form of the rollers used, which include cylindrical, needle, tapered, and spherical types.

Furthermore, the categorization of rolling bearings extends to the orientation of the loads they accommodate; radial bearings are designed to sustain loads perpendicular to the axis, known as radial loads, while thrust bearings are equipped to manage loads that run parallel to the axis, referred to as axial loads. Additional methods of classification encompass: 1) the count of rolling element rows, which may be single, double, or four-row, and 2) whether the bearings are separable or non-separable, indicating if either the inner or the outer ring can be removed.

Specialized bearings also exist for specific uses, such as roller bearings for railway car journals, bearings for ball screw support, bearings for turntables, and bearings suited for linear motion (including linear ball bearings, linear roller bearings, and linear flat roller bearings). A depiction of the various types of rolling bearings can be found in Fig. 1.

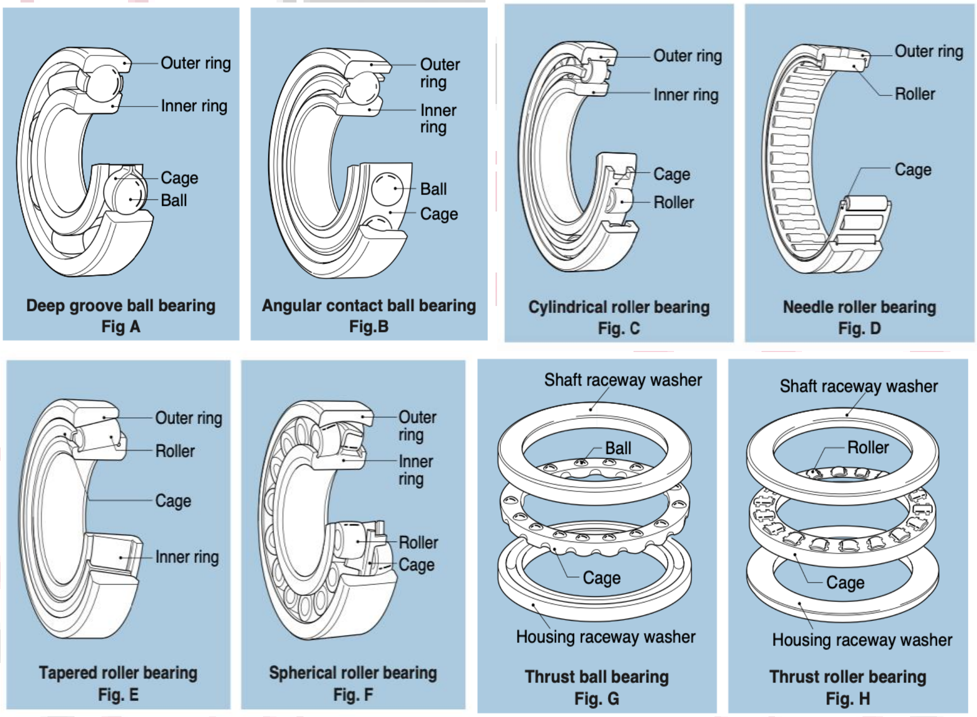

Figure 1 Rolling bearing

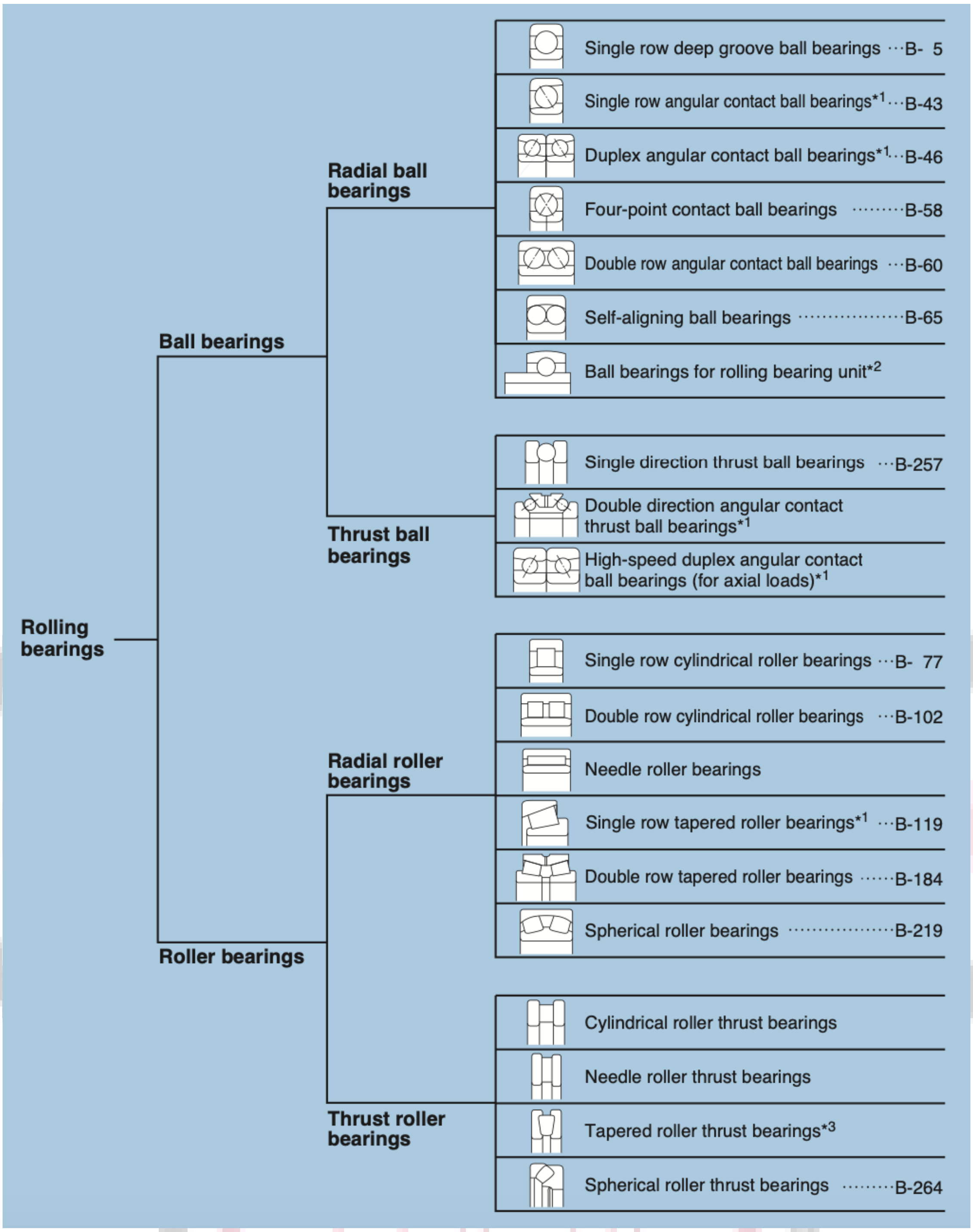

Figure 2 Classification of rolling bearings

C. Uses of Cylindrical Roller Bearings

Cylindrical roller bearings are versatile components employed in a range of mechanical assemblies. Various kinds of cylindrical roller bearings provide distinct functional benefits:

Axial Displacement: These bearings are engineered to bear axial loads and permit movement in both axial directions within a machine. The N and NU types of cylindrical roller bearings are ideal for scenarios requiring axial displacement, with single-row cylindrical roller bearings allowing for a certain degree of movement relative to the housing.

