DESIGN AND ANALYSIS OF A PROPOSED CYLINDRICAL ROLLER FOR CRB USING FEA

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Abstract: In Cylindrical roller bearing, the cylindrical rollers are supported by line contact. Due to the line contact cylindrical roller bearings are allowed to carry heavy radial loads. The end corners of cylindrical roller are crowned to maximize load carrying potential, uniformly distribute the pressure, reduce edge loading with stress concentration and tolerate some minor misalignment. In this paper, the new proposed design of cylindrical roller has concentric ellipse shape cavities on both roller end faces and maximum crowned profile. The concentric ellipse shape circular cavity on both end face of roller has the characteristic of deflecting at two ends of the roller in response to radial loading. This results in a reduction of the contact stress at the rollers ends. The concentric ellipse shape cavity on the both end faces of roller design establishes an elastic behaviour of roller ends and allows deflection of the roller ends in the radial direction of the applied contact load. The use of this approach for profile modifications resulted in to sustain uniform contact stress distribution across the roller contact length. In addition to these benefits, this design concept reduces the mass of a bearing and inertia effects acting on the outer raceway, which directly improves overall bearing life span. The aim of this work is to create a uniform contact-stress distribution along the length of the roller, minimize the edge stress concentration and to recommend a roller profile design which stand with high work load.

Keywords: Cavity, Circular Crown Profile, Contact Stress, Cylindrical Roller, FEA.
INTRODUCTION

The work and design of cylindrical roller bearing is based on the line contact theory and due to the line contact between the roller and the raceways, the roller bearing can carry heavy radial loads (perpendicular to the shaft axis) only. The roller has a greater contact area with the race than a traditional ball bearing, to better distribute the applied load. The roller plays an important role in the cylindrical roller bearing performance. Hence in the design of roller, the study of roller profile, contact stresses, stress distribution is important. In CRB, the roller is subjected to only radial load. The circular crowning of roller is made to increase the load carrying capacity of roller without edge stress formation, to uniformly distribute the contact pressure uniformly over roller length. Bearing design calculations require a good understanding of the Hertzian contact stress due to which high stress concentration is produced which greatly influence the fatigue life and dominate the upper speed limits as in the case of solid rolling elements. Since being originally introduced, cylindrical rolling element bearings have been significantly improved, in terms of their performance and working life. A major objective has been to decrease the Hertz contact stresses at the roller–raceway interfaces, because these are the most heavily stressed areas in a bearing. Whereas making the proposed rollers design which is flexible enough reduces stress concentration, uniformly distribute pressure and finally increase the life and performance of bearing. If cylindrical roller profile is circular crowned, the stress concentration can be eliminated in low and moderate loads. However at heavy load cases, the stress concentration still exists [1]. Lundberg developed a logarithmic function in addition to the crowned profile which could develop uniformly distributed stress along the length of the roller at low, medium and high loads [2]. But when the load on roller is misaligned, the stress concentration will still occur even if the roller is logarithmically profiled [2].

1.1 Design and development of cylindrical roller

It was recognized from theoretical formulation proposed by H. Hertz, G. Lundberg theory and laboratory tests that changes by a few micrometers to the profile of the roller has a significant effect on the bearing life. A concrete theoretical relationship between roller profile and bearing life was never known; even to this date such theoretical relationships have not been successfully established. The optimum geometry of the roller profile modifications has been established more or less by trial-and-error or by empirical approaches. The fig. 01 shows two cylindrical bodies with their longitudinal axes parallel. The cylinders are pressed by a force of ‘p’ per unit length as shown in Fig-01. The contact area between the two bodies is a rectangle of width ‘2a’ having a length equal to that of the cylinders.
Both roller and race-way are of the same length and come to end at the same cross-sectional plane. On cross-sections away from the ends, an axial compressive stress exists to maintain the condition of plane strain.

![Fig -01: Geometry of contact of two cylindrical bodies [17]](image)

This compressive stress reduces in value at the free ends, allowing the solids to expand slightly in the axial direction and thereby reducing the contact pressure at the end as shown in fig. 02. An estimate of the reduction in the pressure at the end of the roller may be obtained by assuming that the end of cylinder is under a state of plane stress.

