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Modelling and Comparative Study for Deep Groove Ball Bearing Based on Structural Analysis using FE Simulation

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ABSTRACT: A deep groove ball bearing is a rotary element designed for supporting a radial as well as axial load, low friction, and widely used due to little noise and vibration which supports high rotational speeds. In this article, the author carried out a structural analysis (using FE Simulation) of a single row deep groove ball bearing for estimating contact stress and total deformation for three grades of materials viz. Silicon Nitride (Si3N4), 440C Stainless Steel, and AISI 4140 Alloy Steel. Under the scope of the study, modeling is done using Autodesk Platform and analyzed using ANSYS as an FEA tool. The natural boundary conditions were applied to estimate the fatigue life of bearings under standard operating conditions. The obtained results indicate Silicon nitride material was found to be more significant amongst all materials taken for considerations.

KEYWORDS: Deep groove ball bearing, Silicon nitride, Equivalent stress, Equivalent strain

1. Introduction

Most of the industries uses single row deep groove ball bearing most common type of rolling bearings. For the movement of machine elements concerning each other different types of bearings are used flawlessly for supporting skyscrapers and allowing them for movement at the time of earthquakes, bearings can make excellent watches happily tick away. If there is nothing like bearings, all would have ground to rest, including many of those whose joints are containing sliding bearings, The DGB usage is the most widely in industry and the market share of DGB bearings is about 80 % of total industrial rolling element bearings. For better load carrying capacity double row deep groove ball bearings are more suitable for bearing arrangements [1]. While designing the bearings and selecting its applications load capacity is the important thing. Also, it has high authority on fatigue life prediction of bearings. Ball bearings are the most commonly used machine elements. Having the same physical parameters double row deep groove bearings are wider than single row bearings, also they consist of higher loading capacity [2]. There are two types of bearings, contact bearings, and non-contact bearings. From which Contact-type bearings consist of contact between elements, it consists of sliding, flexural and rolling bearings. Mechanical contact shows stiffness in the direction which is normal to the direction of motion and it can be very high, but their life can be limited by wear and fatigue. In case of machine design, the designer decide to use bearings then it is very much mandatory thing for them to calculate strength (contact), the lifetime of bearing, and radial and axial rigidity of rolling bearings. But still, it is very difficult thing to calculate the contact strength, radial rigidity, and total lifetime of the rolling bearings precisely in theory [3]. A thrust load of about 70 % can be supported using a DGB bearing of its radial load. In Past, a lot of researchers have analyzed effectiveness for bearing defect detection using statistical parameters for different conditions [4]. To find out the location of stress concentrations also to determine the minimum and maximum of shear stress in rolling ball bearings finite element analysis is used [5]. Condition monitoring of bearings has a very big role in the maintenance of any rotating machines such as bearings for detecting the fault earlier [6]. The bearing failure causes economical loss. Various analysis protocols are well articulated for industrial components for structural loading [7].

2. Design consideration in deep groove ball bearing

In ball bearings, it consists of inner, outer races and a set of balls. All races have a ring with a groove for placing the balls as shown in Fig. The shape of the groove is made such that the ball fits loosely in the groove. The race has dents for pressing each ball on it, the contact between ball and race contains finite pressure and they show finite contact between them. Each ball and race contacts have opposite forces and sliding motions [8].

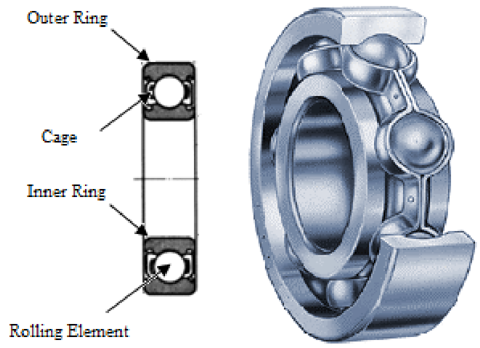


Figure. 1. Deep groove ball bearing [9]

As per Hertz's theory, the contact between two bodies having curved surfaces under force W is considered. Rolling elements and races have line contact or theoretical point contact between them. But the elliptical shape is formed due to elastic deformation in the contact area between two curved bodies of point contact. In machine elements and setups, it includes vibrations and sudden shocks. Also, there can be high contact stresses. The over-temperature of bearing can alter the state of lubrication and form premature failure of bearing or machinery element due to increment in heat further. These deep groove ball bearings can withstand both radial and axial loads in a particular direction, are quite easy to mount, and maintenance requirement is also less than other types of bearings. If there is a need for higher load capacity mandatory, hence double row bearing can be a better alternative for single row DGB bearing.

The usage of deep groove ball bearings is wider in industry and they acquire around 80 % of the industrial market share. To provide preload that induces stiffness of bearing it is crucial to provide a suitable amount of interference [10].

