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Original Article

Development of Angular Contact Clutch Ball Bearings Using Hertz Contact Stresses and FE Analysis

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Abstract *- Ball bearings are essential components in machinery. They use balls positioned between two races to support axial and radial loads and reduce rotational friction. In applications such as automotive clutch bearings, where frequent clutching and declutching operations occur, the bearing must endure a large number of operational cycles. It is crucial to assess the distribution of stress and deformation within the bearing to determine its true lifespan. Identifying areas of high stress and deformation provides insight into potential modifications to the design or material composition to achieve the necessary bearing longevity. This iterative process involves scrutinizing the bearing, making necessary adjustments to the design or material properties, and then reassessing it until the desired bearing lifespan is achieved. This meticulous approach ensures the reliability and durability of bearings in demanding operational environments.*

Keywords *- Contact bearing, Clutching and declutching cycles, Radial load, Thrust load, FE Analysis.*

1. Introduction

One kind of rolling element in the bearing is a ball bearing., which employs balls to preserve separation among its moving parts. The dynamic features of ball bearings notably influence the rotor-bearing system's performance [1]. Its main goals are to support axial and radial loads and reduce rotational friction. This is achieved by utilizing a minimum of two races in order to cover the balls and move the load through them. Usually, one race spins while the other stays still, causing the ball to rotate.

The rolling action of the balls results in a significantly reduced coefficient of friction when compared to what happens when two flat surfaces meet [2]. Owing to the balls' and races' reduced surface area of contact, comparing ball bearings to traditional rolling-element bearings, the former has a lower load capability. They do, however, show tolerance for the outer races not aligning with the inner races.

Because it is often less expensive to manufacture the balls used in ball bearings than it is to manufacture other rolling-element bearings, ball bearings are the most affordable option [3]. Properly preloading angular contact ball bearings is significantly important for enhancing the bearing-rotor system's stiffness, rotational accuracy, temperature management, and fatigue life [4].

2. Literature Review

2.1. Angular Contact Clutch Ball Bearings

Angular contact clutch ball bearings (AC Ball Bearings) are designed through axially asymmetric races, enabling axial loads to travel straight through the bearing while radial loads take an oblique path, causing the races to separate axially. The inner race's and outer race's angles of contact are aligned by this design. These bearings are particularly effective for supporting combined loads, where both radial and axial forces are present, with the contact angle optimized for load distribution [5].

The contact angle, typically ranging from 10 to 45 degrees, dictates the bearing's ability to withstand axial loads; higher angles can support greater axial loads but lower radial loads [1]. Centrifugal forces from the balls can change the contact angle at the high-speed inner and outer race devices like turbines, jet engines, and dental equipment [6]. The interaction between a ball and a torus ring is the main subject of the investigation., resembling that of ball bearings.

It entails analyzing the nonplanar contact area's sliding velocity field to calculate the friction force that results and moment, presumptuous a consistent friction coefficient at every contact point [7]. Because silicon nitride ceramics are low-density (40 percent steel), they are becoming more and more popular as a solution to this problem. They help counteract centrifugal force and perform well under high temperatures, displaying wear patterns akin to bearing steel rather than fracturing like glass or porcelain [8].

Angular contact bearings find widespread use in bicycle headsets, as they effectively manage both radial and axial forces typically encountered in these bearings [9].

There are mainly three types of AC ball bearings, as shown in Figure 2.