Withstand Incidental Thrust Loads: Thrust loads are those applied in a direction parallel to the axis of rotation. The NF, NJ, and NUP series of cylindrical roller bearings are specifically crafted to handle these incidental thrust loads in addition to radial loads.

Applications in Robust Machinery and Intensive Environments: Cylindrical roller bearings are utilized in systems that operate at high speeds and are suitable for high-performance applications, including agricultural equipment, wind turbines, mining machinery, and similar demanding industrial settings.

D. Advantages of Cylindrical Roller Bearings

The functionality and structural attributes of cylindrical roller bearings make them particularly fitting for certain applications. They provide a range of benefits, including:
- Enhanced durability against fatigue and shock compared to ball bearings.
- Ease of mounting and dismounting, thanks to their distinctive design.
- Capability to support a combination of loads, with N and NU types handling radial loads, and NJ and NUP types equipped to manage both radial and thrust loads.

E. Materials of Bearing

The bearing material should have following characteristics from the service point of view.

- High strength to sustain bearing load, high compressive and fatigue strength.
- High thermal conductivity to dissipate the heat quickly.
- Low coefficient of friction.
- Less wear and tear.
- Low cost.
- Bearing materials should not readily weld itself to the shaft material.
- Good corrosion resistance in case the lubricant has the tendency to oxidize the bearing.
- Good conformability. The bearing should adjust to misalignment or geometric errors. Materials with low modulus of elasticity usually have good conformability.