The objectives and scope of the study are to design the SKF 6302 Ball Bearing and study the structural stress analysis for high performance. their consequence on fatigue life of bearing. After analysis, a comparison is made between silicon nitride, stainless steel alloy (AISI 440c), and 4140 Alloy steel bearings following structural and contact stresses.

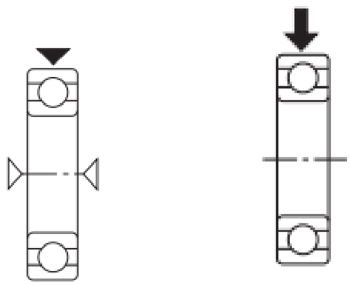


Figure. 2. Loading in Deep groove ball bearing (Axial and Radial with Axial combined) [8]

3. Modelling and simulation

3.1. Materials used for analysis

The developed model was analyzed for three different materials namely Silicon Nitride, AISI 4140 Alloy Steel, and 440C Stainless Steel; and materials properties used for those materials are stated in Table 1.

Table 1. Material properties

Parameter	Materials		
	Silicon Nitride	AISI 4140 Alloy Steel	440C Stainless Steel
Density (Kg/m^3)	3395	7861	7799
Young's modulus (Pa)	3e12	4.15e8	1.9e11
Poisson's ratio	0.23	0.3	0.285
Bulk modulus (Pa)	2.27e12	3.45e8	1.66e11
Shear modulus (Pa)	1.171e12	1.596e8	8.39e10

Table 2. Dimensions of bearing

d	15 mm
D	42 mm
B	13 mm
d_1	23.7 mm
D_2	36.23 mm
$r_{1.2}$	min. 1 mm

3.2. Analytical Calculations

For analytical approach Hertz theory of contact stress is considered. Hertz theory include mathematical analysis of the affiliation between, the overall contact area size, the stresses distributed in two bodies having some curvature, the profile of the geometry. This study includes elliptical contact surface between the applied load, inner race and balls [11].

I. Steps to Determine the Contact Stresses –

Step 1: Consideration of applied load on DGB bearing.

Step 2: Determine the design P_d load at which the ball bearing will be subjected. The static shaft analysis determines the axial (Fa) and radial (Fr) forces. Defining of the equivalent load p-value is done using Equation

$$P = XF_r + YF_a \tag{1}$$

As in this study only axial force acting on the bearing is considered, equation (1) can be termed as,

$$P = 0 + YF_a$$

Determination of the design load value using axial force P with V as a rotation factor

$$P_d = V \tag{2}$$

The value of V =1.2 if outer ring is rotating and V = 1 if inner ring is rotating.

II. Steps to Determine the Contact Area of the Ball Bearing

Step 3: Now find the total curvature of contact area, in current study analysis of curvature is done between inner race and ball bearing. Total curvature of ball bearing in the directions x and y is termed as

$$\frac{1}{R} = \frac{1}{R_X} + \frac{1}{R_Y} \tag{3}$$

$$\frac{1}{R_x} = \frac{1}{r_{aX}} + \frac{1}{r_{bx}} \tag{4}$$

$$\frac{1}{R_y} = \frac{1}{r_{ay}} + \frac{1}{r_{bY}} \tag{5}$$

Here, r_{ax} is ball radius in x direction and r_{ay} is ball radius in y direction. So $r_{ax} = r_{ay}$. Also r_{bx} and r_{by} are radius of curvature from ball bearing centre to exterior ring and radius of curvature of external ring respectively. The overall analysis in this study is performed on the whole DGB bearing.

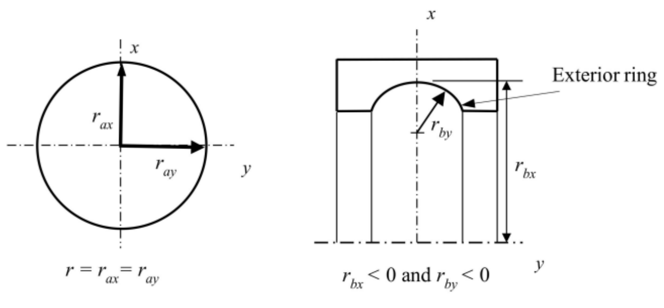


Figure.3. Race of ring and ball ratio [11]

Step 4: The radius of ring R_r, the curvature's index (a_r), elliptical parameter (k_e) can be determined from catalogues as this bearing is standard SKF bearing.

Step 5: Now effective elasticity module (E') is determined as:

$$E' = \frac{2}{\frac{1-v_a^2}{Ea} + \frac{1-v_b^2}{Eb}} \tag{6}$$

In this, v_a and v_b are the Poisson coefficient of the ball and inner/outer ring respectively. Also, E_a and E_b are the elasticity module of ball and rings.

