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Journal bearing performance and metrology issues

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ABSTRACT

Purpose: In this paper, a radial clearance of a journal bearings and the metrology of the radial clearance measurement is described.
Design/methodology/approach: In this experimental study out-of-roundness and radial clearance of journal bearings were measured with high precision and the impact of their metrology was examined on the specific oil film thickness of the bearing. Some metrological issues were emerged and these should be taken into account when bearings are designed.
Findings: An investigation showed that the radial clearance measurements can vary from one measuring device to another and the specified clearance may not necessarily meet the design criteria of specific oil film thickness. The study indicates that the radial clearance measurement can differ from one measuring device to another depending upon the precision that can be achieved by the device. The radius of the bearing or the shaft also varies along the circumference, mainly due to out-of-roundness. The out-of-roundness contributes to the error in radial clearance measurement and hence similar to the cut off length specified with the surface roughness, the out-of-roundness needs to be specified with the radial clearance.
Practical implications: The radial clearance of a journal bearing is a key design parameter and bearing performance mainly depends upon this parameter. In this paper was showed that the metrology of the radial clearance measurement plays a significant role and not only that the bearing manufacturer or the user of the bearing is aware of this fact but the bearing designer must also take this fact into account while designing bearings
Originality/value: This paper showed that The radial clearance is a sensitive micro-geometry parameter and hence metrology plays a vital role in making decisions
Keywords: Bearing metrology; specific film thickness; out-of-roundness; radial clearance

1. Introduction

Micro-geometry of journal bearings plays a vital role in enhancing the bearing performance. Surface roughness, out-of-roundness and radial clearance are the main micro-geometry parameters which influence the bearing performance. It is important that the surface roughness and out-of-roundness of the bearing components are controlled for achieving high performance. Effect of surface roughness on bearing performance was investigated by several researchers [2,6,8]. The research findings revealed that the roughness is mainly responsible for higher friction in the bearing. However, the transverse roughness is responsible for restricting the oil flow through the bearing contact and hence for the rise in minimum oil film thickness. Ultimately the rise in minimum oil film thickness results in increased load carrying capacity of the bearing. On the other hand, the circumferential roughness provides easy flow to the solid contaminants suspended in the lubricating oil. However, no conclusive results have been drawn from the roughness theory yet and the concept of "smooth is best" still buzz around.

Radial clearance is the only micro-geometry parameter, treated as key design parameter, which affects the bearing performance seriously. A variation of few microns in radial clearance may cause a serious effect on the load carrying capacity of the bearing. [3] demonstrated that each micron rise in radial clearance results in reducing oil film thickness by 1%. Thus, the control of this parameter is necessary for achieving high performance. It is important that this parameter is controlled at three stages important stages of bearing life cycle –design, manufacturing and usage. Monitoring of changes in radial clearance is one of the condition monitoring activities, to ensure the required bearing performance. The radial clearance is a sensitive micro-geometry parameter and hence metrology plays a vital role in making decisions.

Specific oil film thickness is one of the basic design requirement of a hydrodynamic bearing and lambda ratio 10 or above ensures that the two bearings surfaces are separated by at least 10 times their composite roughness.

Researchers have emphasized the need for controlling the out-of-roundness in a bearing. However, there are no firm guidelines for controlling this parameter. If errors in measuring the radial clearance are known, the designers can take an account of it and design better bearings to achieve high performance. It is evident that the radius of a bearing may change at a fixed location with the change in its out-of-roundness. This may influence the radial clearance and so the bearing performance and hence, it is important to incorporate the out-of-roundness also in the metrology of the bearing radial clearance.

In this experimental study out-of-roundness and radial clearance of journal bearings were measured with high precision and the impact of their metrology was examined on the specific oil film thickness of the bearing. Some metrological issues were emerged and these should be taken into account when bearings are designed.

2. Radial clearance measurements

Radial clearance constitutes the micro-geometry of a bearing and is a key design parameter for determining the load carrying capability. As a guide the radial clearance for a bearing is taken as one thousandth of its radius. Smaller, clearances generate higher load carrying capacity of a bearing for the same operating conditions. However, misalignment, solid contaminants and roughness of the bearing surfaces pose some limitations on minimizing the radial clearance.

