Vol. 34, No. 3 (2012) 111-118

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Experimental Investigation of Friction Effect on Liner Model Rolling Bearings for Large Diameter Thrust Bearing Design

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Keywords:

Experimental set-ups
Measurement methodologies
DIC
Stiffness
Static friction coefficient
Allowable loads

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A B S T R A C T

Studying friction coefficient has significant importance, especially when dealing with high load and temperature applications that have frequent starting and stopping points. Towards that, two sets of angular contact Linear Model Mockup Bearings (LMMB) were designed and fabricated. This linear model assembly was made up of high precision, grounded raceways (AISI 4140) and commercially purchased balls (AISI 52100). The experimental studies were carried out by placing different number of balls between the raceways under different loads at dry lubricating condition. The static friction coefficients were measured using two different experiments: viz gravitation-based experiment and direct linear force measurement experiment. And Digital Image Correlation (DIC) technique was used to find the stiffness of LMMB set.

1. INTRODUCTION

Friction is a complex process, that has molecular, mechanical and energetic nature and it occurs between the surfaces of two bodies in contact during relative motion on exact starting point (area). Coefficient of friction is one of the parameters describing the amount of resistance to the relative motion of two sliding objects. The classical Coulomb's laws of friction state that the friction force is proportional to the normal load and independent of the apparent contact area. Amonton (1700) formulated the relationship in [1] that shear stress is proportional to normal stress by coefficient of friction. Friction due to rolling of non lubricated surfaces over each other is considerably less than that encountered by sliding the same surfaces over each other. Friction of any magnitude retards motion and results in energy loss.

The quantity known as friction coefficient or Coefficient of friction has long been used in science and engineering [2,3]. It is easy to define but not easy to understand on a fundamental level. Conceptually coefficient of friction, defined as the ratio of two forces acting, respectively, perpendicular and parallel to an interface between two bodies under relative motion or impending relative motion. Both static and dynamic friction coefficients can be measured with little difficulty under laboratory conditions. In the case of solid-on-solid friction (with or without lubricants), these two types of friction coefficients are conventionally defined as follows: $\mu = F_f/F_n$ and $\mu = F_k/F_n$; where F_f is the force just sufficient to prevent the relative motion between two bodies, F_k is the force needed to maintain relative motion between two bodies, and F_n is the force normal to the interface between the sliding bodies as stated by researchers in [4,5]. It has been shown that the surface effects and other surface properties [6,7] might influence the value of the rolling friction coefficient. It was reported by the researchers in [8,9] that for viscoelastic materials, rolling friction is due to surface interactions and the major part is due to deformation losses within the bulk of Material.

The effects of rolling friction on a ball rolling up on an inclined track have been studied in [10]. Found that the rolling friction coefficient is dependent on the radius of the ball. Researchers in [11] built up an experimental analogous to cyclotron for accelerating protons and used it to measure the speed dependent coefficient of rolling friction. Researchers in [12] analyzed the effects of rolling friction on the path of a ball spinning on turn table using the perturbation. These effects were also studied by Ehrlick and Tiersten[13] and they proposed to use an inclined mirror method to measure the coefficient of rolling friction when the ball starts to rotate, which is tangent of the inclination angle. A similar method was used to measure the breakaway coefficient of rolling friction for rolling element bearings. In the study, experiments were carried out to determine whether the test was repeatable enough to be an ASTM standard and researchers in [14] investigated the friction coefficient between aluminium and steel using a test apparatus which works on the basis of twist compression with new configuration of applying load and torque.

Rodica Cozma [15] established an equivalent friction coefficient value for different types of Hertz contacts. The rolling friction between ball and ball bearing ring is studied under dry and lubricated condition at low rotating speed in [16]. Several recent experimental investigations of static friction, that cover a large variety of test conditions also showed the behavior of friction force and friction coefficient that predicts the classical laws of friction. In literature survey no one pact to measure friction coefficient on huge loading condition with consideration of stiffness factor.

The main purpose of the present work is to explore the peculiarities of static coefficient friction in roller bearing and to investigate the validity of contact and sliding inception models for high load and temperature applications. Effects of friction coefficient have been examined using sets of linear model mockup bearing. The high load thrust bearing design is solely based on static coefficient of friction (dynamic/kinetic coefficient of friction is very minimal when compared to static coefficient of friction) and stiffness on bearing. Also huge starting frictional torque is required for large diameter bearings in nuclear power plant and truck cranes and applications that have frequent starting and stopping points. Effects of friction coefficient have been examined at different loads and balls at dry lubrication condition. These works will help in improving the design requirement in large diameter bearing.

