Stiffness Optimization of Squirrel Cage in Aircraft Engines

Abhishek M, Kiran M, Sathyanarayanan S, Shriharsha Patil

***Abstract:** A squirrel cage is a component used in engine shafts to make the shaft stiffer and able to withstand high cycle fatigue loads continuously for a long time. A squirrel cage can be of many shapes and sizes. The critical speed and the stresses acting on the shaft play a key role in determining the performance of shafts in engines. The squirrel cage in the shaft absorbs stress and extends shaft life. This paper deals with the structural design and analysis of the squirrel cage of an aircraft engine. The design of the squirrel cage was done on SolidWorks, and analysis was carried out on the Ansys workbench. To meet the strength and stiffness, the squirrel cage was optimized by introducing slots in it. Stress analysis of the bearings has been carried out for axial and radial loads from 1 to 20 kg. The radial load is applied to individual bearings, and then the axial load is applied to only one bearing. Then results are plotted into curves, and a slope is obtained based on deformations obtained. The stiffness value is noted, and the same procedure is performed for an optimized slotted squirrel cage. These values are compared, and then the squirrel is proved to be weight optimized and has improved stiffness.*

***Keywords:** Critical Speeds, High Cycle Fatigue Load, Squirrel Cage, Stress Analysis*

I. INTRODUCTION

The squirrel cage plays an important role in the stiffness of a shaft in the aircraft engine. At its most basic level, rotor dynamics is concerned with one or more rotors supported by bearings. Major objectives of rotor dynamic studies are to predict critical speeds and corresponding mode shapes, unbalance the response of the system, and determine design changes for critical speed placements. Rolling element bearings are most employed in rotating machinery. There are different types of squirrel cages available based on their shape, size, length, diameter of the cage, sizes of the bearings, and types of bearings used. They can be manufactured by any CNC machine to meet specific requirements. The stiffness of the squirrel cage has a great deal of influence on the performance of the engine shaft.

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The squirrel cage aids in the elimination of critical stresses on the shaft, prolonging the life of the shaft. The squirrel cage also protects the bearings inside from HCF loads.

II. LITERATURE SURVEY

A. Instability in Rotor-Bearing System

Investigation on the stability of rotating machine on oil film journal bearing [1] found that the upper limit of the whirling frequency is one half of the rotating speed, and experimental investigation on oil whirl [2] showed the effect of loading, speed, viscosity, unbalance, flexibility, and external excitation on it.

B. Effect of Unbalance on Rotor-Bearing System

Unbalance is caused by vibration observed in the rotor bearing system [3] and external factors like manufacturing defects, machine wear, material non-homogeneity, etc., as they also affect stiffness [4] and gyroscopic effect.

C. Non-Linear Dynamic Analysis of Rotor-Bearing

The dynamic behavior of a rotor bearing system depends on unbalance forces as well as the nonlinear characterization of the fluid film forces.

D. Porous Oil Bearing

Porous oil bearings can be used where other bearings cannot be placed due to lack of space or when replenishment of lubricant is difficult.

E. Application of Finite Element Method in Rotor Dynamics

FEM [5] is the most effective and flexible method to be used in squirrel cage and rotor dynamics when the system is very large and complicated. Also, it reduces risk by saving computational time and modelling accuracy [6].

F. Characterization of a Multistage Axial Compressor Test Rig Rotor System

Squirrel cage rotor bearing systems operate at very high rpm, so the dynamic analysis of multistage compressors [7] needs to be supported with the help of squeeze film dampers and rolling element bearings as their dynamic properties must be calculated more precisely.

G. Automatic Balancing of Rotor-Bearing Systems

Also, at higher rpm's, the balancing of the squirrel cage bearing system is very important to maintain the stability, and therefore active magnetic bearings [8][9][10][11] are utilized gadgets in most parts, but their utilization is restricted due to low firmness.

H. Dynamics of Rotors Incorporating Squeeze Film Dampers

So, because of that, squeeze film dampers are incorporated into rotor dynamics in squirrel cages to reduce vibrations.

I. Dynamic Simulation of Squirrel Cage Rotor

Later, many simulations were carried out on the squirrel cage rotor to reduce the vibration problem, and various strategies were proposed to extend damping. So, these simulations and analyses were illustrated at different speeds of operations.