Minimum oil film thickness is the direct measure of the bearing performance. Therefore, radial clearance in a bearing must be measured with a degree of accuracy. It becomes even more important when required oil film thickness in the bearing is even small. Because, each micron added to the radial clearance results in reducing the minimum oil film thickness by approximately 1%.

The radial clearances of six test bearings were measured using different measurement method. These bearings were subsequently used in an experimental study for studying the effect of solid contaminants on the minimum oil film thickness in the bearing.

2.1. Metrology of Radial clearance

A bearing was designed using ESDU 84031 method for conducting tests on a journal bearing test rig on a 16 micron minimum oil film thickness. The bearing specimens were fabricated in the workshop according to the drawings supplied. To confirm the dimensions, the ID and OD of each test bearing was measured separately to cross check the actual radial clearance. The measurements of radial clearance were obtained by finding the difference in the ID and OD of the bearing and shaft sleeve respectively. The data was collected using different measuring devices with high to low precision.

The design guidelines indicate that the nominal ID and OD were 40.00 mm and 39.82 mm respectively, giving minimal radial clearance 90 microns. However with the allowable tolerances the maximum ID could be 40.00 + 0.016 mm and minimum OD 39.82-0.016 mm and hence the radial clearance can fall any where between 90 microns and 106 microns. Thus theoretically the radial clearance could vary more than 16 microns. If each micron radial clearance added to nominal radial clearance of 90 microns will reduce the film thickness by 1% (Chiu and Kay, 1974), it may compound the problem. Thus the maximum variation in minimum oil film thickness can be reduced by 16% (2.5 microns) of the required minimum oil film thickness (16 microns). Thus the actual minimum film thickness in the bearing contact could be as low as 13.5 microns which is approximately 84% of the required value. This indicates that the radial clearance

This showed that the metrology of the radial clearance measurement plays a significant role and not only that the bearing manufacturer or the user of the bearing is aware of this fact but the bearing designer must also take this fact into account while designing bearings

2.2. Procedure

The ID and OD of the test specimen were measured by recording measurements at 10 different angular locations along the bearing circumference (5 locations at one end of the bearing and 5 on the other) equally spaced by 36 degrees covering the whole circumference. The main focus was on the bearing ID measurements using four different devices as stated i.e. vernier caliper, Sigmascope, Hole-test-gauge and Metroscope. Where, Metroscope gave the highest precision of up to 2 microns and Vernier caliper the poorest.

The OD of the shaft sleeve was measured with the help of HP Laser system, which gave maximum precision up to 1 micron. It was noticed that the shaft sleeve radius did not vary more than 2 microns and hence the main focus was on the measurements of bearing ID.

It was concluded that the variation in bearing ID may be due to poor control over manufacturing process, including deformations caused by holding the work piece in the chuck for performing other operations after the boring. Thus, it was necessary to verify the radial clearance. Following which, the radial clearance for each set of bearing was determined.

2.3. Results

The measurements have been recorded in Table 1. The data indicates that the measured radial clearances varied from one method to another. It also varied from one location to another along the circumference of the bearing. Even though the precision of each measuring device is known, the accuracy in measurements is not assured due to human errors in handling the equipment (Vernier and hole-test-gauge) or observing the readings in optical devices (Metroscope and Sigmascope).