Cast iron, brass and alloy materials viz., bronzes (copper-tin), Babbitt (alloys of tin-copper-lead-antimony), copper-lead alloys and aluminum-tin alloys are used for making sliding contact bearings. Rubber and synthetic composite materials are also used for certain applications (synthetic bearings).

II. LITERATURE REVIEW

Kushwaha et al. (2020) conducted a detailed study of heat transfer within a bearing system, employing the finite element method to model and analyze a standard ball bearing and its surrounding environment. By simulating the temperature dynamics over time, with the variable of rotational speed, they aimed to determine the rate at which temperature changes within the system and whether the bearing would hit a critical temperature threshold — such as the maximum temperature endurance of the lubricant or the bearing metal. Their findings revealed that an increase in rotational speed leads to a quicker attainment of thermal equilibrium within the system. However, at none of the rotational speeds tested did the bearing approach a critical temperature limit. Additionally, they explored the occurrence of scuffing, a type of failure linked to thermal conditions within the bearing.

Wu& Tan (2018) analyzed a thermo-mechanical coupling analysis model of the spindle-bearing systembased on Hertz's contact theory and a point contact non-Newtonian thermal elasto-hydrodynamiclubrication (EHL) theory are developed. In this model, the effect of preload, centrifugal force, thegyroscopic moment, and the lubrication state of the spindle-bearing system are considered. Accordingto the heat transfer theory, the mathematical model for the temperature field of the spindle system isdeveloped and the effect of the spindle cooling system on the spindle temperature distribution isanalyzed. Theoretical simulations paired with empirical data suggest that the preload applied to bearings significantly influences the generation of frictional heat, while the cooling fluid markedly impacts the heat equilibrium of the spindle system. Should there be an imbalance, where the cooling system fails to offset the heat produced by friction, thermally-induced preload can exacerbate frictional heat production, potentially leading to thermal overload and subsequent failure of the spindle system.

Subramaniam et al. (2016) conducted a study to examine the heat transfer characteristics of a conventional ceramic ball bearing, focusing on how heat dissipation, temperature profiles, deformations, and thermal stresses vary with changes in rotational speed. Their findings indicated a direct correlation between heat generation and temperature rise within the bearing. Analysis of different operational speeds revealed that rotational velocity is a critical factor affecting bearing temperature, with higher speeds leading to higher temperatures. The relationship between the temperature and the rotational speed was such that the peak temperature experienced by the bearing was determined by the amount of heat generated. Additionally, as rotational speed increased, there was a corresponding increase in displacement, which in turn caused deformation and induced thermal stresses within the bearing. The investigation also noted that rotational speed exerted a significant impact on the bearing's stiffness.

Reddy (2015) undertook a detailed investigation into the heat transfer dynamics within a ball bearing assembly and its immediate surroundings through finite element analysis. By modeling a typical ball bearing and evaluating it with computational tools, Reddy calculated the maximum temperatures reached within the bearing as a function of the heat generated, considering rotational speed as a significant variable. The primary aim of this research was to assess the rate at which temperatures changed within the bearing system as a consequence of varying rotational speeds. The study specifically focused on higher speed ranges, conducting steady-state thermal stress simulations to discern the temperature distribution across the bearing. Findings from the study confirmed that temperature within the bearing escalated in tandem with increases in rotational speed. These results were corroborated by analytical calculations. Additionally, the study noted that as rotational speed augmented, the centrifugal displacement of the inner ring also increased, leading to more pronounced contact deformation and stress. Analytical exploration of the dynamic stiffness of bearings under variable preload revealed that radial stiffness tended to decrease as rotational speeds escalated.

Kumar & Rao (2015) had done laboratory experiments were performed to determine a minimum temperature and environment necessary to reproduce these discolorations which are mostly due to roller temperatures greater than 232ºC (450ºF) for periods of at least 4 hours. Ongoing research is examining scenarios where the rollers within a bearing assembly might reach high temperatures without correspondingly raising the temperature of the bearing cup (outer race) to levels that would activate High Bearing Detectors (HBDs). Building on prior experimental studies and analytical work, researchers have conducted a static-thermal finite element analysis (FEA) on a railroad bearing that has been mounted onto an axle. This analysis, executed using the ANSYS software, takes into account specific radial and thrust load conditions to assess the thermal behavior of the bearing under these loads. Present work shows the stresses at various temperatures, fatigue life, vibration characteristics and the dynamic response of a structure under the action of time dependent loads. Also, Present work evaluates the Hot Box Detector (HBD) temperature by showing the bearing safe temperature, failure temperature and stresses under cyclic loading.