1. Single-row bearings
2. Double-row bearings
3. Single-row bearings with 4-point contact

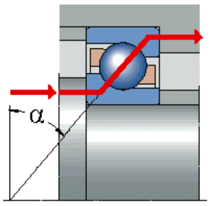


Fig. 1 Contact angle for AC ball bearings

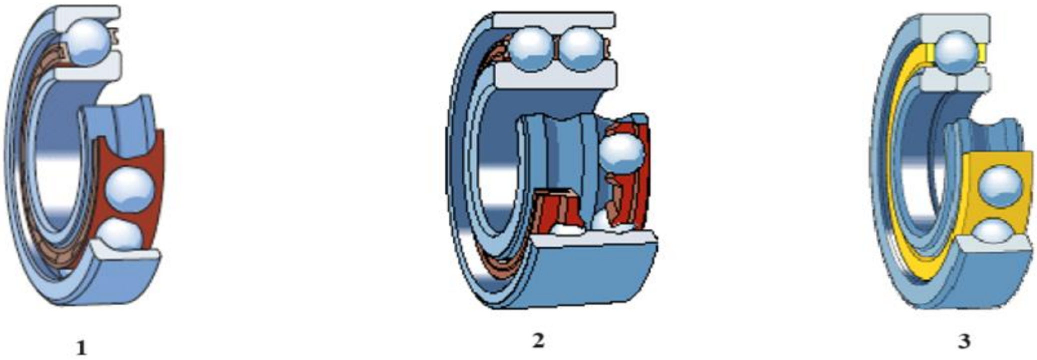
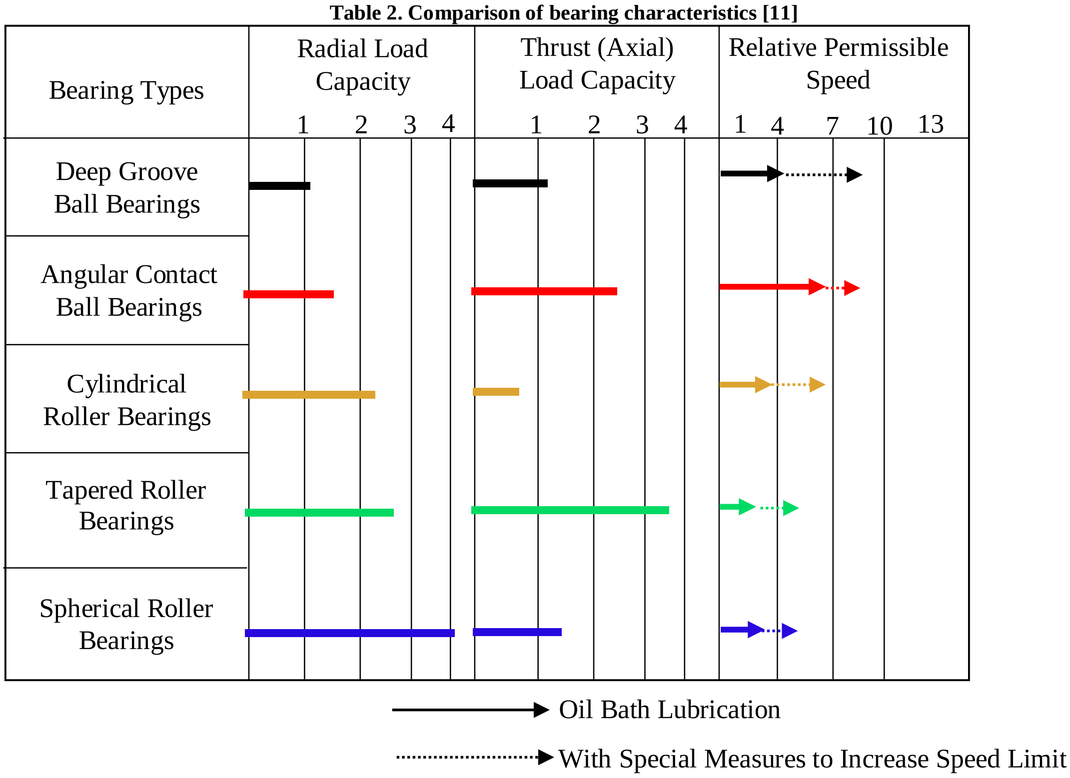


Fig. 2 Types of AC ball bearings [10]

Table 1. Ball Bearing Characteristics [11]

Characteristics	Deep Groove	Angular Contact	D-R Ang. Contact	Duplex Ang. Cont.
Combined Load	3	4	4	4
Radial Load	3	4	4	4
Axial Load	3	4	4	4
High Accuracy	5	-	5	5
High Speed	5	3	5	4
Angular Misalignment	4	2	3	2
Low Noise and Torque	5	3	4	4
1: Impossible 2: Poor 3: Fair 4: Good 5: Excellent				

Table 2. Comparison of bearing characteristics [11]



2.2. Ball Bearings Characteristics

Table 1 shows the characteristics of different bearings for loading conditions and operating parameters.

