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Tribology of Journal Bearings Subjected to Boundary and Mixed Lubrication

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Abstract

The purpose of this research paper is to examine the tribological characteristics and issues related to journal bearings under boundary and mixed lubrication conditions during shaft startup, shutdown, and low speeds. The key issues and problems related to journal bearings, most notably wear, are discussed as well as the subsequent issues created in the field. The mechanical analysis of the loading conditions is documented for both numerical calculations and experimental test methods.

Studies prove the negative effect bearing wear has on performance and pressure loads. Solutions include polymer liners, surface hardening, and using lubrication fluids with additives. Ultimately, the solutions help to optimize journal bearing design and improve product reliability. In addition to the on-going pursuit to reduce wear, finding effective environmentally friendly lubricating fluids is a difficult challenge.

Summary of Problem

A journal bearing is a journal (such as a shaft) which rotates within a supporting sleeve or shell [1]. Hydrodynamic journal bearings use the rotation of the journal to pressurize a lubricant which is supplied to the bearing to eliminate surface-to-surface contact and bear the external load as seen in Figure 1 [4].

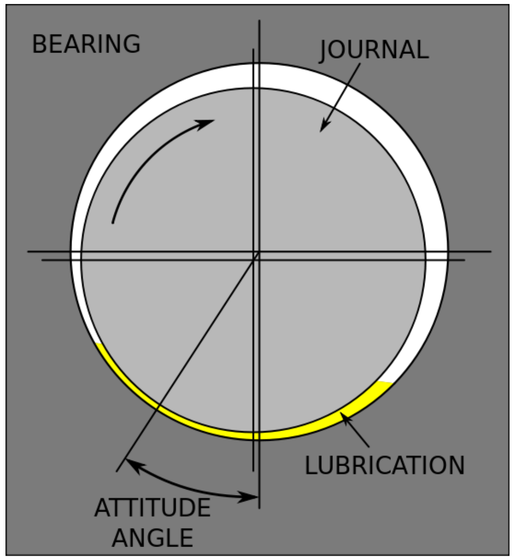


Figure 1: Journal Bearing [4]

Sliding lubricated surfaces can be broken down into three lubrication regimes corresponding to the Stribeck Curve seen below in Figure 2. The curve represents the minimum value of friction between full fluid separation and direct asperity contact of two surfaces. The friction is plotted as a function of a lubrication parameter $\eta N/P$, where η is the dynamic viscosity, N is the shaft speed and P is the external load [7]. The highest friction condition occurs in the boundary lubrication region, which represents significant or complete asperity contact between the two surfaces. On the other hand, the hydrodynamic lubrication region represents a load fully supported by the lubricating fluid with no asperity contact. Finally, the mixed lubrication region represents partial load support from the lubricating fluid and partial load support from asperity contact.

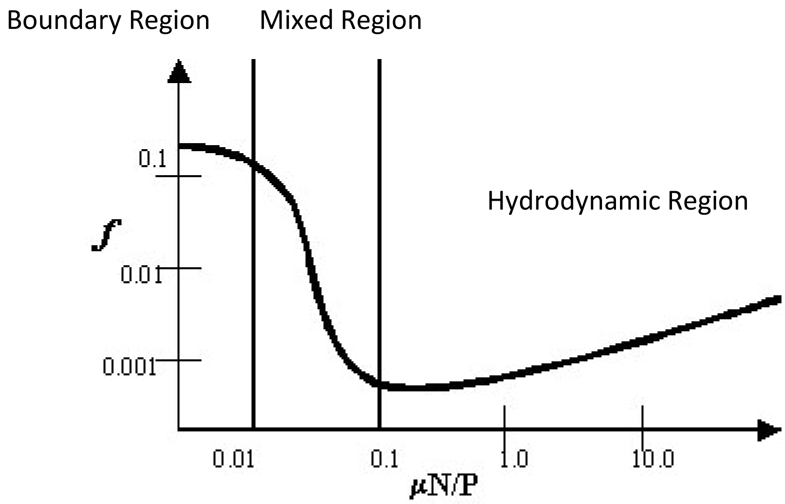


Figure 2: Stribeck Curve [8]

Significant wear of journal bearings can occur during boundary and mixed lubrication conditions when there is not enough pressure generated in the lubricant to carry the load. These conditions occur during startup, shutdown, and low speeds of shaft rotation [1]. Excessive wear of journal bearings will degrade their performance over time and can result in bearing failure. Failure of a journal bearing can result in significant production losses and maintenance costs to companies that rely on them within their machinery. Research indicates that among other factors, bearing wear rate is dependent upon frequency of starts and stops, surface velocity, load, and material hardness [2].