III. OBJECTIVES

- To enhance the understanding of stiffness to help dampen
- the shaft during whirling or during critical speeds [12].
- To design a 3D squirrel cage model and conduct simulations on it.
- To optimize the shaft to reduce weight while keeping stiffness constant.
- To compare the results between the initial squirrel cage model and the optimized squirrel cage model.
- To draw out a conclusion between the initial squirrel cage model and the optimized squirrel cage model in terms of weight and stiffness.

IV. MATERIAL

The squirrel cage is made of General aluminum alloy with itsmaterial properties show in below table.

Table 1: It's Material Properties

Sl No	Property	Value	Unit
1	Density	2770	Kgm^{-3}
2	Young'smodulus	7.1E+10	Pa
3	Poisson's ratio	0.33	No unit
4	Bulk modulus	6.9608E+10	Pa
5	Shear Modulus	2.6692E+10	Pa

V. METHODOLOGY

A. Selection of Baseline Model

Squirrel cages used in aircraft engines are of different sizes depending on the size of the engine and shaft to be incorporated. For this study, a 3D model of a squirrel cage was designed. It is 5.3 cm in length, and the max diameter is 6 cm. The squirrel cage can incorporate two roller bearings of diameter 4 cm, respectively.

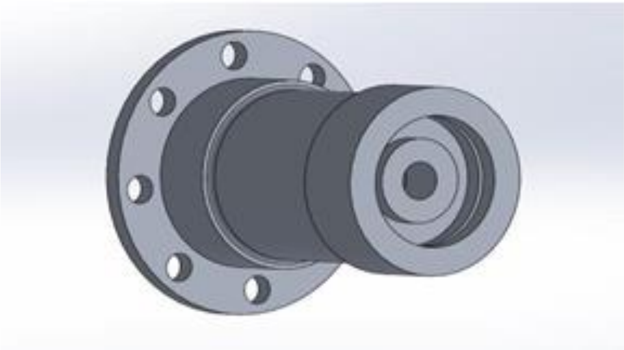

Figure 1: Baseline Model

B. Analysis Approach of Baseline Model

The loads and geometry are symmetric about the vertical plane, so radial and axial loads are distributed uniformly at the bearings individually. Also, the mesh is refined to ensure high accuracy in the simulation results.