2.3. Bearing Characteristics Comparison

Table 2 shows the comparison of the bearing for loading conditions and operating parameters.

3. Design of AC Ball Bearings

The number of components indicated below is mostly used to assemble angular contact. Pumps and air compressors, metallic rolling mills, electrical motors, machine tool spindles, generators, and self-propelled hub bearings are just a few of the several uses for angular contact bearings [12]. Angular bearings are utilized in automobiles for the clutch; hence, they are also referred to as clutch bearings. They serve as release bearings in clutch assemblies. Loads applied above the bearing are generally thrust loads, It could include loads that are radial and axial [13]. In contrast to the 1225 N applied axial load above the bearing, the radial load is insignificant.

Table 3. The main part of AC ball bearings

Sr. no.	Part Name	Qty. No.
1	Outer race	1
2	Inner race	1
3	Rubber seal	1
4	T seal	1
5	Cage	1
6	Steel Ball	12

The inner race of this bearing is fixedly supported, while the outer race is free. The table below indicates the materials used for different parts of the AC clutch ball bearings.

Here, the load is transferred through the outer race to the ball and through the ball to the inner race. All these three parts are made of SAE52100. Table 5 provides the SAE52100 material's chemical composition.

Table 4. Material for the different parts of the bearing

Part Name	Material
Outer Race	SAE52100
Inner Race	SAE52100
Rubber Seal	NITRIL & CRCA
T Seal	Rubber & CRCR M.S.
Cage	Nylon 66 (A4H)
Steel Ball	SAE52100
Lubrication	UNIREX N3

Table 5. SAE 52100 Chemical-Composition

Chemical Composition of SAE 52100 (%)					
C	**Mn**	**P**	**S**	**Si**	**Cr**
0.93-1.05	0.25-0.40	0.025 max.	0.015 max	0.15-0.35	1.35-1.60
Ni	**Mo**	**Cu**	**O max.**	**Al**	
0.10 max	0.10 max	0.10 max	15 ppm	0.050 max	

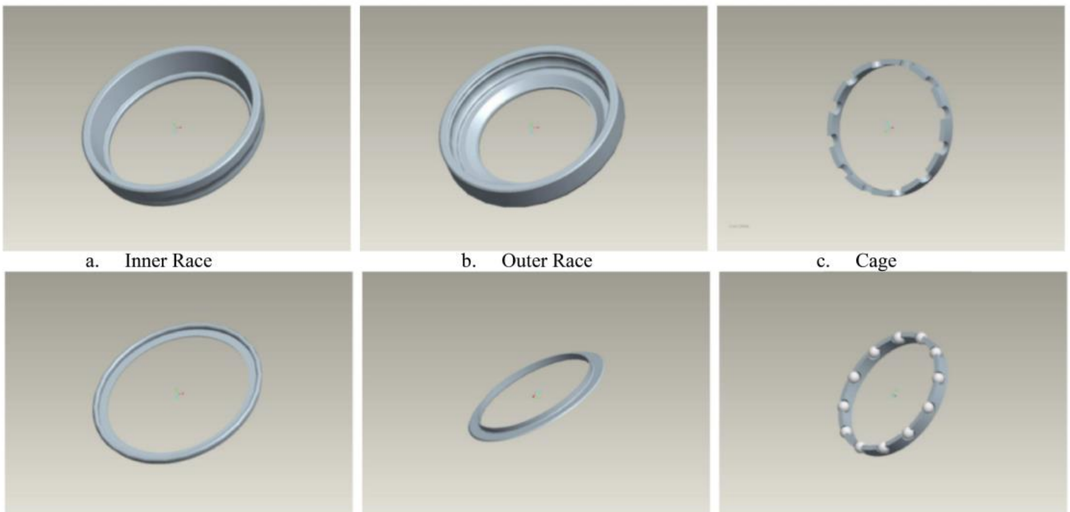
Table 6 below lists SAE52100's structural and thermal scharacteristics.