Key Problems/Issues

Wear is most notably the biggest problem encountered by journal bearings. Direct contact between the journal and bearing creates high friction conditions, which ultimately causes the bearing liner to wear. In most applications, journal bearing designs introduce lubrication fluid to decrease the friction between the two surfaces, however contact between the surfaces can still occur in the presence of lubrication [11]. The period of increased contact occurs most frequently during start-up, shut-down, and low speeds of the machine in which the bearing is used. As was previously discussed, these are known as boundary or mixed lubrication conditions.

Journal bearings can be seen within products such as a gear pump. The shaft serves as the journal and its own rotation pressurizes the fluid between itself and the bearing face [11]. Higher speeds create higher pressure, therefore a minimum speed is required for proper operation. An example of such an application is an oil pump used for a jet engine. As expected, each time the engine is started or shut-down it transitions through speeds below the minimum needed to pressurize the lubricant. Over time, repeated starts and stops lead to excessive wear of the bearing. Wear of journal bearings lead to increased leakages across the bearing, which reduces the total flow discharged from the pump. Decreased flow could ultimately starve the components being supplied with oil and could cause them to seize or fail.

In addition to insufficient lubricant pressurization, during start-up there is also an inadequate oil supply as the pump is driven by the shaft. Therefore, the pump operates solely from the oil leftover from previous operation. If the lubricant is cold it may be thick enough to separate the two faces, however, if several start and stops are made in quick succession excessive wear may occur due to heat reducing the film thickness [11]. When the lubricant film thickness decreases too much, the asperities of the two faces begin to contact one another.

This problem is not unique to jet engines or even gear pumps, but rather all machinery using hydrodynamic journal bearings in which shafts rotate within a supporting sleeve. In short, journal bearing wear reduces the efficiency of all these machines and numerous starts and stops can cause them to fail prematurely.

Example of Journal Bearing Issue

An example of the issues caused by journal bearing wear at the mixed or boundary lubrication regions is in the Indian Sugar industry. In the sugar factories, the sugar cane is crushed to extract juices using three rollers arranged in a triangular formation as seen in Figure 3. The top roller drives the bottom two rollers and the journals of the rollers sit on plain bearings which are supported by the machine [10].

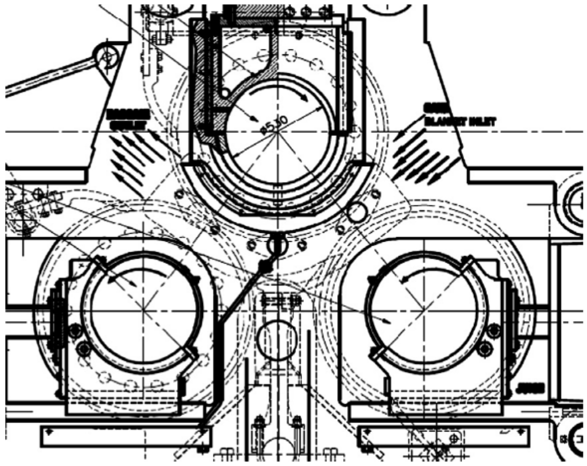


Figure 3: Sugar Cane Rollers with Journal Bearings [10]

The premature failure of the bearing is common in the industry (4-6 months life) and drives high costs for maintenance and production loss. The failure is driven by the low speeds (4-5 RPM) at which the rollers are turned in order to properly crush the cane. The bearings all exhibit characteristics of fatigue cracking, despite the fact that the bearings are only exposed to a relatively low number of cycles [10]. This occurs because the low speeds do not allow for proper pressurization of the lubricant and create high loads due to the direct surface contact.