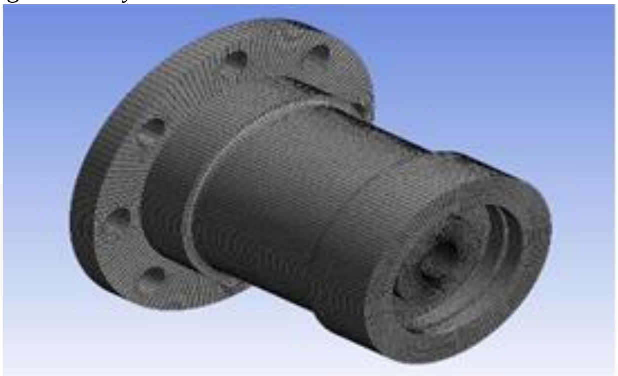

Figure 2: Mesh Model

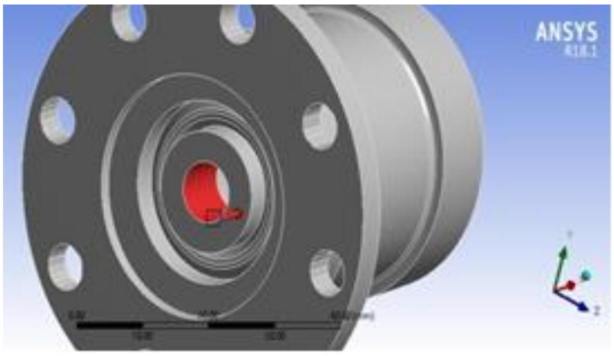

Figure 3: Axial 1st Bearing Loading Region

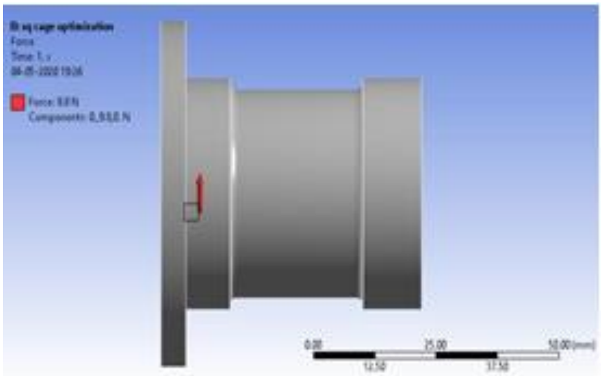

Figure 4: Radial 1st Bearing Loading Region

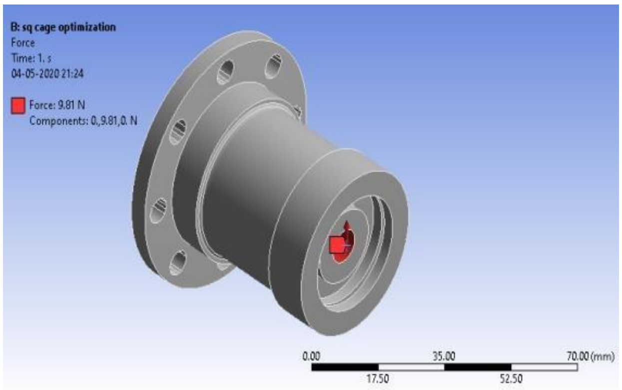

Figure 5: Radial 2nd Bearing Loading Region

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C. Structural Analysis of Squirrel Cage- Baseline Model

Analysis is carried out for three load cases, namely axial loads for the 1st bearing, radial loads for the 1st bearing, and radial loads for the 2nd bearing. Loads of 1 kg to 20 kg are applied on squirrel cage bearings uniformly for all three load cases. All loading conditions are simulated in software, and only 1sr and 20th Kg results are displayed in the below figures. The load vs. deformation graph is plotted considering all loads in Kg's (i.e., 1, 2, 5, 10, 15, 20 Kg's). The slope of this graph is obtained. The slope of the graph is the stiffness value of the bearing. This value is then compared with the modified model stiffness value (i.e., optimized slotted model). The same procedure is carried out for the optimized model to do the simulations.

i. Axial 1st Bearing Analysis- Baseline Model

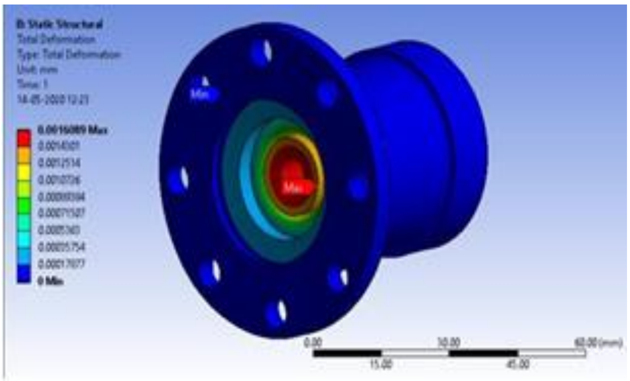

Figure 6: Deformation in mm for Axial 1st Bearing

Table 2: Load V/S Deformation in MM for Axial 1st Bearing

Load (KG)	Deformation (mm)
1	8.0446×10^{-5}
2	0.00016089
5	0.00040223
10	0.00080446
15	0.0012067
20	0.0016089

ii. Radial 1st Bearing Analysis- Baseline Model

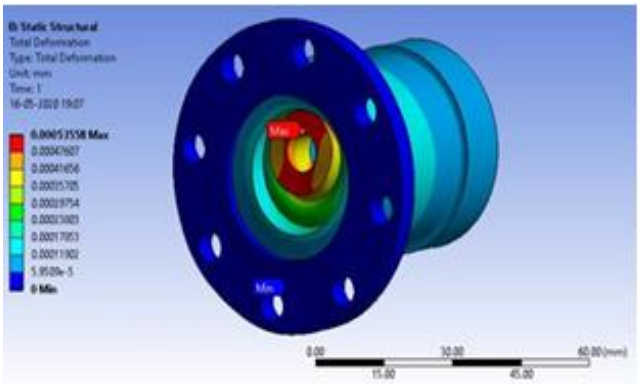

Figure 7: Deformation in mm for Radial 1st Bearing

Table 3: Load v/s Deformation (mm) for Radial 1st Bearing

Load (KG)	Deformation (mm)
1	2.672×10^{-5}
2	5.3558×10^{-5}
5	0.00013389
10	0.00026779
15	0.00040168
20	0.00053558