Table 6. Material property of SAE52100

Properties	Value
Young's Modulus	$2x10^5$ MPa
Poisson's Ratio	0.3
Density	7850. kg/m³
Thermal Expansion	$1.2x10^{-5}$ 1/°C
Tensile Yield Strength	250 MPa
Compressive Yield Strength	250 MPa
Tensile Ultimate Strength	460 MPa

3.1. Modelling of AC Clutch-Ball Bearing

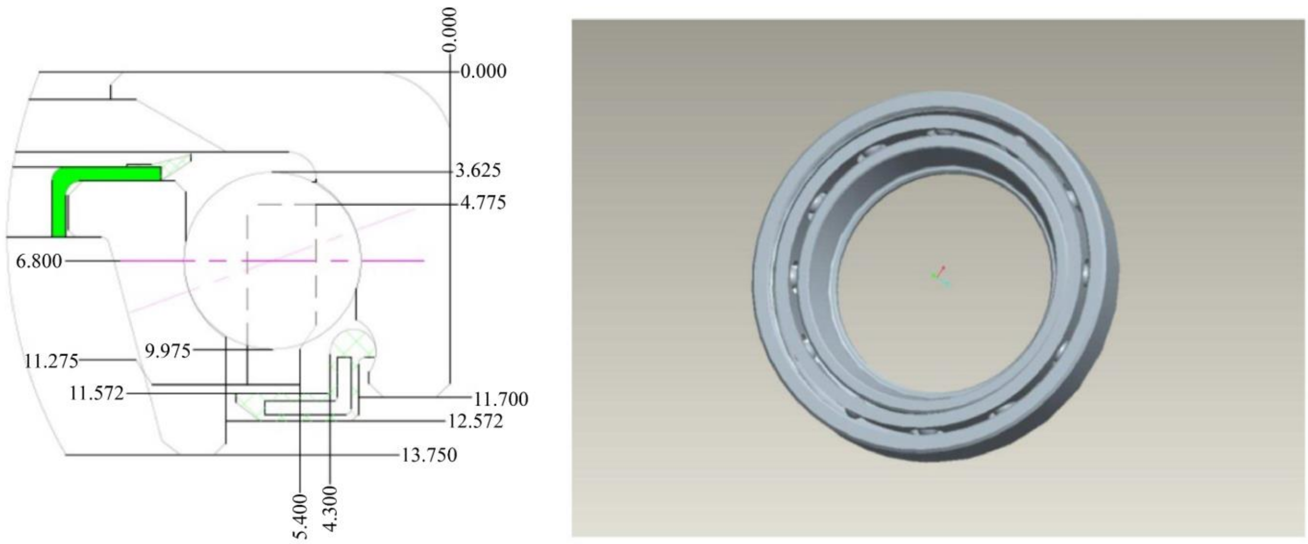
The 3D Design of AC ball bearings and their assembly is given below [14].



a. Inner Race b. Outer Race c. Cage

d. Rubber Seal e. T. Seal f. Cage and ball

Fig. 3 Main component of AC ball bearings



a. 2D Drawing b. 3D Modelling

Fig. 4 Assembly of AC ball bearings (a) 2D Drawing, and (b) 3D Modelling.

4. Methodology

4.1. Hertz Theory

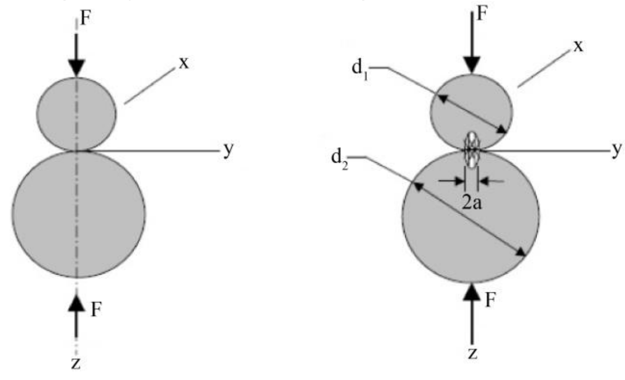
The point or line contact between two bodies becomes an area contact when their surfaces are curved, and the stresses that are created between them become three-dimensional. Touch-stress issues can occur when a wheel comes into touch with a rail, when rolling bearings roll, when mating gear teeth meet, and in automobile valve cams and tappets. Common failures manifest as surface material flaking, pitting, or cracking [15].