Mechanical Analysis of the Loading Conditions for the Interface

There are several ways to analyze loading conditions at the bearing interface using both experimental tests and theoretical calculations. In a numerical analysis of the loading conditions within a journal bearing several assumptions need to be made. In an ideal case, it can be assumed that the bearing and journal surfaces are separated by the lubricant and the journal rotation pumps the lubricant around the bearing in the rotation direction [10]. It will only consider a 2D geometry in which there is pure tangential motion and density of the fluid is constant. The resulting lubrication pressure distribution can then be described by the Reynolds equation below:

$$\delta/\delta x\ [(h^3/12\eta)*(\delta P/\delta x)] + \delta/\delta z\ [(h^3/12\eta)*(\delta P/\delta z)] = 0.5*[\delta(U2-U1)h/\delta x] + 0.5*[\delta(W2-W1)h/\delta z] \qquad [10]$$

Where: P = fluid pressure; x = coordinate in tangential direction; U2, V2, and W2 = velocity components of the bearing surface; U1, V1, and W1 = velocity components of the journal surface; z = coordinate in axial direction, g = fluid dynamic viscosity; h = gap between shaft and bearing surfaces

Further theoretical calculations can also be made for the film thickness of the lubrication fluid. This is an estimate as Rq represents surface measurements at one location, despite the fact the surface roughness varies over the course of a surface [3].

$$\lambda = h/\mathrm{sqrt}(R_{q1}^{2}+R_{q2}^{2}) \qquad [3]$$

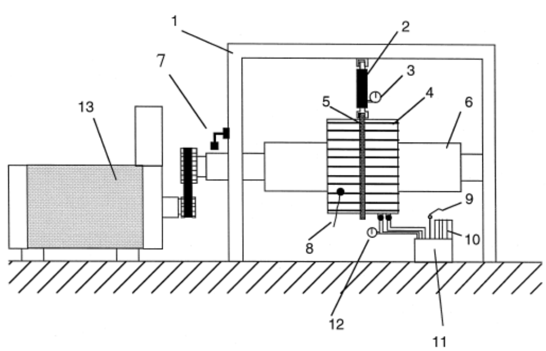
Where: λ = film thickness coefficient (typically between 8 – 10 for journal bearings), h = film thickness, Rq = equivalent surface roughness

Finally, calculations can also be made to determine the coefficient of wear. This can be calculated using Archard's equation of wear below:

$$V/S = K*(F_N/H) \dashrightarrow K = (V/S)*(H/F_N) \qquad [3]$$

Where: V = Wear volume; S = Sliding distance; K = Coefficient wear; H = Materials hardness; F_N = Load

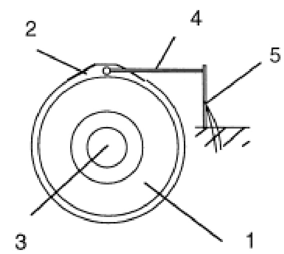
Numerous experiments have been conducted to analyze the tribological characteristics of journal bearings. One particularly popular test method involves loading a test bearing using what is called a "block-on-ring" test apparatus as seen in Figure 4.



1. Frame
2. Hydraulic cylinder
3. Manometer
4. Bearing housing
5. Steel ring
6. Shaft
7. Tachometer
8. Temperature gauge liner
9. Temperature gauge oil
10. Pump
11. Tank
12. Manometer
13. Motor with fan

Figure 4: Example Test Rig [3]

As seen above, a test bearing is mounted to a shaft and loaded by a hydraulically actuated ring that fits around the bearing housing. Oil is supplied to the bearing by an external pump. During the test, the oil and bearing liner temperatures are measured using thermocouples and speed is measured by a tachometer. Friction torque is measured using strain gauges attached to an L-Shape bar attached to the top of the bearing as seen in Figure 5 [3].



1. Bearing housing
2. Steel ring
3. Shaft
4. Lever
5. Strain gauge

Fig. 2. Torque measuring equipment.