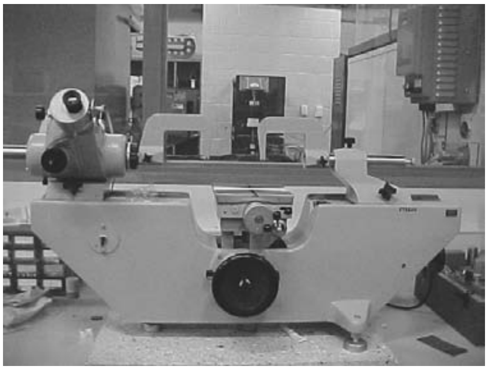

Fig. 1. Metroscope

Table 1.
Bearing ID measurements

Observation No.	Vernier calliper	Sigma-scope	Hole test gauge	Metro-scope
1	39.90	39.948	40.015	40.005
2	40.01	39.974	40.000	40.000
3	40.00	39.951	40.005	40.002
4	39.95	39.956	40.005	40.005
5	39.96	40.000	39.990	40.000
6	40.02	39.985	39.990	40.005
7	40.03	40.005	40.010	40.002
8	40.02	40.008	40.010	40.002
9	40.66	39.282	39.966	40.004
10	39.88	39.246	39.962	40.000
Average	39.986	39.9783	40.0031	40.0026

If error in shaft sleeve's OD is ignored, the results show that the variations in a bearing's radial clearance could be as high as 780 microns and as low as 25 microns respectively. The highest and lowest values for each method have been highlighted and an average value has been calculated for each measuring device. A statistical analysis shown in Table 2 clearly states the superiority of ID measurement with Metroscope (Figure 1) which works on the optical comparator principle.

The variations in ID measurements at different locations were observed more than the tolerance limits. In the worst case the variation in the measured and reported value was as much as 50%.

The results show that the vernier measurements are the poorest in terms of accuracy and Sigmascope results are the poorest for repeatability. With the latter there is significant subjectivity involved in focusing the lamp and positioning the cursor. The gauge test proved to be a better instrument but the Metroscope gave the best results with an accuracy of up to 5 microns. The results of bearing ID measurements have been discussed as an example but a similar situation occurred with the measurements of shaft sleeve OD also. The use of all the above devices was unsatisfactory in measuring the OD of the shaft sleeve and the best results were obtained with the HP Laser System. The errors and problems associated with the metrology of radial clearance measurements have also been discussed in a separate publication [7].

An exaggerated end-view of one of the measurements has been plotted in the form of radar graphs (Figure 2). The graphs is the exaggerated radar plot of ID and OD of concentric bearing and shaft sleeve together and highlight the metrological problem associated with the radial clearance measurements. The Figure shows that there could be event when bearing surfaces are contacting each other in the lubricated contact and thus the hydrodynamic lubrication may seize to exist in such a situation. The metal contact duration will depend on the rotating part of the bearing surface if a bearing surface with higher out-of-roundness rotes it may cause transient metal contact and hydrodynamic lubrication regime may not exists all the time. However, a surface that has lower out-of-roundness rotates, against a surface that has higher out-of-roundness in the bearing contact zone will seize to act as a hydrodynamic bearing through out the rotation.

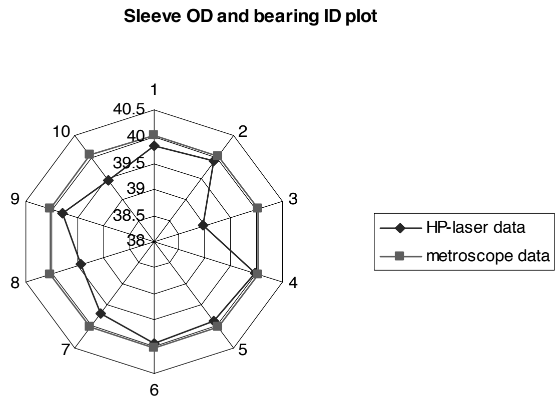

Fig. 2. Concentric bearing and shaft sleeve diameter graphs

2.4. Boundary lubrication regimes during each revolution of the shaft sleeve

Table 2.
Bearing ID measurements: statistical analysis

Instrument	Standard Deviation	Median	Mean
Vernier	0.222962	40.005	40.043
Sigmascope	0.302116	39.965	39.8355
Hole-test-guage	0.018421	40.0025	39.9953
Metroscope	0.002121	40.002	40.0025

2.5. Sources of error

The main sources of variation in the radius of the bearings could be as follows:

1. Measurement errors
2. Out-of-roundness

2.6. Measurement errors

The error in the equipment depends upon the inherent quality of the equipment for handling the precision or errors in handling the device. The results showed that the vernier caliper or micrometer are not the right equipment for measuring the radius of these bearing elements with required precision. Similarly there are errors involved with the Sigmascope and Metroscope as these devices are optical comparators and hence human errors are possible with these devices. However, the Metroscope results show that the precision obtained from the device is of the highest order.