Nam et al. (2018) had done theoretical, experimental and numerical research on heat generation in bearings has been performed for a long time. Forecasting temperature variations within bearings presents challenges, both experimentally and theoretically, due to the highest temperatures often occurring in localized areas that vary according to each bearing's specific shape. These localized regions of heat generation can hasten the deterioration of bearings. To address this, the current study proposes a numerical model that estimates the heat produced by the frictional forces at the contact surfaces and explores the thermal distribution within bearing systems through the application of the finite element method (FEM). The energy created by frictional force calculated in contact analysis is converted into heat energy. Most numerical research to predict distribution of temperature in bearings is considered in the steady-state disregarding the effect of rotation. However, it is important to consider the effect of rotation which affects the thermal distribution and lubrication.

Li et al. (2018)established an improved theoretical modelof friction power loss distribution in high-speed and light-load rolling bearings (HSLLRBs)considering skidding and the effects of various operating parameters on the frictionpower loss are investigated. The results show that the friction power loss of the inner ring and outerring as well as the total friction power loss of the bearing increase as the slip ratio increases, but thatthe friction power loss of the cage guide surface and roller oil churning show a reverse trend. Inaddition, the increase in inner ring speed and kinematic viscosity leads to an increase in bearingfriction power loss. The steady and transient temperature field distribution of HSLLRBs is obtainedby the finite element method (FEM), and the results show that the inner ring raceway has the highesttemperature, whereas the cage has the lowest. The temperature distribution test rig of a full-sizeroller bearing is constructed, and the influence mechanism of the slip ratio, rotation speed, load,lubrication, and surface topography on the bearing temperature distribution are obtained. Theexperimental results are consistent with the theoretical results, which also validates the theoreticalmethod.

III. OBJECTIVES

1. To examine the failure analysis of roller bearing
2. To examine the failure analysis of roller bearing on the basis of load, vibration and temperature
3. To analyse the failure analysis of roller bearing in between two different material
4. To analyse the failure analysis of roller bearing on the basis of variation of thickness of inner and outer race
5. To perform the comparative study of two material structural steel and AISI52100 alloy steel.

IV. FEM MODELLING OF BEARING

In this section methodology is discussed in relation to failure analysis of roller bearing.