iii. Radial 2nd Bearing Analysis- Baseline Model

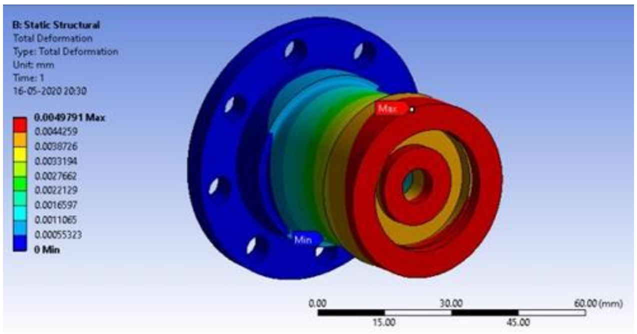

Figure 8: Deformation in mm for Radial 2nd Bearing

Table 4: Load v/s Deformation (mm) for Radial 2nd Bearing

Load (KG)	Deformation (mm)
1	0.00024896
2	0.00049791
5	0.0012448
10	0.0024896
15	0.0037343
20	0.004991

D. Modification of Baseline Model

The selected squirrel cage model is optimized by introducing slots to keep the stiffness constant and reduce the weight, thereby improving the stiffness of the squirrel cage. The weight reduction target was set to 20%, and the slotting dimension was set to 20×10mm. Figure below shows the modified squirrel cage model with slots as well as its simulations.

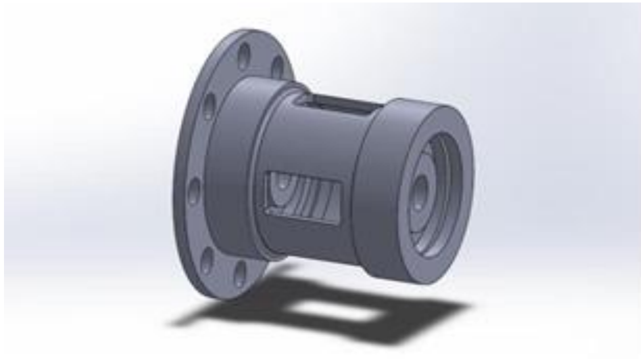

Figure 9: Slotted Cage

i. Axial 1st Bearing Analysis- Modified Model

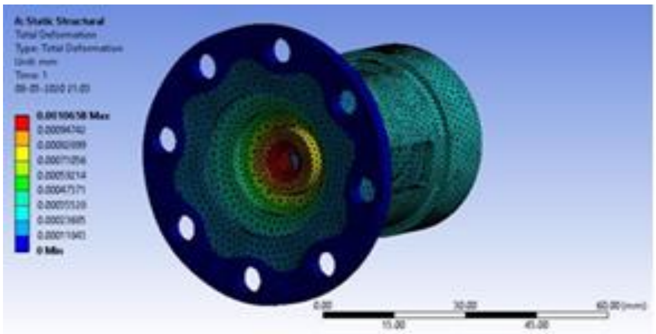

Figure 10: Deformation in mm for Axial 1st Bearing for Slotted Cage

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Table 5: Load v/s Deformation in mm for Axial 1st Bearing for Slotted Cage

Load (KG)	Deformation (mm)
1	5.3292
2	0.00010658
5	0.00026646
10	0.00052392
15	0.00079938
20	0.0010658

ii. Radial 1st Bearing Analysis- Modified Model

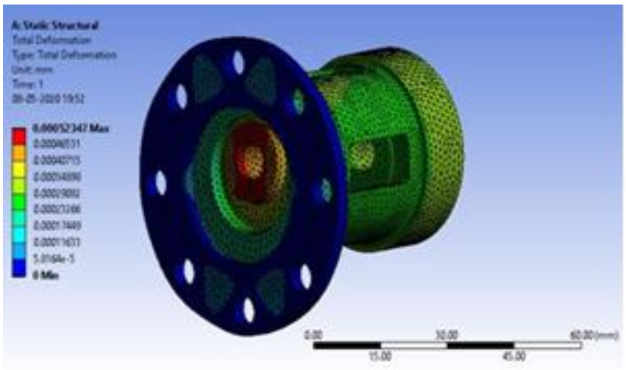

Figure 11: Deformation in mm for Radial 1st Bearing for Slotted Cage

Table 6: Load v/s Deformation in mm for Radial 1st Bearing for Slotted Cage

Load (KG)	Deformation (mm)
1	2.6174×10^{-5}
2	5.2347×10^{-5}
5	0.00013087
10	0.00026174
15	0.00039261
20	0.00052347