Normal and tangential forces for all contacts are determined using the principles of Hertz theory and Coulomb's friction law [16]. When there is a double radius of curvature for each contacting body, contact stress develops in the most common scenario.; that is, both planes are taken through the axis of the contacting force when the radius in the rolling plane differs from the radius in a perpendicular plane. The results presented here are commonly called Hertzian stresses because they are attributed to Hertz [17].

4.2. Features of Stresses in Contact Area

- Depict the stresses caused by compression that developed when two curved bodies were pushed together due to their pressures created at the surface.
- Obtain a contact zone. When the bodies are forced against one another, the preliminary point contacts or line contacts transform into areas of interaction.
- Comprise the primary stresses in a tri-axial nature of stress.
- Cause the development of a crucial area underneath the part's surface.
- Failure usually causes the surfaces of the bodies to flake or pit.
- Sphere-sphere contact (Circular Contact Area Point Contact).

Here, we shall consider the sphere-sphere contact case for angular type clutch ball bearing.



a. Two spheres held in contact b. Contact stress

Fig. 5 Shere -sphere contact [18]

Examine two solid elastic spheres that are in contact with one other and are retained by a force F in such a way that the contact area between them grows within a circle having radius a.

$$K_a = \left[\frac{3}{8}\frac{(1-V_1{}^2)/E_1+(1-V_2{}^2)/E_2}{(1/d_1)+(1/d_2)}\right]^{1/3} \quad (1)$$

$$a = k_a\sqrt[3]{F} \quad (2)$$

F is the force exerted (N),

Poisson's ratios V1 and V2, which denote spheres 1 & 2.

Elastic modulus (MPa) for spheres 1 and 2 is equal to E1 and E2.

The diameter of spheres 1 and 2, respectively, is given by d1 and d2.

There are two more typical scenarios to which this overall statement in case of contact radius can be considered:

1. Sphere interacting with a flat surface.
2. The sphere and an internal spherical surface, or "cup," are in touch [19].

In the case of the sphere-sphere, the ultimate pressure at contact, P_{max}, arises at the mid-point of the meeting area [20].

$$P_{max} = \frac{3F}{2\pi a^2} \tag{3}$$

4.2.1. Case Study: AC Ball Bearings

AC Ball Bearing is utilized for the clutch release bearing, so during application of the bearing, only thrust load applies above the bearing, and radial load is negligible. The outer race is free, and the inner race is fixed during the application of the bearing. UNIREX N3 is utilized as a bearing grease lubricant. The bearing operates at RPM 4600, and the load applied above the bearing is 1225N. During operation, the bearing temperature of the chamber is about 105^{O} C., and the bearing remains in disengaged and engaged condition for 1 second. The bearing is put together without any parts, and load is transferred between the internal and external races of the bearing. Thus, we take into account the material characteristics of the ball, inner race, and outside race. During application amount of stress produced is considered by the contact stress theory of Hertz.

F = 1225 N, V_1 & V_2 = 0.3, E_1 & E_2 = $2.1*10^5$ MPa d_1 and d_2 = 6.35 mm and 6.5 mm, putting the above value in Equation (1) gives $K_a = 9.78 \times 10^{-5}$