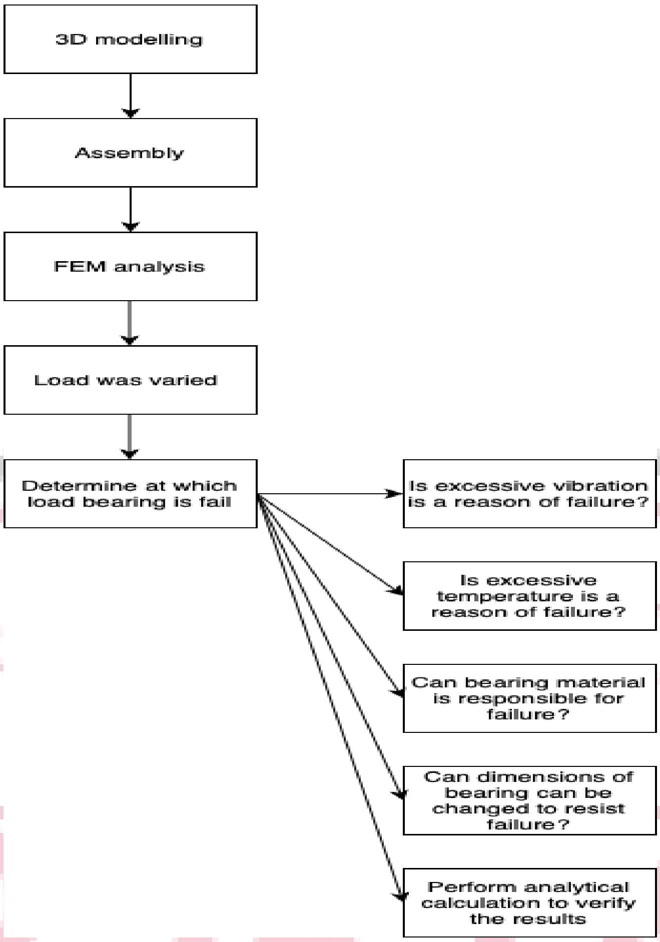

Figure 3 Flow chart of methodology adopted

A cylindrical roller bearing is considered which is used in centrifugal pump and was failed during its service. To examine the root cause of failure of cylindrical roller bearing, transient structural analysis of a roller bearing system, is adopted and later on analyzed by using the finite element method. The methodology followed for the analysis is given below in flowchart tagged as figure no 3 First of all, 3D Modeling carried out by using modeling software. The transient structural analysis is carried out by using Ansys 15.0.

A. Modeling of Roller Bearing

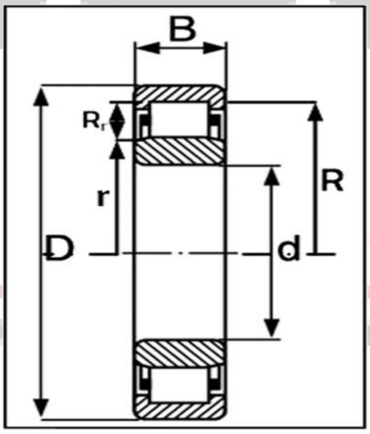

Figure 4 NU 205 cylindrical roller bearing

V. RESULT AND DISCUSSION

A. Grid independence test

Convergence analyses are carried out to determine a reasonable mesh size that allows obtaining a good estimation of the radial bearing stiffness while maintaining a relatively low computational time. A grid independence test is a computational simulation technique commonly used in numerical modeling and simulations, particularly in the fields of computational methods. The purpose of a grid independence test is to assess the sensitivity of simulation results to changes in the grid or

mesh resolution. This test helps ensure that the numerical results are not significantly affected by the size or density of the grid used in the simulation.
Here's how a grid independence test typically works:

- Grid Generation: Initially, a computational grid or mesh is generated to discretize the domain of interest. The grid consists of elements (e.g., cells, elements, nodes) that represent the geometry and physics of the problem. The grid can be fine (dense) or coarse (sparse), depending on the computational resources and desired accuracy.
- Simulation: The simulation is run using the chosen grid/mesh. This involves solving the mathematical equations governing the physical phenomena being studied. For example, in CFD, the Navier-Stokes equations are solved to simulate fluid flow.
- Results Analysis: After the simulation is complete, the results are analyzed. This may include examining variables of interest such as pressure, velocity, temperature, stress, or any other relevant quantities at specific locations in the domain.
- Grid Refinement: The grid resolution is then increased (refined) by dividing existing elements into smaller ones or adding more elements to make the grid finer. This process increases the overall number of grid points and computational complexity.
- Repeat Simulation: The simulation is repeated using the refined grid. The same boundary conditions and problem settings are applied.

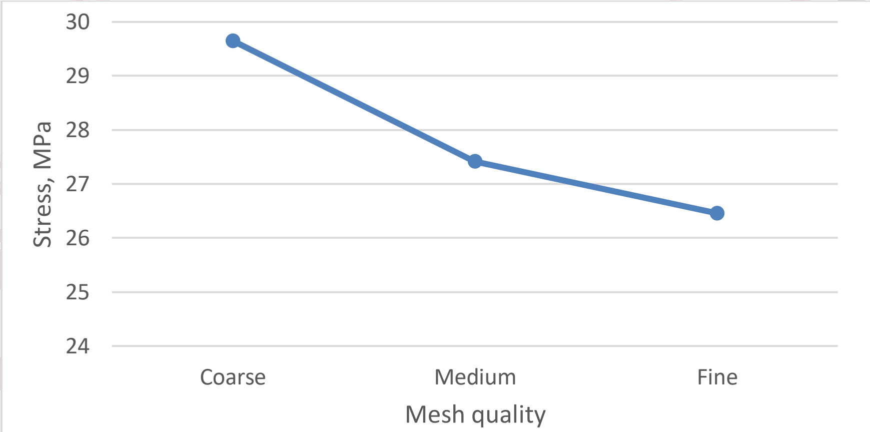

Figure 5 Convergence check

B. Determination of load at which bearing is fail

The load was varied from 250 to 400N towards the determination of load at which bearing is fail. Further stress distribution was analyzed in a roller bearing using Finite Element Analysis (FEA).