1.2 Contact stress behavior at the boundaries of cylinders roller pressed together:

The contact stress at the end points of two cylinders pressed together exhibits stress concentration behaviour. In order to avoid these stress concentration points in a typical roller bearing, the axial profile of the roller is modified from a straight cylindrical shape to a barrel shape configuration [11].

![Fig. 02 (a) Crowned cylindrical roller and (b) Contact pressure of two contacting surfaces for crowned end cylindrical roller](image)
This geometric modification results in eliminating or minimizing the stress concentration at the ends of the rollers. The different possible modified end conditions that yield a fairly uniform contact stress is discussed below [17]. Therefore for the consistent pressure \( p \) distribution, the pressure should sum-up to

\[
p = \frac{\pi a^2 E}{4R} 
\]

\[
p(x) = \frac{2p}{\pi a^2} \left(a^2 - x^2\right)^{\frac{1}{2}}
\]

And \( p(x) \) tends to zero at the edge of contact. Hence, the maximum pressure \( p_0 \) is,

\[
p_0 = \left(\frac{pE}{\pi R}\right)^{\frac{1}{2}}
\]

This gives the maximum pressure \( p_0 \) at end of cylindrical roller profile. The pressure distribution across the contact area is uniformly distributed.

The contact stress behaviour at the end points of two cylinders pressed together exhibits stress concentration behaviour. In order to avoid these stress concentration points in a typical roller bearing, the axial profile of the roller is modified from a straight cylindrical shape to a barrel shape configuration.

![Contact stress distribution of different roller profile](image-url)
The circular arc profile, commonly known as crowning, resulted from the Hertzian theory, whereas the cylindrically crowned profiles is a straight central portion with crowned edges which was based on the Lundeberg theory.

2 ANALYTICAL SOLUTIONS

A solution based on the theory of elasticity can be applied to the case of a roller bearing, with a few assumptions. Firstly, all strains must be small and linear (below the proportional limit strain). Also, the geometry of the roller and its mating surface are assumed to be invariant along the axis of the cylinder. The pressure, stress, and deformation will also be constant, so that the interface can be modelled as semi-infinite, i.e. infinite and invariant in one direction. As soon as any load is applied to press the two bodies together, the elastic nature of the solids will cause local deformation at the interface, and the area of contact will begin to have width. This local strain will cause stress to develop in the material, and the characterization of that stress is the ultimate goal. Analytically, both surfaces are assumed to be smooth on a small scale such that their profile is exactly as described by the equations of the bodies’ boundary lines.

Fig-04: 3D contact model of roller and flat raceways with coordinates

This limits the contact to only one continuous, rectangular area. The defining equations of surfaces must also have continuous second derivatives, meaning that there are no discontinuities and no sharp transitions between regions of the contacting surfaces.
Table 01 Cylindrical roller profile specifications,

<table>
<thead>
<tr>
<th>Description</th>
<th>Dimension of cylindrical Roller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of roller</td>
<td>10 mm</td>
</tr>
<tr>
<td>length of roller</td>
<td>15 mm</td>
</tr>
<tr>
<td>Circular crown radii</td>
<td>1.23 mm</td>
</tr>
<tr>
<td>Type of material</td>
<td>Bearing steel</td>
</tr>
<tr>
<td>Youngs modulus</td>
<td>208 GPa</td>
</tr>
<tr>
<td>Poisions ratio</td>
<td>0.30</td>
</tr>
<tr>
<td>Material density</td>
<td>7.85 g/cm³</td>
</tr>
</tbody>
</table>

By using the equations (1), (2) and table no 01 for numerical calculation, the maximum contact stress for the cylindrical roller under application of 100 KN radial load, the analytical result is given in table no 02.

Table 02 Analytical results from hertz’s theory,

<table>
<thead>
<tr>
<th>Hertz’s Theory Mathematical formulation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Load P (N)</td>
<td>100000 N</td>
</tr>
<tr>
<td>Roller radius R₁</td>
<td>10 mm</td>
</tr>
<tr>
<td>Circular crown radius</td>
<td>1.23 mm</td>
</tr>
<tr>
<td>Total of roller (mm)</td>
<td>15 mm</td>
</tr>
<tr>
<td>Max. Hertz contact stress</td>
<td>1.9E+10 Pa</td>
</tr>
</tbody>
</table>

The maximum contact stress value obtained from analytical solution is used for the reference value for further work.