Now, putting the value of a Ka in Equation (2) gives a = $4.5x10^{-4}$

Now the value of P_{max} is obtained using Equation (3) is 240 MPa

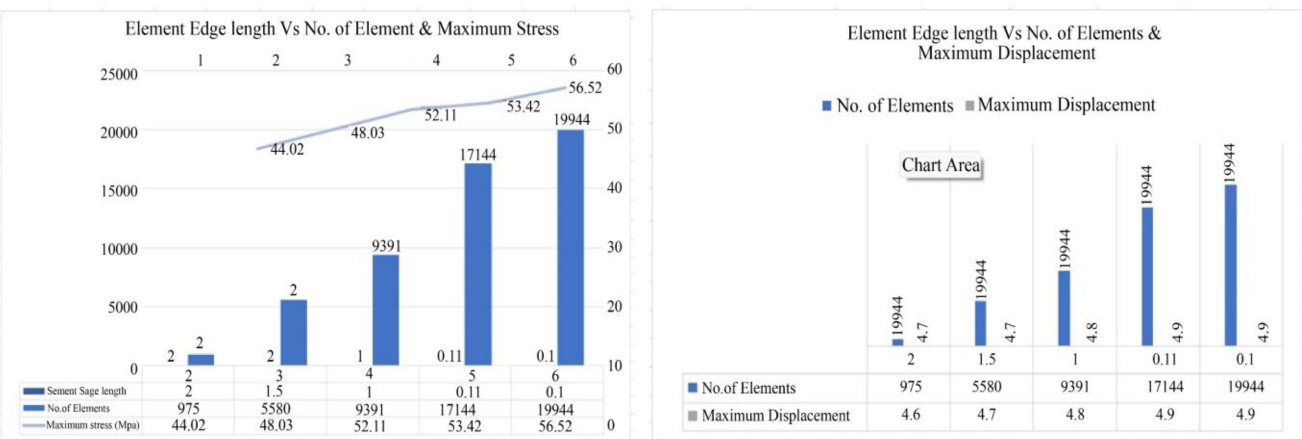
5. FEA of AC Ball Bearing

A computer-based numerical method called FEA is used for the determination of the behavior and strength of engineering structures [21]. Numerous other phenomena, including deflection, stress, vibration, and buckling behavior, can be calculated with it [22]. Analyzing deviation due to applied loading is possible with it. The plastic deformation that "permanently bends out of shape" is analyzed by elastic deformation [23].

5.1. Mesh Convergence

Convergence entails discretization first, followed by observation and documentation of the result [24]. The challenge is then repeated with a finer mesh (i.e., more elements), and the outcome is compared to the test conducted earlier.

In the event that the outcomes are almost identical, the initial mesh is most likely sufficient, given the specific geometry, loading, and constraints. It will be required to experiment with a finer mesh, though, if the results differ significantly. This might be accomplished in a solid mechanics problem by building models with various mesh sizes and contrasting the deflection and stresses that resulted.



a. Element Edge length Vs No. of Element & Maximum Stress

b. Element Edge length Vs No. Of Elements & Maximum Displacement

Fig. 6 Summary of convergence test (a) Element edge length vs No. of element and maximum Stress, and (b) Element edge length vs No. of elements and maximum displacement.

5.2. Model Solution

The AC Ball Bearings, also known as the clutch bearings when used in clutches, play a critical role in transferring loads within the clutch mechanism. The load moves from the outer race to the ball and back to the internal race when a load is applied above the clutch bearing.

This load transfer is facilitated by each of the twelve balls in the bearing, which come into contact with both the internal and external races. This configuration guarantees the bearing's ability to sustain applied loads and preserve the clutch's smooth operation while distributing the load uniformly across the bearing.