The inner race has to withstand these elevated contact stresses, leading to higher overall stress levels. In transient loading conditions, the applied load varies with time. As the load magnitude increases, the inner race experiences dynamic loading, which includes both static and dynamic components. The dynamic component of the load introduces time-varying stresses that can be higher than those experienced under purely static loading conditions.

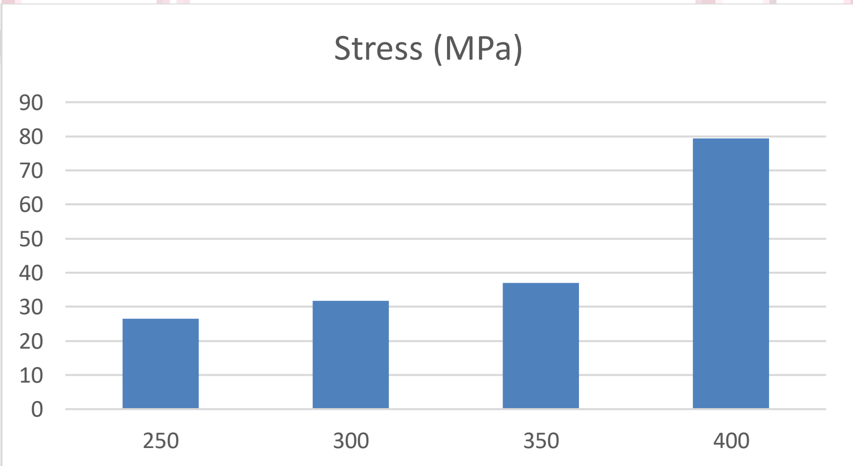

Figure 6 Estimation of stress at different forces

C. Deformation at different load

We also analyzed the deformation at different loads. Studying deformation in roller bearings using Finite Element Analysis (FEM) analysis is essential for several reasons:
Design Optimization: FEM allows engineers to assess how different design parameters, such as material selection, geometry, and clearance, affect the deformation behavior of roller bearings. By understanding how these factors impact deformation, designers can optimize the bearing's design for better performance and longevity.
In roller bearings, the outer race typically carries a significant portion of the radial load. When the applied radial load increases, the outer race experiences a higher load, resulting in increased deformation in the radial direction. In transient loading conditions, the bearing may undergo dynamic changes in load, such as during startup, acceleration, or deceleration. These variations in load can lead to dynamic deformation responses in the outer race, which are directly related to the changes in applied load magnitude.

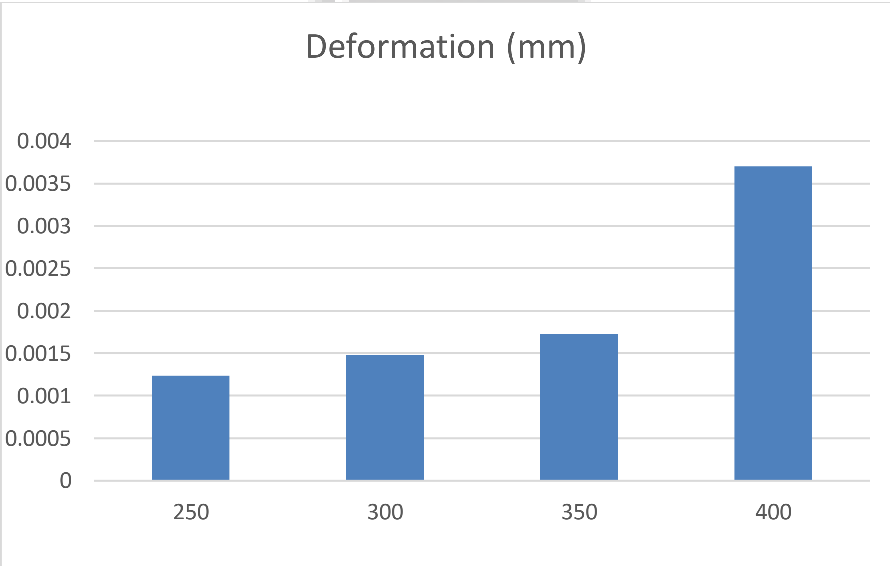

Figure 7 Estimation of deformation at different forces

By the variation of load from 250 to 400 N, we came to know that at 400N bearing was failed with excessive stress (large as compared to analytical one) and deformation.