3. PROPOSED CYLINDRICAL ROLLER DESIGN

During the past few decades the design of cylindrical roller bearings has been significantly improved. These improvements are mainly achieved by advancement in bearing steel materials and geometric design improvements. The design enchantments are mostly focused on contact stress reduction at the bearing rolling contact regions.

The concentric ellipse shape end-cavity shaped roller has the characteristic of deflecting at two ends of the roller in response to radial loading. This results in a reduction of the contact stress
at the rollers ends. In other words, concentric ellipse shape cavity on the both end of roller design establishes an elastic behaviour of roller ends and allows deflection of the roller ends in the radial direction which is along the direction of the applied contact load. Use of these methods of profile modifications resulted in considerable progress to identify relative accuracy of edge profiles necessary to sustain uniform contact stress distribution across the roller length. In addition to these benefits, this design concept reduces the mass of a bearing and inertia effects acting on the outer raceway, which directly improves overall bearing life span.

![Graphical model of proposed cylindrical roller](image)

**Fig.4.1 Graphical model of proposed cylindrical roller**

4. **FEA OF PROPOSED CYLINDRICAL ROLLER DESIGN**

Finite Element analysis of proposed as well as typical roller is performed with the ANSYS 14.5 to study the internal and contact stresses developed in a proposed and typical roller. This FEA work examines difference between the structural changes for both rollers.

1. **Structural analysis of typical cylindrical roller**

For the typical flat circular crown cylindrical roller (maximum circular crowning radius), the circular crowning radius for the roller is \( r = 1.23 \text{mm} \), the length and diameter of roller is 15mm and 10 mm respectively. Refer the table 01 for the properties and specification for roller. The roller is places between two flat raceways of thickness 5mm which is equal to raceways thickness. The material for roller and raceways is bearing steel material. The load is 100KN in compressive nature.
Fig. 05 Typical cylindrical roller model between the flat raceways

Table 03 FEA results for the structure analysis of typical cylindrical roller

<table>
<thead>
<tr>
<th>Circular crown radius (mm)</th>
<th>Total deformation</th>
<th>Strain (m/m)</th>
<th>Stress (Pa)</th>
<th>Strain energy (j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.23 mm</td>
<td>0.000207</td>
<td>0.0696</td>
<td>1.04E+10</td>
<td>0.01354</td>
</tr>
</tbody>
</table>

The FEA results of typical roller are given in table 03 for deformation, strain, stress and strain energy. These results are used as reference and comparison with proposed roller design.

2. Structural analysis of proposed cylindrical roller design

In the proposed design consist of circular crowning radius = 1.23mm and concentric circular ellipse shape cavity on both end faces of the roller as in fig-06. The dimension of circular cavity are as Major axis (diameter of cavity) =6 mm; Minor axis (depth of cavity) = 2.46 mm. material properties and loading conditions are same as considered in above model.

Fig-06: 3D model proposed cylindrical rollers.
Table No-04 FEA results for the proposed cylindrical roller design.

<table>
<thead>
<tr>
<th>Circular crown radius (mm)</th>
<th>Total deformation</th>
<th>Strain (m/m)</th>
<th>Stress (Pa)</th>
<th>Strain energy (j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.23</td>
<td>0.0003106</td>
<td>0.049056</td>
<td>6.45E+09</td>
<td>0.010941</td>
</tr>
</tbody>
</table>

3. Contact stress analysis for typical flat circular crown cylindrical roller of crowning radius $r = 1.23\, \text{mm}$.

The contact stress analysis is conducted under the load of 100KN for the typical cylindrical roller between the flat raceways. The chart shows the contact pressure at the contact surface of typical cylindrical roller of circular crowning radius 1.23 mm.

![Chart 01 Contact pressure distributions over the contact length of typical cylindrical roller](image1)

The maximum contact stress developed at the edge of typical cylindrical roller. The stress distribution is uniform and edge stress concentration is somewhat less. The maximum contact stress is $2.1 \times 10^{10} \, \text{Pa}$.

