

Stress Analysis of SKF 6206 Bearing under Radial Load using Theoretical and Numerical Evaluation

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Abstract. Deep groove ball bearings play a critical role in rotating machineries. Their structural performance under radial and axial loading is vital for reliability. Static analysis is important to understand deformation, stress distribution, and load capacity to avoid premature failures. This study discusses about performing Static analysis and validating Finite element analysis (FEA) with established theoretical results under radial load. A 3D model of ball bearing is created in ANSYS SpaceClaim and static structural analysis is performed using ANSYS software to simulate deformations and stresses. The extracted results particularly maximum contact stresses on the inner raceway and the static load distribution between the rolling elements were compared with the classical Hertzian contact theory and analytical load distribution formulas. With minimal deviation in stress values, FEA results showed similarity with theoretical calculations. The study gives the confirmation about FEA as highly reliable tool for predicting static behavior of deep groove ball bearings, giving a solid foundation for design validation and dynamic analysis. Conventional maintenance practices, such as scheduled inspections or time-based replacements, are still common in industries. While these approaches can prevent sudden breakdowns to some extent, they are not always efficient in identifying incipient faults at an early stage. Once a fault is allowed to progress, it becomes much harder to manage and may demand complete machine stoppage for repair. This limitation has motivated the development of more reliable, data-driven approaches, where vibration analysis combined with machine learning is seen as a promising solution.

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1. Introduction

Amongst various types of rolling element bearings, Deep groove ball bearings are widely used because of their simple design, and their ability to carry comparatively larger, both radial and axial loads. They are used in many industrial components such as pumps, motors, gearboxes, turbines etc. Deep groove ball bearings consist Outer race, Inner race, Balls and Cage. The reliability and efficiency in such rotating machineries is very critical. Their design and analysis is essential area to study because the service life and performance directly influence overall durability of systems. Failures in such systems lead to stress concentrations, and fatigue damage resulting to noise, increased vibrations, friction, and in several cases breakdown of equipment. Such failures are induced due to improper lubrication, contamination in the lubricant, localized defects, misalignment in shafts, overloading or wear and tear of bearing components. Mostly vibration signature analysis is employed for fault detection, but analyzing and predicting stresses and deformations prior to that using static analysis is equally important for various loading conditions. This ensures safety and also prevents premature failures. When there is radial or axial load produced in the ball bearing, rolling elements transmit these forces to the races, which generate contact stresses and localized deformations. The bearing can undergo plastic deformation or surface fatigue due excessive stresses which leads to reducing bearing life. So to predict contact stresses at various locations within this assembly, and to analyze maximum load carrying capacity static analysis is done.

Conventionally, static analysis used to be carried out using theories such as Hertzian contact theory, which calculates contact stresses and deformations theoretically. However, theoretical approaches involve assumptions such as rigid races, purely elastic deformation, and ideal load distribution. To overcome this gap numerical technique such as finite element analysis is being widely used to validate theoretical calculations. Through this dual approach, the present approach aims to assess the accuracy of theoretical methods with Finite element simulations. Thus the study contributes in designing more reliable bearing models, which ensures optimal design and prevents premature failure in the rotating machinery.

2. Literature Review

The evolution of finite element analysis to understand behavioral aspects of deep groove ball bearing is significant. Early researches by Sethi and Panigrahi [1] elaborated the potential of finite element analysis in detection of faults. The study covered how reducing the radius of ball affects natural frequencies and mode shapes of a bearing. It established that FEA detects the changes in vibrational characteristics effectively. Utpat [2] performed a numerical and experimental study on defective deep groove ball bearings. Wide operational parameters such as speeds up to 5000 rpm and various defect sizes from 0.25 mm to 2.00 mm were explored by this research. It concluded that amplitude vibrations produced due to outer race defect are higher than the inner race defect of same size. The study also validated ANSYS based numerical results with experimental data successful, which confirms the reliability of FEA for vibration analysis under varied conditions. Expanding this further, Shaha Rohit D. and Kulkarni [3] conducted a study which compares between FEA and experimental vibration analysis in deep groove ball bearing having outer and inner race defects. Their research showed a correlation between experimental and simulated results for BPFO and BPF1 (defect frequencies), which validated FEA as good tool for analyzing bearings at dynamic conditions. A significant leap in understanding was gained by Singh et al. [4], by developing an explicit dynamics FE model of a ball bearing which