Figure 5: Frictional Torque Measurement [3]

Wear can be measured using several methods. A simple way to characterize wear is by weighing the test article both before and after the test to measure weight loss. In addition, more detailed surface measurements can be taken using a perthometer or a Scanning Electron Microscope both pre and post test [3].

The test rig measurements, in combination with theoretical calculations, can be used to analyze various bearing designs and oil types to help understand the effects of wear and determine optimal designs.

Using Experimental Data to Understand Effects of Wear

Experimental data can be used to better understand the effects of wear on bearing performance when subjected to numerous starts and stops. In an experiment conducted by Fillon and Danos [9], a two-lobe journal bearing (Figure 6) was subjected to 2000 cycles of startups and stops. One cycle consisted of rotating the shaft up to 1690 rpm within one minute and then subsequently rotating the shaft down to a stop. Measurements taken both pre and post test showed an increase of 3.8% in the maximum pressure exhibited by the worn bearing compared to the new bearing [9].

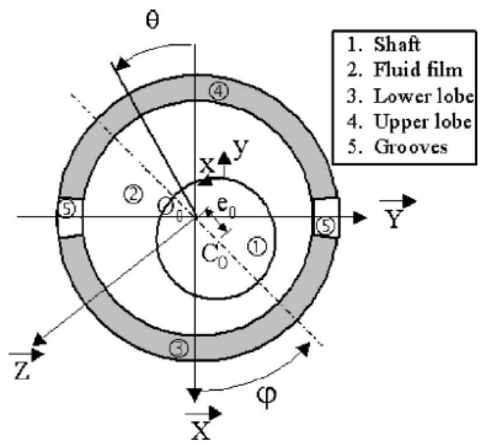


Figure 6: Two-Lobe Journal Bearing [9]

Clearly the numerous starts and stops have a negative effect on the bearing characteristics. Increased pressure puts increased loads on the bearing and over time could cause the loads to exceed the bearing capability.

Materials issues

Key bearing materials issues are directly related to the same wear issues extensively covered above. Therefore, materials are often chosen based on the material hardness and frictional properties needed to meet the desired performance, life, and cost of the design. Typical bearings are made of metal alloys such as copper, bronze, steel, or aluminum [5].

However, it is important to note there are other issues caused by bearing materials beyond the obvious and generalized issue of frictional wear of two contacting surfaces. For example, ferrous-based materials are not commonly used due to adhesive wear effects with shafts having similar materials [6]. Essentially, two materials in contact having similar materials create adhesive forces in material or debris transfers from one surface to the other. Another example is the tradeoffs of using pure PTFE for bearing material. Although the polymer has beneficial frictional properties and a high wear resistance, it is highly susceptible to creep and therefore cannot be used in high load situations [5].

Solutions Cited in the Literature

As discussed, bearing wear at low speeds is characterized by the relationship between the lubricating fluid and the two contacting surfaces. Naturally, solutions for reducing bearing wear involve optimizing the contents of the lubricating fluid as well as using superior materials for the bearings. Numerous experiments have been conducted to determine the effectiveness of these design solutions and have produced positive results.

It has been proven that additives containing substances with long chain carbon atoms can help to improve lubricant performance. Additives create a chemical reaction on the surfaces of the bearing and journal which ultimately decreases the friction coefficient between the two during conditions of mixed or boundary lubrication. The additives contain sufficient cohesive forces to create a thin surface film which serves as a protective layer and absorbs most of the pressure applied by the radial load in the contacting area [11].

An experiment was carried out to prove the effectiveness of additives by Durak, Adatepe, and Biyiklioglu [11]. Standard engine car oil was tested as the lubricating fluid between a steel alloy bearing and a 1030 hardened steel journal. The journal (shaft) was ramped up to a chosen speed within 30 seconds, before being slowed down to a full stop within 30 seconds. This cycle was run a total of 102 times (~6000 seconds) to simulate numerous starts and stops of a machine. This test was run at a specified speed and load using the standard oil and then repeated using the same standard oil with 3% additives.

The test was repeated several times at various speeds and loads before plotting the average coefficient of friction. As expected, in each instance the measured average coefficient of friction was significantly lower when using the standard oil with 3% additive [11].