4. Contact stress analysis for proposed cylindrical roller design of crowning radius $r = 1.23\, \text{mm}$ and both end ellipse shape circular cavity $2a = 4\, \text{mm}$, $2b = 2.36\, \text{mm}$.

![Chart 02 Contact pressure distributions over the contact length of proposed cylindrical roller having 1.23 mm circular crowning radius and cavity](image2)
The chart shows the contact pressure at the contact surface of typical cylindrical roller of circular crowning radius 1.23 mm and concentric cavity. In this less contact stress developed at the edge of proposed cylindrical roller. The stress distribution is uniform and edge stress concentration is lesser than typical cylindrical roller. The maximum contact stress is \(2.0 \times 10^{10}\) Pa. In this case study, the maximum contact stress developed at the edge of cylindrical roller. The stress distribution is uniform and edge stress concentration is somewhat less. The maximum contact stress at the edge is \(2.1 \times 10^{10}\) Pa.

### FEA Results comparison

<table>
<thead>
<tr>
<th>FEA results</th>
<th>Proposed cylindrical roller</th>
<th>Typical cylindrical roller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Bearing steel</td>
<td>Bearing steel</td>
</tr>
<tr>
<td>Contact stresses at ends of cylindrical roller</td>
<td>(4.17 \times 10^8) Pa</td>
<td>(5.7 \times 10^8) Pa</td>
</tr>
<tr>
<td>Stresses induced in cylindrical roller</td>
<td>(6.45 \times 10^9) Pa</td>
<td>(1.04 \times 10^{10}) Pa</td>
</tr>
<tr>
<td>Maximum contact stress</td>
<td>(2.0 \times 10^{10}) Pa</td>
<td>(2.1 \times 10^{10}) Pa</td>
</tr>
<tr>
<td>Factor of safety</td>
<td>1.47</td>
<td>1.4</td>
</tr>
<tr>
<td>Strain</td>
<td>0.049056</td>
<td>0.0696</td>
</tr>
</tbody>
</table>

From the FEA results, it is clear that proposed cylindrical roller design is better than typical flat circular crown cylindrical roller. As the concentric circular cavity gives the cylindrical flexibility and allows the deflection of roller ends in the radial load direction. Hence the proposed cylindrical roller design establishes the elastic behavior of roller ends.

### 5 EXPERIMENTATION RESULTS

The both proposed and typical cylindrical roller are manufactured and tested for compression, hardness test successfully. The results are obtained for the hardness, weight, contact geometry, micro structural changes and given in table 05. From test results and visual inspection of samples, the comparison is made between proposed and typical cylindrical roller.

### Table 05 Comparison of experimental results between proposed and typical cylindrical roller

<table>
<thead>
<tr>
<th>Properties</th>
<th>Proposed cylindrical roller</th>
<th>Typical cylindrical roller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>10 mm in diameter, 15 mm in total length</td>
<td>10 mm in diameter, 15 mm in total length</td>
</tr>
<tr>
<td>Circular crown radius</td>
<td>1.23 mm</td>
<td>1.23 mm</td>
</tr>
</tbody>
</table>
From the experimental results given in table 05, the proposed cylindrical roller is the best design than the typical design. It saves the material hence cost is less. Edge stress concentration is less as compared to typical roller. The stresses induced in it under the load are much less than typical roller.

4. CONCLUSION

The design of proposed cylindrical roller is relies on the uniform pressure distribution according to H. Hertz theory, reducing the edge stress concentration and it is achieved successfully. The internal stresses induced in the cylindrical roller are also reduced. The manufacturing of proposed roller design is easier as compared to Lundberg crown profile. In the proposed design, there is no sharp corner hence the friction will be less. The difference between FEA results and practical test results is very small. So the application CAE in mechanical designing component is efficient, reliable. With the proposed design following goals are achieved.

The loading capacity of proposed design of roller is more than the typical roller of same material property as less stresses are developed in the roller under load. Edge stress concentration is less as compared with typical and uncrowned cylindrical roller. In proposed design, the contact pressure is uniformly distributed. The material is saved by amount 2.56% in proposed design and hence less cost is required for manufacturing process. Fatigue and dentations failure of roller get minimized as the proposed design is more stable than typical. The depth of cavity on end face of roller should not more than the crowning radius.

REFERENCES