had a outer race defect. This study was crucial because it analyzed the contact forces between rolling elements and the raceway by moving beyond vibration analysis, which was nearly impossible through experimental analysis. Through this analysis they identified the precise mechanism of impulse generation, concluding that the reason of high amplitude, high frequency vibrations is re-stressing of rolling elements while exiting the defect, rather than initial impact upon entry. The research emphasized upon the importance of designing bearing components as flexible bodies so as to get most appropriate results. Parallel to these advancements, Khaire and Phalle [5] integrated FEA and Machine learning in dynamic simulation. They trained artificial neural network (ANN) and a decision Tree (DT) Classifier by using FEA to generate vibration data for a healthy bearing and also ones with inner race defects. This approach used to create robust synthetic datasets for training machine learning models. In recent time Apani et al. [6] applied numerical techniques for solving the problem of static validation. Their Study focused on the static structural analysis of SKF6206 for contact stress and deformation validating it further with classical hertzian theory. Through minimal deviation between these two techniques formed a crucial foundation for all subsequent dynamic analysis.

3. Methodology

3.1 Static structural analysis using ANSYS

3.1.1 3D CAD Model Generation

A 3D Cad model of SKF 6206 Deep groove ball bearing was created using ANSYS SpaceClaim. The Models consists of all the components of ball bearing- Outer race, inner race, cage, rolling elements. The dimensions are defined by taking reference from the catalogue of SKF.

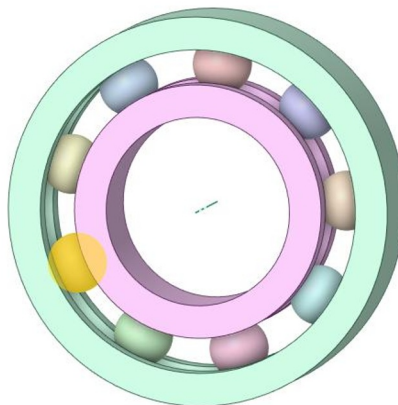


Fig. 1. SKF 6206 Deep groove ball bearing model.

3.1.2 Material properties

The bearing is analyzed by assigning four different materials. The materials are structural steel, chromium steel, bearing steel and ceramic. The material will be modeled as linear elastic, homogeneous and isotropic. These are the properties of materials:

- Structural steel : Young's Modulus – 200-210 GPa
Density – 7850 kg/m³
Poisson's Ratio – 0.3
- Bearing steel : Young's Modulus – 200-215 GPa
Density – 7810-7830 kg/m³
Poisson's Ratio – 0.3
- Chromium steel : Young's Modulus – 200-215 GPa
Density – 7650-7700 kg/m³
Poisson's Ratio – 0.28-0.3
- Ceramic : Young's Modulus – 300-320 GPa
Density – 3200-3300 kg/m³
Poisson's Ratio – 0.26 -0.28

3.1.3 Meshing

Meshing determines the accuracy of the model. It is discretized using combination of tetrahedral and hexahedral elements. A fine and controlled mesh is applied between the critical regions like contact surfaces between raceways and rolling elements. The quality of mesh directly impacts the result accuracy.

3.1.4 Contact Definition

A nonlinear surface to surface Contact was defined between the balls and raceways. The contact between Outer race and balls was defined as no separation and contact between balls and inner race is given as bonded.

3.1.5 Boundary Conditions and Loading

For simulating the model, the outer race is kept fixed. A radial load is applied at inner race in downward direction.