iii. Radial 2nd Bearing Analysis- Modified Model

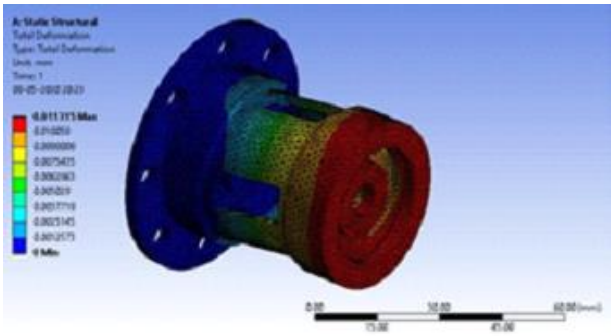

Figure 12: Deformation in mm for Radial 2nd Bearing for Slotted Cage

Table 7: Load v/s Deformation (mm) for Radial 2nd Bearing for Slotted Cage

Load (KG)	Deformation (mm)
1	0.00056576
2	0.0011315
5	0.0028288
10	0.0056576
15	0.0084864
20	0.0011315

VI. RESULT AND DISCUSSION

The radial stiffness and axial stiffness of the cage for first bearing from the initial squirrel cage analysis were found to be 37341.29 N/mm and 12430 N/mm, respectively. The radial stiffness of the second bearing was found to be 4016.70 N/mm. The radial and axial stiffness of the slotted cage for first bearing from the analysis was found to be 38205.85 N/mm and 19420.49 N/mm, respectively. The radial stiffness of the second bearing of the slotted cage was found to be 1767.53 N/mm. Using load v/s deformation curve stiffness values are obtained for both the baseline model as well as the modified model. Slotting is responsible for the reduction in weight and improved stiffness for the optimized model. Following are the graphs obtained for both the baseline model and the modified model, considering all the load cases from 1 kg to 20 kg.