2. MODEL PREPARATION

Two sets of angular contact linear model mockup bearings were fabricated at Indra Gandhi Center for Atomic Research (IGCAR), Kalpakkam, India as a part of development program for large diameter bearings. The cost of making actual bearing is highly expensive. Hence, sections of complete raceways as shown in Fig. 1. were made of same material, hardness with geometrical and design constriction similar to an actual bearing designed [9].

Fig. 1. Linear Model Mock-up bearing assembly.

Each block has a cylindrical groove on one face with radius slightly greater than that of the ball with which it was to be used. The linear raceway length is 150 mm with semi circular raceway radius is 16.51 mm. Grooved races are used in practice as the area of contact between the ball and raceways are greater when compared to plane races and therefore the allowable load on the bearing is high in grooved raceway.

The raceways were made of medium carbon chromium steel (AISI 4140) and hardness around 48 HRc ±2. This minimum hardness of the raceway is necessary to prevent the pressing-in of the rolling element. The rolling elements (balls of standard sizes 31.75 mm) made of hardened (62 HRc) high-carbon chromium bearing steel (AISI 52100) were purchased from commercial manufacturers.

3. FRICTION COEFFICIENT MEASURING METHODOLOGY AND EXPERIMENTS

Friction has been studied extensively by many researches, but only little work has been reported for ball and contact raceways. Our studies are solely based on high load and dry lubrication condition because lubrication oil fuses in high temperature (nuclear reactor) and also in high load applications; static friction coefficient remains unaltered. The two methods of measuring static friction coefficient are given below.

3.1 Gravitation-based method

In this approach, the following methodology is used:

1. The LMMB lower raceway was leveled using high precision spirit level;
2. The balls were cleaned and placed on the lower raceway;
3. The top raceway was placed over the balls;
4. Lead screw and LVDT was fixed under the bottom raceway of LMMB, Fig. 2.

Experiment

The experiment was conducted based on gravitation-based principle. Two balls were placed between the bottom and top raceways and its flatness was checked by high precision spirit level. Using lead screw, the bottom LMMB surface is raised gradually at a constant angular velocity until top raceway start sliding due to gravitational force. The height rise of the lead screw was measured using a precise dial gauge and this liner displacement was verified with LVDT. Extra care was taken to prevent the sliding of top and bottom raceways before starting tests by providing stoppers at rear end of the LMMB set. Experimental set up is shown in Fig. 3. The difference in readings before and after the test gives the rise in height of the bearing raceway end by which tilting angle θ can be measured. The static coefficient of friction μ_s calculated using the equation:

$$\mu_s = \tan\theta \tag{1}$$

Experiments were repeated several times to ensure the repeatability of the readings. The above same experiment was carried out by placing three and four balls. One of the subtleties of gravitation-based method is that the self load distribution shifts forward as the angle of inclination increases.

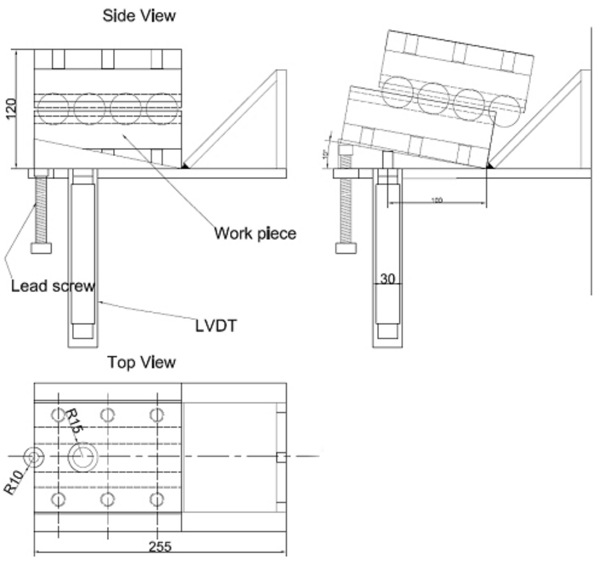

Fig. 2. Gravitation-Based method with LMMB set.

Fig. 3. Experimental set-up for Gravitation-based Method.