Step 6: Calculate a and b for ellipse dimensions, as the contact area between the ball and ring is of ellipse form. Values of a and b are for determined as a and b are half of the (Dy) and (Dx) ellipse diameters written as:

$$D_y = 2\left(\frac{(6K_e^2 \varepsilon P_d\, R)^{\frac{1}{3}}}{(\pi E')^{\frac{1}{3}}}\right) \tag{7}$$

$$D_x = 2\left(\frac{(6\varepsilon P_d\, R)^{\frac{1}{3}}}{(\pi k_e E')^{\frac{1}{3}}}\right) \tag{8}$$

These equations are used for determining the values of a and b.

III. Determination of the equivalent Principal Stress Values

Step 6. Now the maximum contact stress P_{max} is determined using the equation as:

$$P_{max} = \frac{6PD}{\pi D_x D_y} \tag{9}$$

The equation for Von-Mises Stress is

$$\sigma_{VM} = \sqrt{\sigma_1^2 + \sigma_2^2} + \sigma_3^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_3\sigma_1 + 3(\tau_1^2 - \tau_2^2 - \tau_3^2) \tag{10}$$

In this, the stress acting on the bodies (inner and outer ring, ball), is given by $\sigma_{1,2,3}$ and $\tau_{1,2,3}$.

IV. The equation for maximum deformation (δ) is as:

$$\delta = \Im\left[\left(\frac{9}{2\varepsilon R}\right)\left(\frac{F}{\pi k\gamma}^2\right)\right]^{1/3} \tag{11}$$

V. Equivalent strain (ξ) is calculated using below equation[12]:

$$\xi = \frac{\sigma\gamma}{2} \tag{12}$$

3.3. *CAD Modelling of bearing*

The Deep Groove Ball bearings are modeled using Autodesk Fusion 360 and analyzed using the ANSYS workbench simulation tool used for Finite Element Analysis, static structural model setup was used for analysis. The standard SKF deep groove ball bearing model was considered under scope of study.

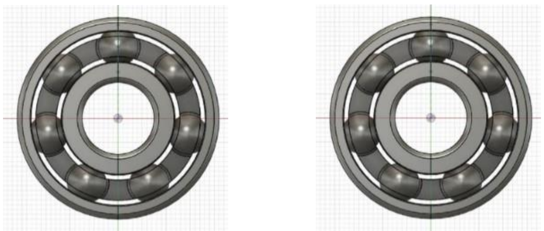


Figure. 4. CAD model

3.4. Boundary conditions

The natural boundary conditions are applied as per the images attached below with tetrahedron meshing and locations of axial load are highlighted with red color [13].

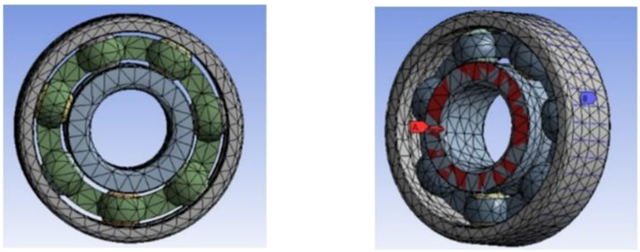
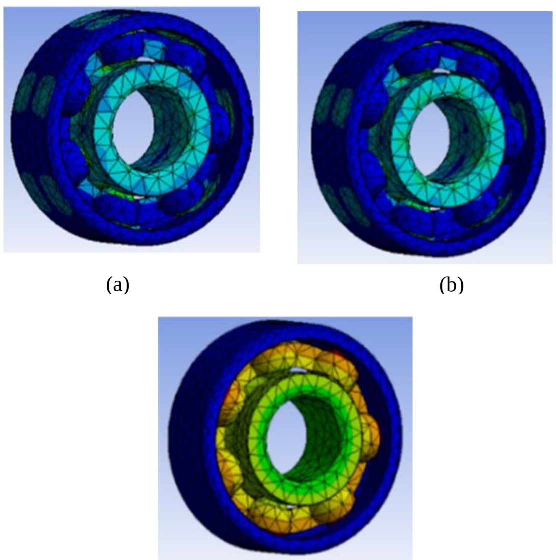


Figure. 5. Model with meshing and natural boundary conditions

3.5. Results and discussion

The resulted analytical and simulated values with the given loading conditions the output such as total deformation, Equivalent Elastic Strain, and Equivalent Stress was compared for all selected materials, and results are tabulated below. After comparing the theoretical and numerical results, the difference is varying in the range of about 5% to 7% which is in better agreement.