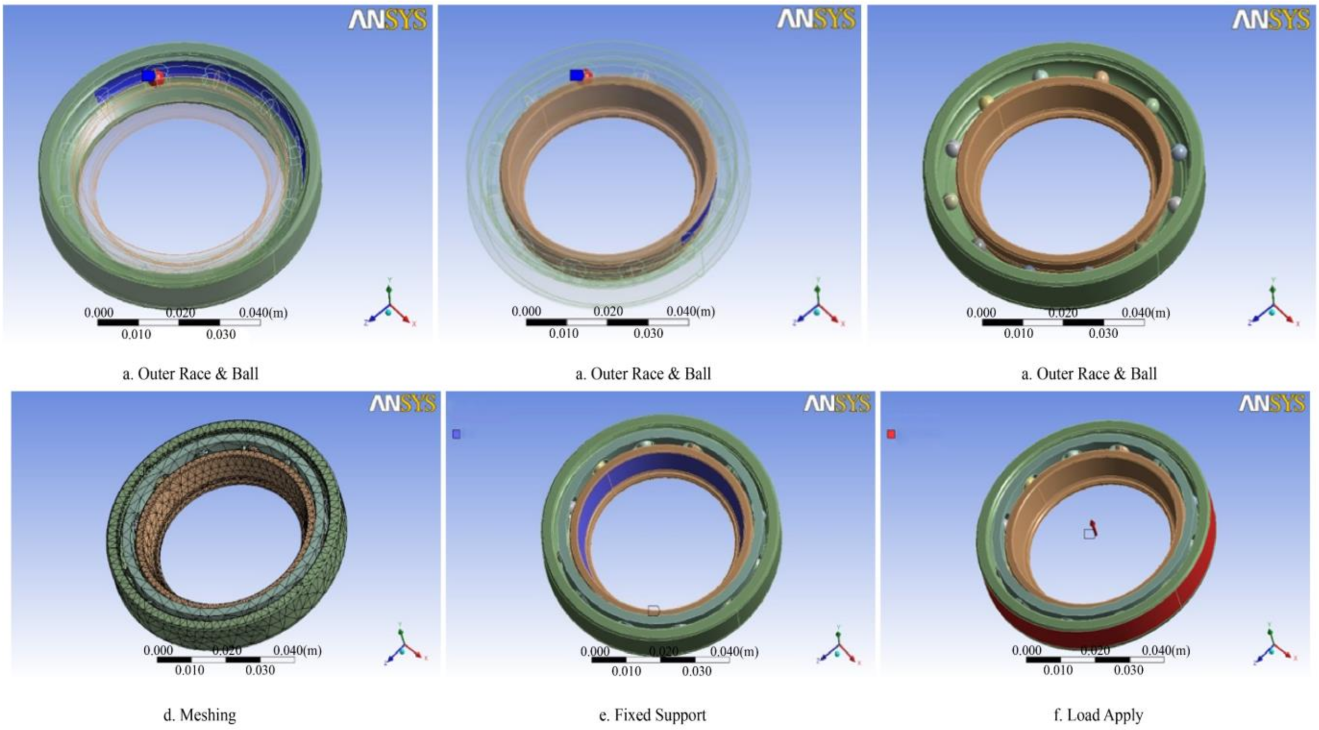


Fig. 7 Analysis of AC ball bearings

The assembly of the AC ball bearings is seen in Figure 7(c), where the bearing cage is obscured. Thus, we can see the ball's touch with both the inner and outer races with ease. It also shows how the ball is arranged.

The mesh's form or topology refers to how the elements are arranged throughout the continuum. As long as the element faces are placed appropriately, the elements can be assembled in any way. Since we are using the default size in this case, 39977 and 19944 nodes and elements are produced, respectively. The AC ball bearings meshing is depicted in Figure 7(d).

When the bearing is applied, The bearing has a free external race, while the inner race is fixed. As Figure 7(e) below illustrates, inner race is fixed supported.

Here, Figure 7(f) shows the direction and magnitude of the load imposed above the bearing. During application, the load applied above the bearing is 1225N in the axial direction.

Maximal shear stress is displayed in Figure 8(a). The cage experiences the least shear stress, whereas the ball experiences the most shear stress. 56 MPa of shear stress is the greatest that can be produced.