3.2 Direct linear force measurement method

Towards direct linear force measurement method:

1. Two sets of LMMB were used;
2. A 36 mm thick plate was horizontally placed and its flatness was verified with high precision spirit meter which was then welded with frame, its forms the lowermost surface and the first set bottom raceway was fixed over this plate;
3. The balls were cleaned and degreased and placed on the first set bottom raceway;
4. First set top raceway & second set bottom raceway were fixed permanently and this bundle was placed over these balls and its surface level was checked using a high precision spirit level;
5. Then the equal number of balls as in and were placed in second set, top raceway fixed with hydraulic jack;
6. Other end of the hydraulic jack was connected with load cell; the load cell was perfectly leveled and fixed with 36 mm thick plate which was welded with another end of the frame.
7. Axis of the load cell, hydraulic jack, fixture plates and two sets of LMMB are perfectly aligned and leveled. Figs. 4. and 5.

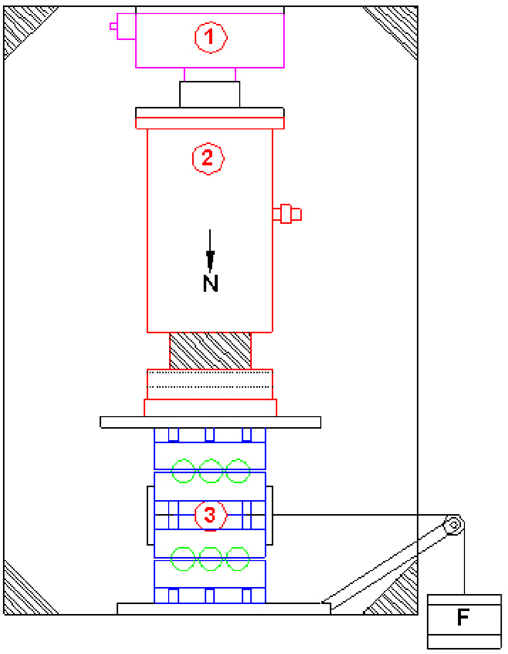

Fig. 4. Sled –Type friction method with LMMB (1. Load cell, 2. Hydraulic jack, 3.Two sets of LMMB).

Fig. 5. Experimental set up for direct linear force measurement.

By measuring the pulling force F in horizontal direction and in applied normal force N in vertical direction, it is possible to calculate the static (starting) coefficients of friction μ_s using equation number 2.

Experiment

The experiment was conducted based on direct linear force measurement; the tests were carried out by placing different number of balls between the raceways (one ball, two balls and three balls) at different normal loads N. a) Extreme care was taken to ensure that the bearing raceways were parallel to each other and also perpendicular to the line of action of normal load. b) The balls were placed symmetrically with relation to the action line of the load on both LMMB sets. Extra Care was taken for balls location and number of balls using designed gauge set-up as shown in Fig. 7. With the help of gauge sets one ball was placed exactly in the center of the raceway, giving the ball some initial load helps in balancing the raceways and the experiment was continued. By using hydraulic jack the normal load (N) was added, the applied load was measured by load cell. Towards that, linear force (F) was measured by adding mass on the rope through weight basin until the middle raceways bundle start to move (In this case rope was passing on radial bearing with weight basin; this radial bearing friction torque was very minimum compare to the normal forces (N) so radial bearing torque did not affect the experimental results). The corresponding values of normal force and linear force were used to determine the static coefficient of friction (μ_s) using the following equation:

$$\mu_s = F/N \quad (2)$$

The same experiment involved by different loads from 0.18 to 2.26 Tons. The above experiment was conducted several times by placing different number of balls. In two balls with 0.29 to 10.48 Tons loads and three balls with 0.43 to 14.08 tons loads and the results were discussed. The Maximum magnitude of load depends up on the relationship of hardness and yield stress in [9].

3.3 DIC techniques

DIC is an optical method to measure displacement fields (or strain fields) on an object surface by comparing pictures of the object surface at different states. One state is recorded before loading, i.e. the reference image, and the other states are subsequent images of the deformed object. The displacement field of a planar object has two in-plane components, say u and *v*. The two in-plane displacement components are directly computed by the digital image correlation. Subsequently, the displacement gradients (or the steel ball displacements) are derived by space differentiation of the displacement field data [17].