For improvements in bearing material, experimental data has shown positive results with applications using polymer liners (Figure 7), especially at low speeds. For example, a wear comparison experiment showed 800% improvement in wear rate for a white metal alloy bearing with a PTFE-lining over a similar bearing without the lining [5]. Compared to traditional metal alloy liners, polymer liner applications show reduced pressures and wear. This is because the polymer or compliant layer has better frictional properties [5].

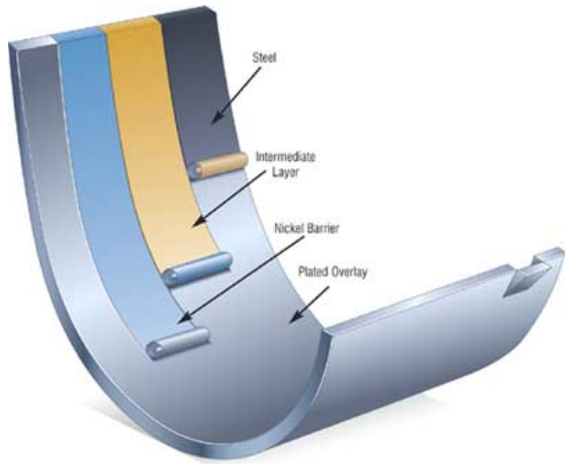


Figure 7: Material Layers of Common Journal Bearing [1]

As a trade off, polymer liners generally result in reduced lubricant film thickness at the bearing edges. This is largely due to the reduced stiffness, which allows the bearing to deform more than the traditional metal alloy bearings. As a result, there is less pressure buildup to pressurize the lubricant [5].

Another surface treatment that can be provided to reduce wear is a process called boronizing, which hardens the surface similar to nitriding. It diffuses the element boron into the surface at high temperatures. The newly created layer forms a thin oxide surface film that helps to reduce adhesion forces [6]. Boronizing is a popular method to reduce the problem of excessive wear forces associated with ferrous bearings mated with similar material shafts sited above. For example, an experiment conducted by Unlu and Atik showed the wear rate of a ferrous bearing (TS-DDK 40 nodular cast iron) in contact with a steel alloy (SAE 1050) shaft reduced its wear rate by nearly seven times simply by boronizing the surface [6].

These are just three of several solutions commonly used in journal bearing design specifically to reduce wear. Clearly, in instances where contact between the journal and bearing cannot be avoided (such as during mixed or boundary lubrication) it is important to reduce the friction in the contact area. Mixing additives in the lubrication can create protective film layers, while polymer liners and boronzing provide physical layers with better frictional properties.

Open Problems in the Field

Despite the advances in technology it should be noted that solutions have only succeeded in reducing wear, not eliminating it. Therefore, the search for improved wear resistant designs is an ongoing process.

Beyond wear, another challenge facing the field is due to the recent emphasis on providing environmentally friendly equipment and machinery to consumers and industries. Therefore, more and more companies are being challenged to produce products that can operate using alternative sources of lubrication fluid such as vegetable oil, rather than traditional mineral oil [3]. The challenge then becomes to ensure the substitute oil matches or exceeds the performance (or in this case wear resistance) of the current oil.

Del Din and Kassfeldt conducted a preliminary experiment that suggests that such environmentally friendly oils exist, however, a more extensive array of tests still need to be conducted before it is fully supported [3].

Conclusions

Hydrodynamic journal bearings are commonly used throughout numerous industries as a way to support a rotating shaft. It is inevitable that during the start-up and shutdown stages of the rotating shaft, boundary and mixed lubrication conditions will allow direct contact between the bearing and journal. The frictional contact causes wear that can lead to unwanted performance degradation or failure which ultimately results in costly maintenance and repair. It is important to understand the characteristics of this wear to determine optimal solutions to improve bearing life and reduce costs. Successful solutions include enhanced materials and lubrication additives that form layers on the contacting surfaces with superior frictional and wear resistance than the parent material. Improvement in wear resistance is an ongoing process and questions remain open regarding the viability of environmentally friendly lubrication fluids.

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