3. Effect of out-of-roundness on radial clerance

Out-of-roundness is the departure of circumference of a work piece from its true circle. As shown in the Figure 3, a Talyrond has been used for measuring the out-of-roundness in this study [1]. Out-of-roundness is measured by drawing a true profile of the circumference of the work piece and then placing two perfect circles such that first circle is inscribed inside the profile such that it touches minimum two points at the trace and another circle is placed such that the true profile inscribes inside this circle by touching the profile minimum at two points. Thus by ASME Y14.5 M-1994 standard [5] the radial distance between the two extreme circles is defined as out-of-roundness. Since there is no object perfectly circular, the radius varies from one location to another all along the circumference of any round object.

Fig. 3. Talyrond

The out-of-roundness defined by ASME is based on the location of the true centre of the work piece, which is arbitrary and it is difficult to locate it physically. It is also difficult to locate the true radius of the work piece as yet there is no standard method by which radius of a circle could be measured taking out-of-roundness into account. However, it is difficult to define the actual location on an out-of-roundness trace. For some it may be the radius of the small circle formed in the above process of finding the out-of-roundness and for others the radius of the big circle. However, others may say that it lies in between. In fact there could be the following three situations:

a) true radius is the radius of the small circle
b) true radius is the radius of the bigger circle or outer circle.
c) true circle is in between the two circle.

The standard practice of measuring the radius of a bearing is to measure the radius at different locations and take an average value. For tribological studies, designer would prefer to use a value that is standard and gives better understanding of the bearing micro-geometry.

3.1. Proposed method

An ideal method of establishing the average radius of a bearing is proposed based on the situation analogous to that of roughness profiles, where roughness is measured from the Central Average Line (CLA). This line does not exist in practice by itself rather it is determined by drawing a hypothetical line that divides the roughness profile excursions such that the area formed by the upper and lower excursions is equal.

As shown in Figure 4a and b the roughness profile and determination of Ra value, a similar method can also be devised for determining the Average radius of the bearing. A mean circle based on similar principle as mean line in roughness measurement can be found out such that the area formed by the true out-of-roundness profile trace gives equal area under and above this circle as shown in Figure 5.

3.2. Effect of out-of-roundness on bearing design

Bearing designers are using roughness as one of the important criteria for defining the lubrication regimes. These have been shown in Figure 6 One of the main principle of designing hydrodynamic bearing is to ensure that the specific oil film thickness (also called lambda ratio) in the bearing is 10 or more in other words the bearing surfaces are separated by at least 10 times or more composite roughness of the two mating surfaces this is shown in Figure 3 a and b respectively.

The Figure shows that the roughness equal to the film thickness indicates the boundary lubrication. In mixed lubrication film thickness is 1.5 to 3 times composite roughness similarly in hydrodynamic lubrication regime film thickness is likely to be 10 or more times thicker than the composite roughness.

As evident from the Figure 4a the lambda ratio 10 can only be ensured if bearing surfaces has no waviness or out-of-roundness. If waviness of a rough surface is taken into account the separation may or may not be ensured of the order of magnitude

10 or more. If out of out –of-roundness value is less than the roughness, the lambda ratio 10 holds good as given in the Eq.1, where σ_1 and σ_2 are the rms values of the roughness of the two bearing surfaces

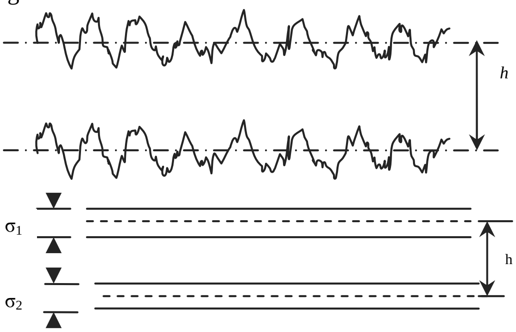

Fig. 4. a) Oil film thickness between the surfaces, b) Oil film thickness based on composite roughness