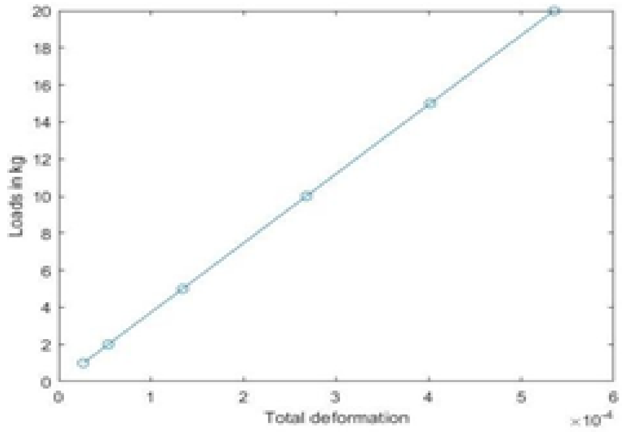

Figure 13: Radial Load v/s Total Def of 1st Bearing

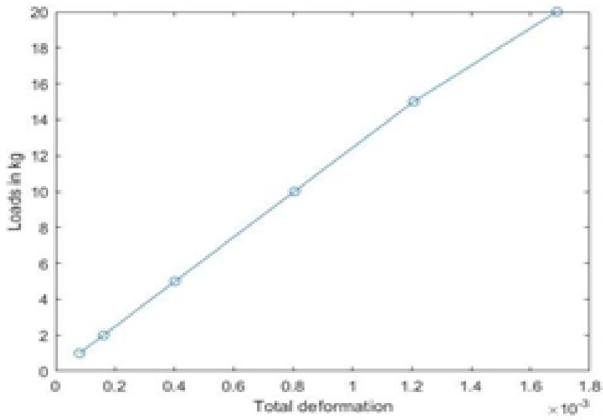

Figure 14: Axial Load v/s Total Def of 1st Bearing

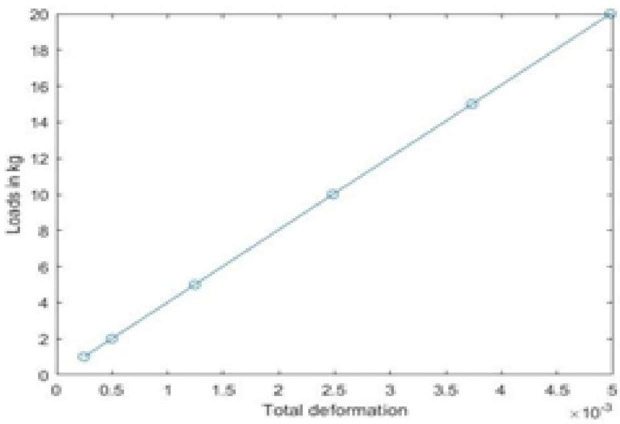

Figure 15: Radial Load v/s Total Def of 2nd Bearing

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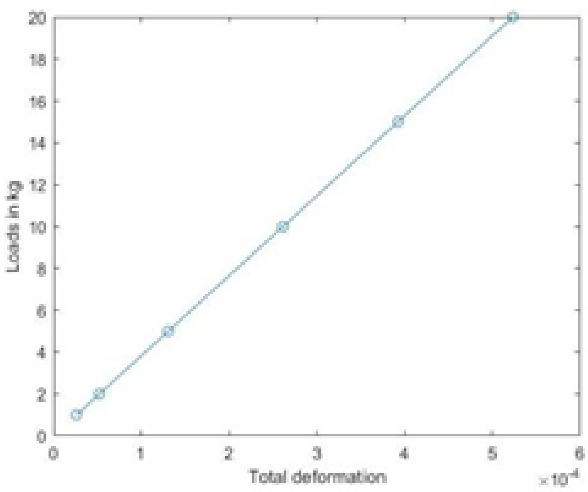

Figure 16: Radial Load v/s Total Def of 1st Bearing Slotted Cage

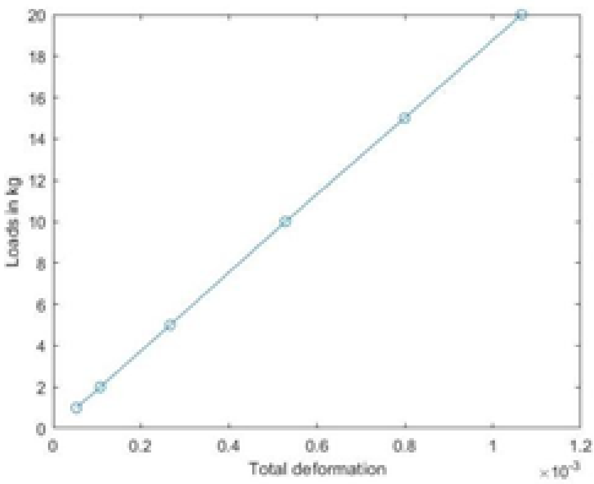

Figure 17: Axial Load v/s Total Def of 1st Bearing Slotted Cage

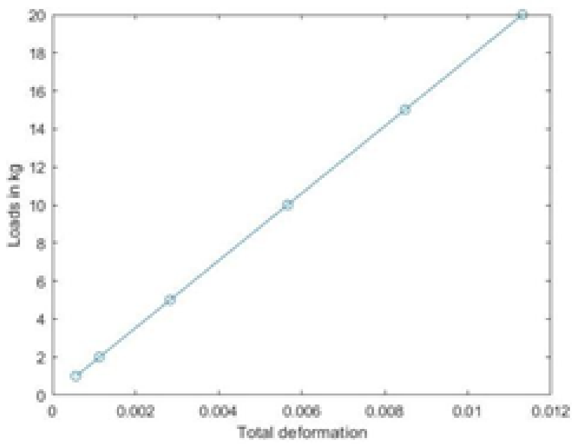

Figure 18: Radial Load v/s Total Def of 2nd Bearing Slotted Cage

VII. CONCLUSION

From this study, it is seen that the squirrel cage is so stiff that the maximum deformation of the cage is very small. The cage is very strong and can bear loads of up to 15-20 kg. The initial cage weighs around 90g, and the slotted cage weighs around 80g. The obtained results have the following conclusions:

- The cage was found to be stiff to withstand loads up to 20 kg and did not fracture.
- The critical points of stress are at the free end of the cage.
- The squirrel cage is elastic in nature as it returns to its initial position after the load is removed.
- The curve is linear, but the load applied was not enough to show the elastic limit.
- Reduction in weight has not affected the stiffness of the cage.
- The weight of the cage is reduced by nearly 10%, and the stiffness improved by nearly 9.7%.
- The slots on the cage managed to reduce the weight of the cage by 10 g.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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