1. One set of LMMB was used.
2. A 36 mm thick plate was horizontally placed and its flatness was verified with high precision spirit meter which was then welded with frame, its forms the lowermost surface and the first set bottom raceway was fixed over this plate.
3. A ball was cleaned and prepared stochastic pattern as per the sixth point mentioned and placed on the bottom raceway.
4. Top raceway was placed above the balls and it was fixed with hydraulic jack, other end of the hydraulic jack was connected with load cell; the load cell was perfectly leveled and fixed with 36 mm thick plate which was welded with other end of the frame.
5. Axis of the load cell, hydraulic jack, fixture plates and LMMB set are perfectly aligned and leveled. Figs. 4, 6 and 7.
6. To make a stochastic pattern on the surface of the steel ball, the ball was sprayed with a white base color and was spattered with black color on the top, Fig. 6.
7. This pattern act as Springer for DIC techniques.
8. Two high quality cameras were focused on the Springer.
9. Reference images were taken unload condition using calibration plates after which the setup should not be disturbed.
10. Loads were applied using hydraulic jack gradually and the image of the ball was captured at each load.

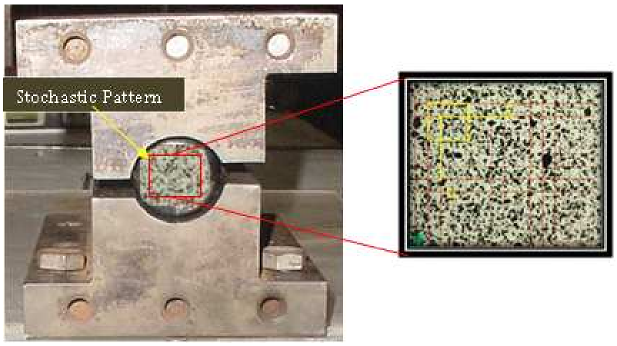

Fig. 6. LMMB set with stochastic pattern.

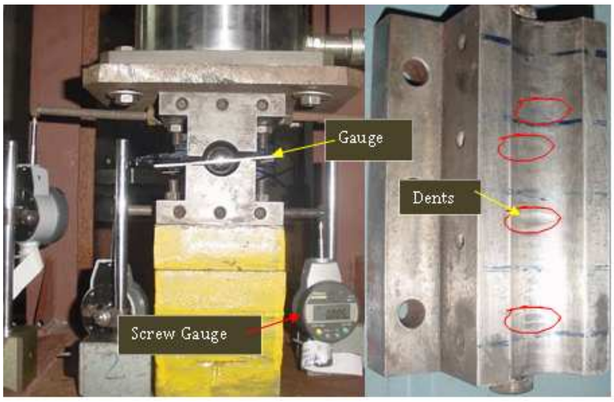

Fig. 7. DIC Experimental set up with dented Raceway.

Experiments

a) Load was applied through hydraulic jack, for each and every ladder of loading condition an image was taken using set of high quality DIC cameras. This image is correlated with previous image as well as reference image. Figure 8 indicates reference image at no load condition. Then, different loads were applied (0.5, 2.5, 5, 10, 15, 20… up to 145 kN).

b) At no load condition deflection is zero; at full load condition deflection is maximum. Centre of the ball is curved and hence it glares, because of which DIC camera doesn't capture that portion as shown in Figs. 8 and 9. From this experiment stiffness verses static friction coefficient and number of balls were studied, also this deflection values were verified with ordinary ball indentation techniques using screw gauge and dented raceway as shown in Fig. 7., the same experiment was conducted with different number of balls and loads.

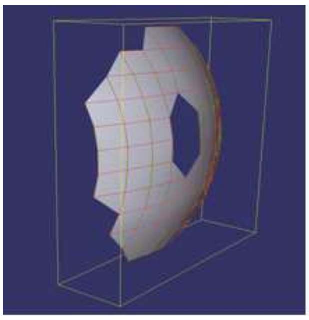

Fig. 8. No load condition.

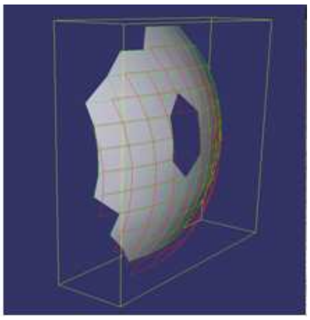

Fig. 9. At full load condition.