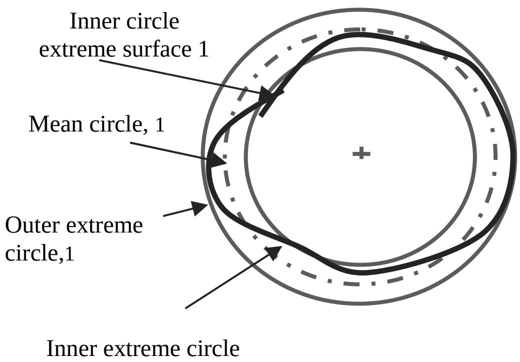

Fig. 5. Out-of-roundness profile

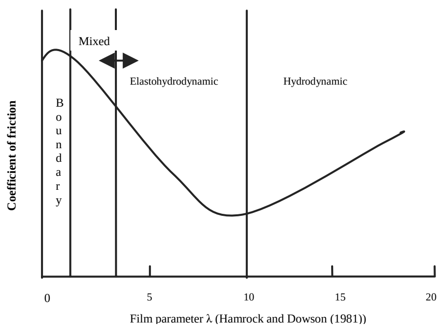

Fig. 6. Lbrication regimes [4]

$$\lambda = \frac{h_{\min}}{\sqrt{\sigma_1^2 + \sigma_2^2}} \tag{1}$$

However the 10 times separation cannot be ensured if out-of-roundness value is higher than the composite roughness value of the bearing surfaces. This has been demonstrated through a diagrams shown in Figure 7.a and b.

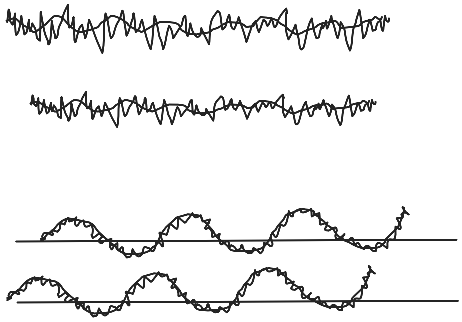

Fig. 7. a) Waviness or out-of-roundness smaller than roughness, b) Waviness or out-of-roundness larger than roughness

The lambda ratio ensures the separation of two bearing surfaces. It guarantees at least 10 times composite roughness of the two bearing surfaces when bearing is operating in hydrodynamic lubrication regime. However, this cannot be ensured when out-of-roundness of the two surfaces is greater than the composite roughness. Tribological concerns

4. Metrological issues

The study revealed that the main reason for variation in radius of the bearing is the out-of-roundness. Like roughness does not mean much without cutoff length. The radial clearance does not mean much without out-of-roundness.

The radial clearance required may be different from the value reported by the manufacturer as specification. However, if the value is measure with less precision may result in mixed or boundary lubrication which may reduce the bearing life.

Bearing designers must take this fact into account and specify limits of roughness as well as out-of-roundness.

There should be a standard method by which radial clearance be measured and the same practice be followed by the user or manufacturer.

The current practice of lambda ratio 10 be reviewed to ensure hydrodynamic lubrication.

Manufacturers should ensure that the radial clearance of the bearing should also be checked before specifying the overall dimensions. They should devise better manufacturing process to ensure control on the out-of-roundness.

Users can make sure that the bearing surface that is stationary does not have maximum out-of- roundness in the contact zone.

5. Conclusions

Radius of a journal bearing changes from one location to another along the circumference. This is mainly due to uncontrolled out-of-roundness.

There is a serious need for establishing a relationship between the radial clearance and the out-of-roundness.

Designers need not follow blindly the lambda ratio 10 as safe measure of ensuring hydrodynamic lubrication in the bearings.

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