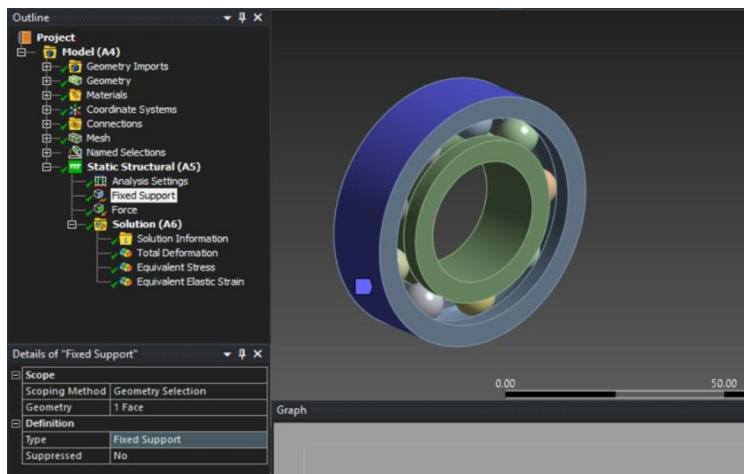


Fig. 2. Boundary conditions.

Figure 2 shows the given boundary condition to bearing model while performing static structural analysis. The outer race of the bearing has been given fixed support as it is connected to housing. The fixed support best replicates real world application.

3.1.6 Solver

The finite element analysis will be performed which will be solved for gaining the

stresses and deformations which are resulted from applied loads of 4000N, 6000N, 9000N and 11000N by neglecting inertial and damping effects. The bearing specifications on which analysis is performed are given in below table:

Table 1. SKF 6206 Ball bearing specifications.

Parameter	Value
Bore diameter (d)	30 mm
Outer diameter (D)	62 mm
Width (B)	16 mm
Fillet radius (minimum r_1, r_2)	1.00 mm
Number of balls	9 balls
Basic dynamic load rating (C)	20.3 kN
Basic static load rating (C_0)	11.2 kN
Reference speed	24 000 rpm
Limiting speed	12 000 rpm
Mass / weight	~0.21 kg
Internal clearance	CN (normal clearance)

3.2 Analytical Analysis using Hertzian contact theory

The Hertzian contact theory is traditional method which studies the load distribution between rolling elements and determines the maximum load on a single rolling element (Q_{max}) when a radial load F_r is applied [12]. The formula to calculate Q_{max} is given as:

$$Q_{max} = \frac{4.3 Fr}{z \cos \alpha} \dots\dots\dots(1)$$

Here the α is contact angle between rolling elements and raceways which is 0 in this case because we have considered purely radial loading.

The maximum pressure (σ_{max}) by Hertzian contact theory is calculated by using equation for semi major and minor contact axes (a,b):

$$\sigma_{max} = \frac{3Q}{2\pi ab} \dots\dots\dots(2)$$

3.3 Comparison between Numerical and Theoretical results

- Maximum contact stresses: The peak stress calculated using static structural analysis will be directly compared to σ_{max} calculated from Hertzian theory.
- Load zone: The load distribution pattern will be compared qualitatively and quantitatively.
- Deformation: The maximum deformation of the bearing structure will be compared.

4. Results and discussion

The figures 3 and 4 shows deformation and equivalent stress at 4000N load. The material used for bearing is structural steel.

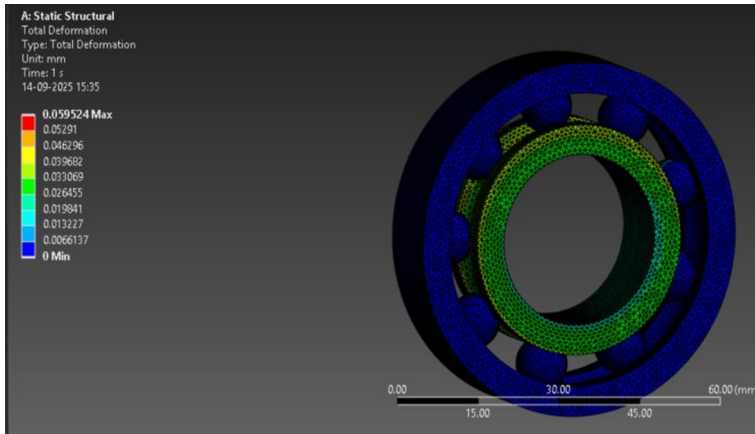


Fig. 3. Total deformation of bearing under 4000 N radial load.