(a) (b) (c)

Figure. 6 Results for Alloy steel 4140 , a) Equivalent strain, b) Equivalent stress c) Total deformation

New material silicon nitride is used for evaluation in different types of bearings and loading conditions for comparing and choosing the better material among the results of analysis of different materials. In this study DGB bearing is modelled using fusion 360 tools and then simulated for structural stress analysis using ansys tools. Analytical calculations are performed based on Hertz theory. By correlating these theoretical and numerical results the best material among the three different used materials is decided. The FE simulation and analytical approach is noble, provides the finest results and it is less expensive[14]. In terms of axial load the results using proposed methodology for this study also suggests that silicon nitride is best suitable material under standard loading conditions. Also when other researchers worked on the different types of bearing under suitable loading conditions, the results indicated silicon nitride as a better bearing material choice if only axial load is concerned.

3.5.1. Silicon Nitride

Table 3. Silicon Nitride

Name	Total deformation	Equ. Elastic Strain	Equi. Stress
Min	0	1.5251e-006 m/m	1.9041e+005 Pa
Max	3.1116e-005 m	5.6229e-004 m/m	1.4892e+008 Pa

3.5.2. Alloy steel 4140

Table 4. Alloy steel 4140

Name	Total deformation	Equ. Elastic Strain	Equi. Stress
Min	0	2.0414e-006 m/m	1.5232e+005 Pa
Max	7.2709e-005 m	7.8877e-004 m/m	1.5719e+008 Pa

3.5.3. Stainless Steel 440c

Table 5. Stainless Steel 440c

Name	Total deformation	Equ. Elastic Strain	Equi. Stress
Min	0	2.1834e-006 m/m	1.5617e+005 Pa
Max	7.757e-005 m	8.4235e-004 m/m	1.5766e+008 Pa

4. Conclusions

From the investigation carried out to investigate structural properties of deep groove ball bearing, following conclusions can be drawn while taking account the limitations of this study:

Silicon Nitride Material was found to be more significant as compared to specified loading conditions. From the analysis completed in this study we can

Table 6. Analytical and simulated results of DGB bearing using three different materials

Sr. No.			Total Deformation	Equ. Elastic Strain	Equi. Stress
1	Silicon Nitride	Analytical	3.3016e-005 m	5.9113e-004	149.97 MPa
		Simulated	3.1116e-005 m	5.6229e-004	148.92 MPa
2	Alloy steel 4140	Analytical	6.9012e-005 m	7.5677e-004	154.46 MPa
		Simulated	7.2709e-005 m	7.8877e-004	157.19 MPa
3	Stainless steel 440C	Analytical	7.4431e-005 m	8.1675e-004	153.19 MPa
		Simulated	7.757e-005 m	8.4235e-004	157.66 MPa

By observing the structural analysis outcomes under the same loading conditions of three materials it is found that the bearings when uses silicon nitride material shows less maximum equivalent stress among the all used materials. Also we can see from the results table that the total deformation is also fewer while using silicon nitride as a bearing material compared to other traditional materials

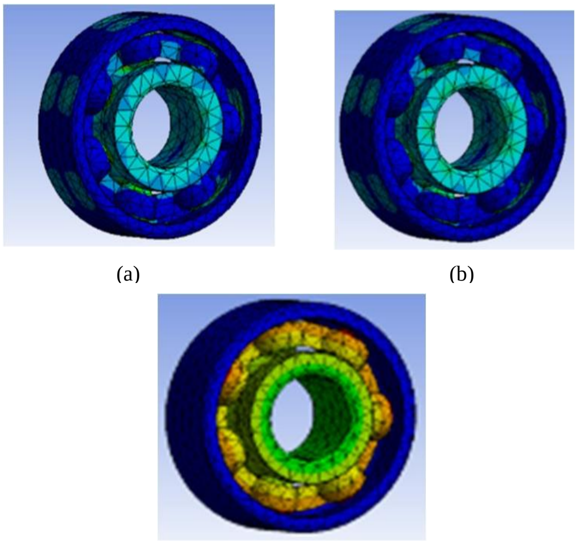


Figure. 7 Results for Stainless Steel 440c , a) Equivalent strain, b) Equivalent stress c) Total deformation

Silicon Nitride Material was found to be more significant as compared to others in specified loading conditions. From the analysis completed in this study we can conclude that the stress and deformation values w.r.t. axial load while using silicon nitride material are found to be within acceptable range compared to other materials. This acceptable ranges are from the standards set by many bearing manufacturing companies. As compared to other traditional metal bearings, bearings of silicon nitride are harder than metal, there is a reduction in contact with the bearing track, which appeared in higher corrosion resistance, 80 % less friction, and higher operating temperature. It also consists of low density about 40 % of steel, so it naturally decreases the centrifugal force and it can operate in high temperature environments.

Future scope – In near future work as various materials are being continuously developed and modified. So as per bearing industry standards and need, various materials can be used for further study under the scope of finding the better materials for use in bearing in specific loading and operating conditions.

Conflict of Interest

The authors declare no conflict of interest.

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