4. RESULTS AND DISCUSSION

Gravitation-based experiment was carried out by placing two, three and four balls and the results are shown in Fig. 10. It was observed from the results that, even with the increases in number of balls Static coefficient of friction remains almost constant which is mainly due to the fact that irrespective of the number of balls, only two balls were physically in contact with the raceway, which is due to ball tolerance and the surface geometry of the raceways.

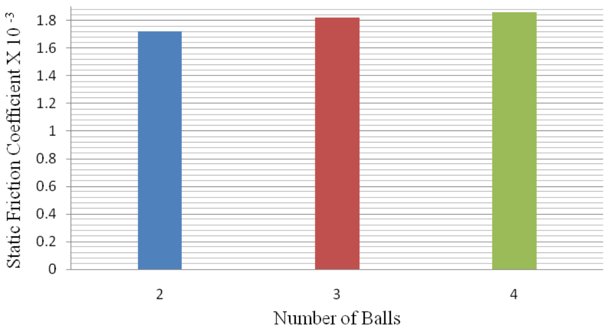

Fig. 10. Static coefficient of friction and Number of balls.

In Direct linear force measurement experiment, the values of normal and linear forces were noted to estimate the static coefficient of friction. The graph between coefficient of friction and linear Force (F) are represented in Figs. 11-13, for various testing conditions. From plots, the following observations have been made. 1) Coefficient of friction varies with the number of balls and loads. This variation in friction force is due to the non uniform hardness of raceway, geometry and stiffness of LMMB set [17]. 2) Normal force (N) increases gradually as static friction increases, at a particular load, static friction becomes very high. 3) From this study, the safer load to be used in frequent starting and stopping applications can be predicted which is shown as shaded portion in the graph. 4) Increase in load is indicated by an arrow in the graph and it is believed to be the permissible load (Critical load) on the bearing raceways and it is shown in Table 1. Same experimental set-up was used for both DIC techniques & direct linear force measurement method.

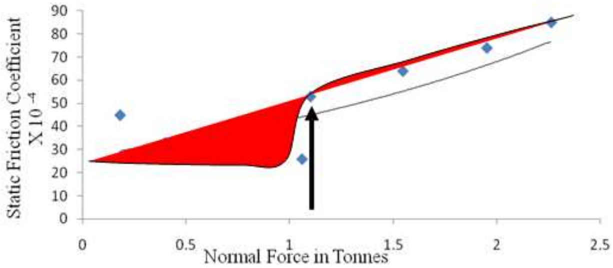

Fig. 11. Normal force and average static coefficient of friction with single ball.

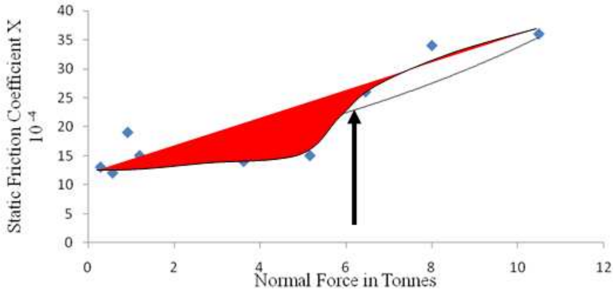

Fig. 12. Normal force (N) and static coefficient of friction with two balls.

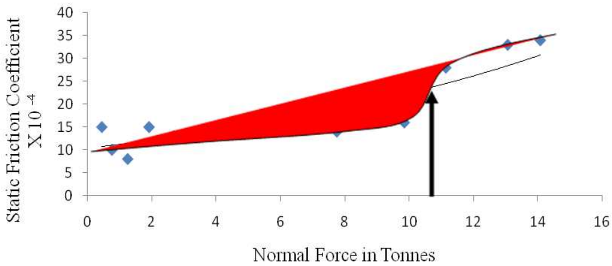

Fig. 13. Normal force (N) and static coefficient of friction with three balls.

Constant normal load (60±0.5 kN) was applied through the experiment and graphs were plotted between number of balls & stiffness (Fig. 14) and between stiffness & static friction coefficient (Figs. 15-17). It was observed that the stiffness increases with the increase in number of balls beyond three, stiffness remains almost constant.