D. Change in dimension of bearing material

In this last step we also change the thickness of inner and outer race, and verify failure of bearing to resist load of 400N with structural steel and AISI52100 alloy steel.

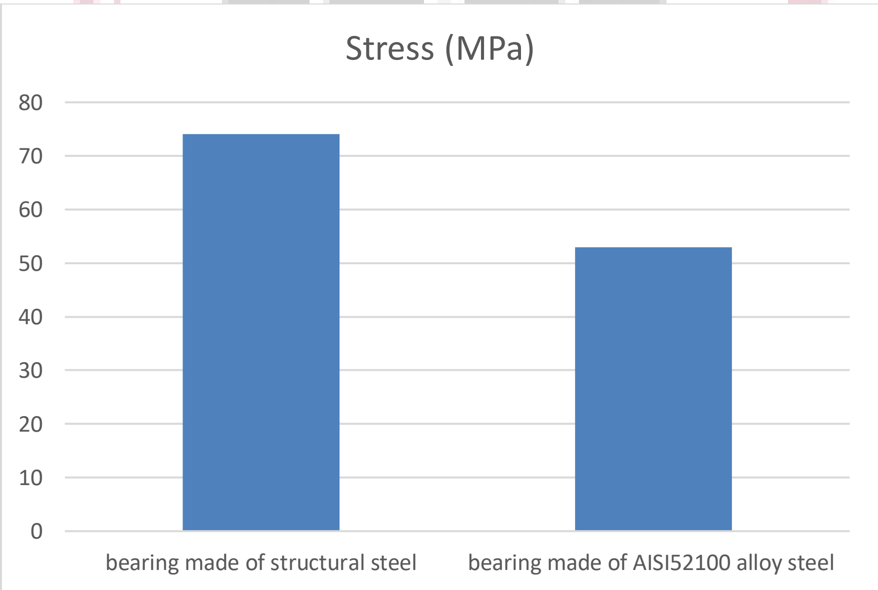

Figure 8 Stress comparison

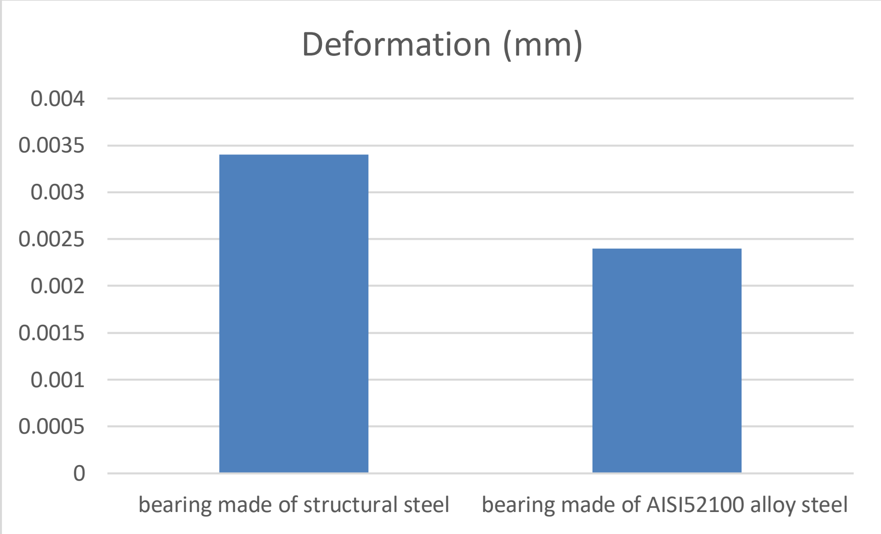

Figure 9 Deformation comparison

When thickness of inner and outer race is increased and structural steel is replaced with AISI52100 alloy steel under same loading conditions, stress is reduced to 52.91 MPa which is below the calculated stress 68.93 N/mm^2, hence in this case, our design is also safe.

E. Discussion on failure analysis

Cylindrical roller bearings are commonly used in centrifugal pump. Excessive vibration and high temperatures are leading factors that precipitate the most prevalent roller bearing malfunctions, which are fatigue spalling and the wearing away of the outer ring raceway and the rollers. The inner ring raceway was specifically compromised due to contact fatigue spalling, while the cage's failure was attributed to fatigue fracture. It is deduced that the fatigue fracture in the cage occurs subsequent to the spalling and deterioration of the raceways and rollers; a prior fracture in the cage would have led to a more even distribution of spalling, wear, and axial damage across the raceways and rollers. The failure affected the outer ring, inner ring, rollers, and cage with significant damage observed on their sides. This suggests that the substantial local contact stress experienced on the sides of the bearing is the primary cause of the failure.