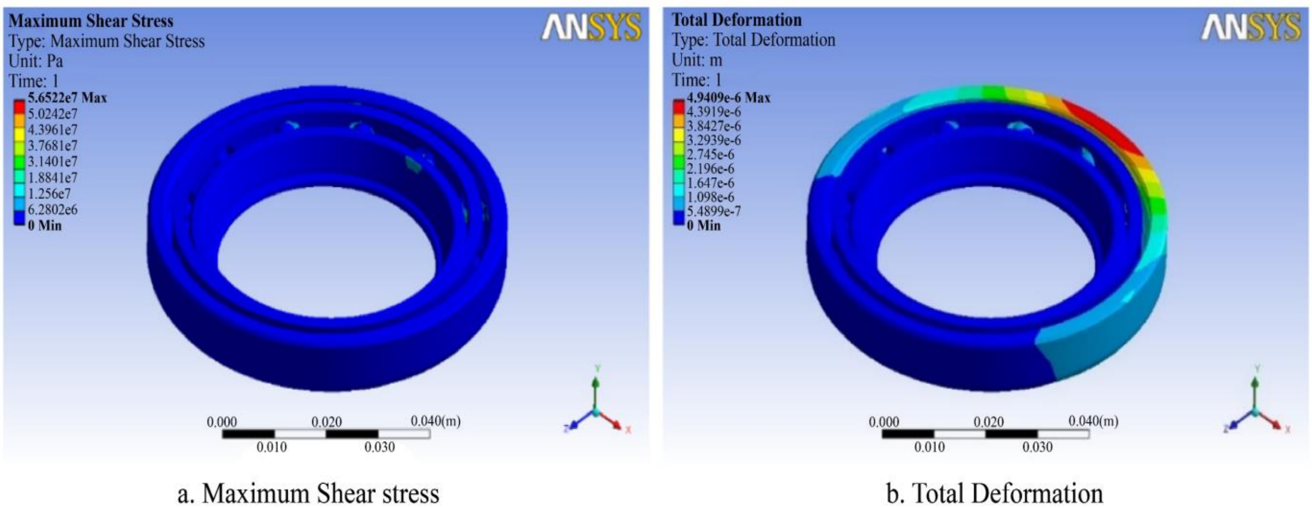


Fig. 8 Analysis of angular contact bearing (a) Maximum shear stress, and (b) Total deformation.

When the load is applied above the bearing at that time total deformation of the bearing is shown in Figure 8(b). Maximum deformation occurs $4.9409*10^{-03}$ mm. Minimum deformation occurs in the inner race and maximum deformation occurs in the Outer race.

5.3. Comparison of FEM Analysis and Hertz Contact Stress Theory Results

In addition to doing FE analysis on the same case study, a comprehensive numerical solution was computed. Below is a comparison of both cases' outcomes. The values of FE analysis for the stresses almost match with theoretical approach given by Hertz contact stress. The stress values of FE analysis are less than the theoretical approach because of the section of element length discussed in 7.44 mesh convergences.

Table 7. Maximum shear stress

Parameter	FEM Analysis	Hertz Contact Stress
Maximum Shear Stress	56.52 MPa	64 MPa

If we select a lower element length than 0.10, it may give a close value but takes no. of hours to solve, or it may be beyond the capacity of the computer.

FE analysis of angular contact ball bearing is carried and according to the solution, Maximum stress produced on the ball and total deformation of the ball bearing is discussed in Table 8.

Table 8. Different parameters of the bearing

Parameter	Value
Total Deformation	$4.9 * 10^{-3}$ mm
Maximum Shear Stress	56.52a

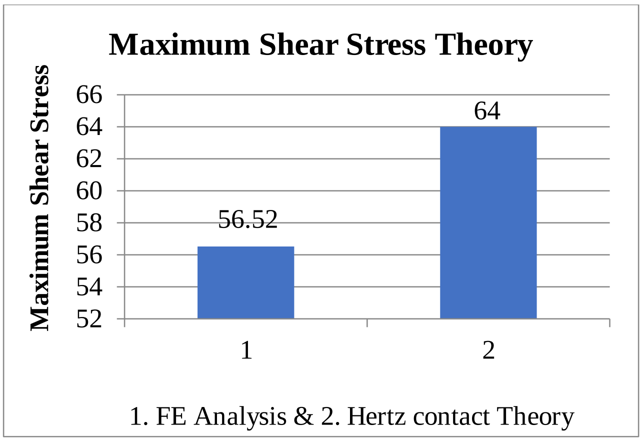


Fig. 9 Maximum shear stress obtained by FE analysis and Hertz contact theory

6. Conclusion

The purpose of this study was to enhance the clutching and declutching cycles through optimized structural design and analysis, ensuring compliance with applied load conditions while keeping stresses within acceptable limits.

Throughout this investigation, Ansys software proved instrumental in achieving accurate analyses. Leveraging Ansys, we were able to construct and analyze 3D part models, refining mesh structures through convergence tests to attain the desired solution accuracy.

Research indicates a strong correlation of about 88.31% between the Hertz contact stress predictions for AC Ball Bearings and the FEA results obtained by simulations using Ansys software. This highlights the robustness and utility of Ansys as a valuable tool for conducting detailed engineering analyses in bearing design and optimizing performance.

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