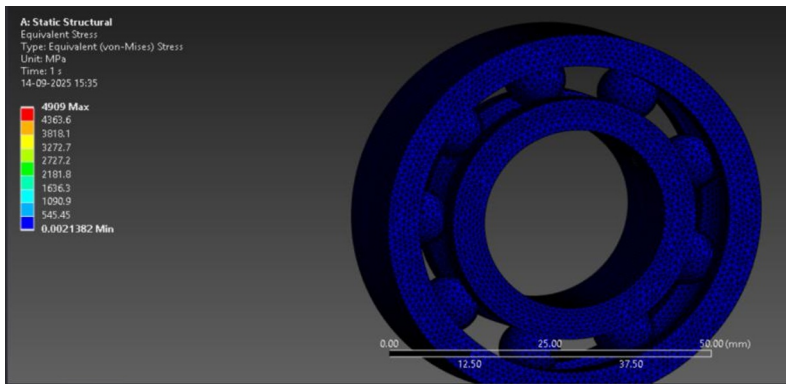


Fig. 4. Equivalent stress produced in bearing under 4000 N radial load.

Table 2. Comparison of results of Deformations obtained through Static structural and Theoretical calculations.

Materials of Bearing	FEA Deformations in mm				Theoretical elastic indentation (δ)			
	Loads in (N)				Loads in (N)			
	4000 N	6000N	9000N	11000N	4000 N	6000N	9000N	11000N
Structural steel	0.0595	0.0893	0.1339	0.1640	0.01891	0.02478	0.03247	0.03711
Bearing steel	0.0567	0.0850	0.1276	0.1561	0.01891	0.02478	0.03247	0.03711
Chromium steel	0.0567	0.1276	0.1276	0.1561	0.01891	0.02478	0.03247	0.03711
Ceramic	0.0384	0.1561	0.0864	0.1059	0.01493	0.01956	0.02563	0.02930

Table 3. Comparison of results of Equivalent stresses obtained through Static structural and Theoretical calculations.

Materials of Bearing	FEA (Von mises stress in MPa)				Theoretical calculations(σ_{max} in MPa)			
	Loads in (N)				Loads in (N)			
	4000 N	6000N	9000N	11000N	4000 N	6000N	9000N	11000N
Structural steel	4909	7363	11045	13500	4888.7	5596.2	6406.1	6849.2
Bearing steel	5071	7605	11408	13945	5,050.4	5,781.2	6,617.9	7,075.7
Chromium steel	5071	7605	11408	13945	5,050.4	5,781.2	6,617.9	7,075.7
Ceramic	6357	9529	14300	17482	6,396.7	7,322.4	8,382.0	8,961.9

In final results obtained through static structural analysis and Hertzian contact theory are given in table 2 and table 3. The deviations seen in both the results is large and it primarily arises due to the differences in modeling assumptions. The Hertz theory predicts under idealized assumptions such as rigid rings, smooth geometry, limited load sharing and point contact between rolling elements and raceways. It predicts the values of local elastic deformation and peak pressure at a single ball-race contact. Contrastingly, FEA assumes realistic structural behavior of complete bearing assembly which includes ring flexibility, multi ball load distribution, nonlinear contact interactions and realistic boundary conditions. The deviations in assumed raceway curvature and number of load carrying balls increase the difference between the two methods. Hence, it can be said that the variations between the analytical and numerical values are consistent and are expected with the inherent limitations and assumptions of hertz theory compared to 3 Dimensional Nonlinear Finite element analysis.

5. Conclusion

In the study various materials have been studied and at variable loading conditions. By the above conducted experiments and comparison it is concluded that Bearing steel (AISI 521000 is the most appropriate choice for SKF 6206 deep groove ball bearings for general industrial purpose operating conditions. It sustains high fatigue conditions, Hertzian stresses and it is compatible with SKF's static load rating definition. Chromium steel behaves most identical to bearing steel and it is suitable for alloying benefits or corrosion resistance. Ceramic is stiff and it minimizes deformation so it is most suitable for high speed and precision operations. However, its brittleness makes it inappropriate under heavy static loads. Structural steel has deforming properties and it has low fatigue strength. From loading perspective 4000-6000 N is the most appropriate range. while beyond this range we have found differences between FEA and Hertzian predictions.

Thus combination of bearing steel and moderate loads is most suitable for reliable long term operation of the rotating machinery.

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