The lock nut's diameter matched that of the inner ring's flange, which suggests that applying a high axial tightening force could potentially deform the inner ring, leading to increased localized stress at specific points—identified as the primary cause of failure. Using ANSYS for analysis, the impact of this axial force on the inner bearing was scrutinized. The technically specified axial tightening torque for the inner ring falls between 338 and 372 Nm. For this analysis, the minimum specified torque (338 Nm), an intermediate value roughly at the midrange of the specification (350 Nm), and the maximum specified torque (372 Nm) were examined. It was observed that following the application of the tightening torque, the roundness—or cylindricity—of the inner ring raceway was compromised, showing a notable increase compared to its state prior to the application of torque.

V. CONCLUSION

This research paper highlights the critical importance of understanding the failure mechanisms and structural behavior of cylindrical roller bearings, particularly in the context of centrifugal pumps. Excessive vibration, high temperatures, and variations in load are identified as leading contributors to bearing failures, primarily manifested as contact fatigue spalling and raceway wear. Finite Element Analysis (FEA) is a valuable tool for assessing the performance of these bearings under different conditions, enabling engineers to optimize their design and material choices.

The study also emphasizes the impact of axial tightening forces on bearing components, demonstrating that excessive forces can lead to deformation and localized stress, ultimately affecting bearing performance. The findings from this research provide essential insights into improving the durability and reliability of cylindrical roller bearings in centrifugal pumps and similar applications, ultimately enhancing the operational efficiency and lifespan of machinery utilizing such components.

REFERENCES

[1] Nguyen, P., Kang, M., Kim, J. M., Ahn, B. H., Ha, J. M., & Choi, B. K. (2015). Robust condition monitoring of rolling element bearings using de-noising and envelope analysis with signal decomposition techniques. Expert Systems with Applications, 42(22), 9024-9032.

[2] Kleckner, R. J., Pirvics, J., & Castelli, V. (1980). High speed cylindrical rolling element bearing analysis "CYBEAN"—analytic formulation.

[3] Bercea, I., Nelias, D., & Cavallaro, G. (2003). A unified and simplified treatment of the non-linear equilibrium problem of double-row rolling bearings. Part 1: rolling bearing model. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 217(3), 205-212.

[4] Takabi, J., &Khonsari, M. M. (2016). On the thermally-induced failure of rolling element bearings. Tribology International, 94, 661-674.

[5] Jeng, Y. R., & Gao, C. C. (2001). Investigation of the ball-bearing temperature rise under an oil-air lubrication system. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 215(2), 139-148.

[6] Kushwaha, N., & Patel, V. N. (2020). Modelling and analysis of a cracked rotor: a review of the literature and its implications. Archive of Applied Mechanics, 90(6), 1215-1245.

[7] Duan, Z., Wu, T., Guo, S., Shao, T., Malekian, R., & Li, Z. (2018). Development and trend of condition monitoring and fault diagnosis of multi-sensors information fusion for rolling bearings: a review. The International Journal of Advanced Manufacturing Technology, 96, 803-819.

[8] Subramaniam, S. B., Harsha, R. D., Vivek, M., & Prasad, V. D. (2016). Thermal Analysis of Ceramic Conventional Ball Bearings. Indian Journal of Science and Technology, 9, 35.

[9] Reddy, M. C. S. (2015). Thermal Stress Analysis of a Ball Bearing by Finite Element Method. International Journal of Advanced Research in Engineering and Technology, 6(11).

[10] Kumar, P. M., & Rao, C. J. (2015). Structural and thermal analysis on a tapered roller bearing. IJISET-International Journal of Innovative Science, Engineering & Technology, 2(1), 502-511.

[11] Mose, B. R., Shin, D. K., & Nam, J. H. (2018). Development of an experimental system to measure stresses in a bearing using photo-elasticity. Experimental Mechanics, 58, 437-447.

[12] Li, Y., Xu, M., Wei, Y., & Huang, W. (2016). A new rolling bearing fault diagnosis method based on multiscale permutation entropy and improved support vector machine based binary tree. Measurement, 77, 80-94.