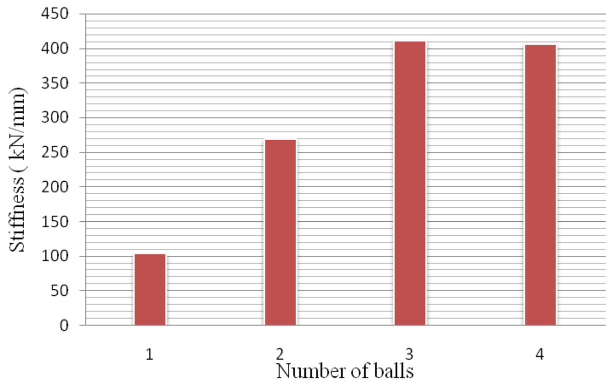

Fig. 14. Number of balls Vs Stiffness.

The maximum allowable loads on raceway are tabulated in Table 1. Beyond this load permanent indentation occurs on the raceway.

Table 1. Critical and Maximum allowable loads for Raceway

No. of Steel Balls	LMMB raceway curvature radius **(mm)**	LMMB raceway hardness **(HRc)**	Critical loads/ based on μ **(kN)**	Maximum allowable loads on raceway/based on indentation **(kN)**
One	16.51	48 ±2	11.059	63.728
Two	16.51	48 ±2	64.570	117.145
Three	16.51	48 ±2	111.470	197.881

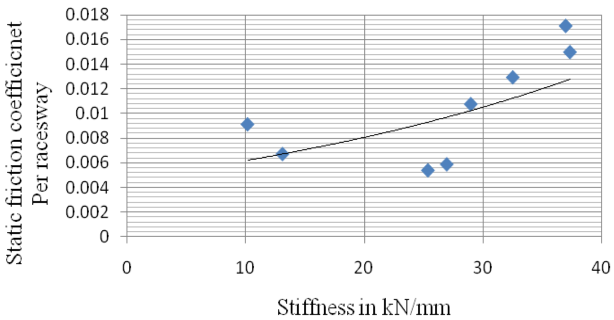

Fig. 15. Stiffness and static coefficient of friction with one ball.

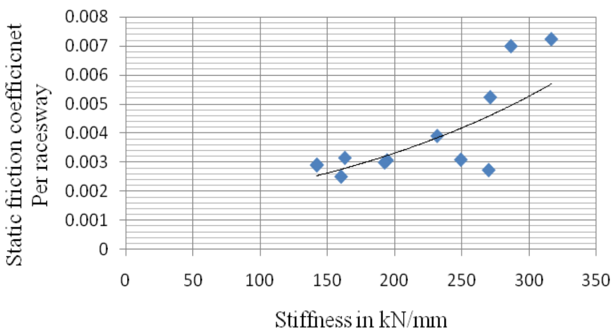

Fig. 16. Stiffness and static coefficient of friction with two balls.

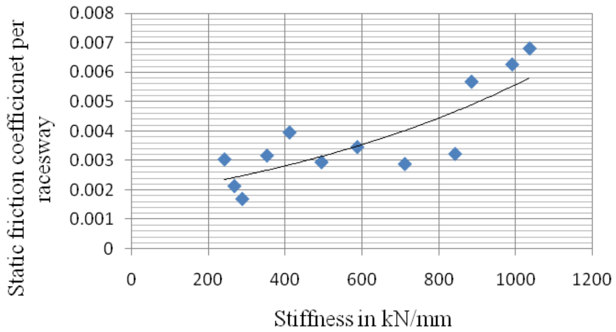

Fig. 17. Stiffness and static coefficient of friction with three balls.

5. CONCLUSIONS

Gravitation based experimental study shows that with the increase in number of balls, static friction coefficient remains almost constant because of ball's tolerance and raceway curvature geometry. In Direct linear force measurement method, variation of static friction coefficient with number of balls indicates that the normal force (N) increase slowly as the static friction coefficient increases. At a particular load, static friction becomes very high and hence stiffness decreases. From DIC study, it is noted that, with the increase in number of balls, stiffness increases and static friction coefficient decreases. This is used in determining the stiffness and surface flatness of the thrust bearing. Critical & allowable loads, stiffness and static friction coefficient of bearing has a significant effect on the design. This study forms the basis for optimizing balls and loads in large diameter thrust bearing design.

Acknowledgement

The authors thank Board of Research in Nuclear Sciences, Mumbai which provided financial support for carrying out this research work at structural Laboratory at Indira Gandhi Center for Atomic Research, Kalpakkam, India.

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