The Benefits of Circulating Oil in Ring-Lubricated Hydrodynamic Bearings

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Abstract

Hydrodynamic bearings depend on a steady flow of lubricant onto the shaft, among other factors, in order to generate the film that separates the shaft and bearing during operation. In many applications, such as fans, motors, and gearboxes, oil rings are used to deliver this lubricant. However, there are limitations to oil ring lubrication, especially during startup, slow speed conditions, and in the presence of solid contamination. Adding an external circulating oil system can overcome these limitations while offering benefits to bearing reliability, providing cooling, and allowing for easier condition monitoring.

Introduction

Hydrodynamic journal bearings, also known as oil film bearings, are frequently used in critical applications such as fans, pumps, motors and high-speed gearboxes, where they are required to run for long periods of time. Advantages of hydrodynamic bearings include long service life, minimal maintenance requirements, and damping that can significantly reduce vibration.

Several methods of lubricating and cooling these bearings can be found in various applications. Methods of lubrication include oil slinger discs, gas lubrication, oil rings, or forced-feed circulating oil. In some applications, bearings can operate without any cooling, but others require external cooling with air, water, or circulating oil.

This document will discuss the benefits of circulating oil, both for cooling and for lubrication, in ring-lubricated hydrodynamic bearings.

Background

In hydrodynamic journal bearings, the shaft rides on a thin film of oil which separates the shaft from the bearing surface, which is usually made of a Babbitt material. There is clearance between the shaft and the bearing bore, which allows there to be eccentricity, or a small distance between the shaft and bearing center, shown in **Figure 1.** The difference in shaft and bearing diameter also creates a converging oil wedge. As the shaft turns, oil is forced into this converging wedge and creates lift, pushing the shaft off of the bearing surface. This changes the coefficient of friction between the two surfaces.

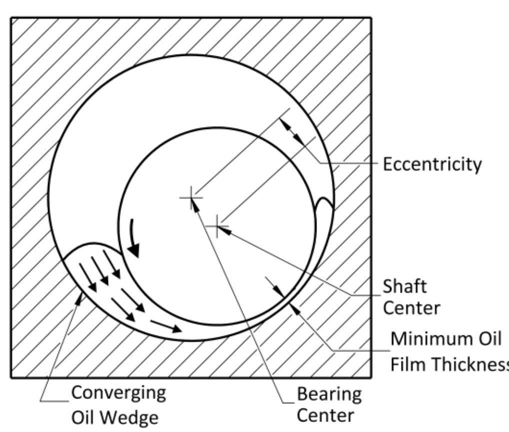

Figure 1. Journal bearing during operation.

In 1902, Richard Stribeck found a relationship between the friction coefficient (μ) and the bearing load (P), speed (N), and dynamic oil viscosity (η), shown below in **Figure 2** [1]. This curve can be divided into three sections, or lubrication regimes.

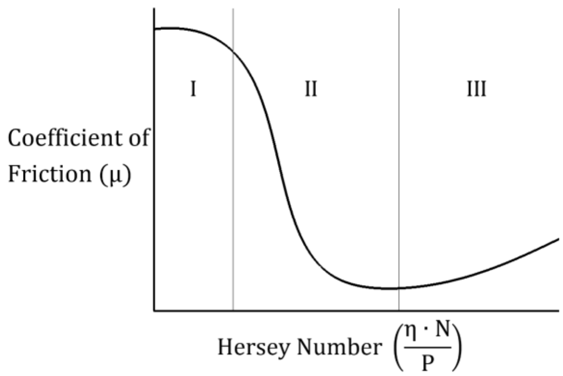

Figure 2. The Stribeck Curve compares the coefficient of friction to the Hersey number, which is a function of load, speed, and oil viscosity.

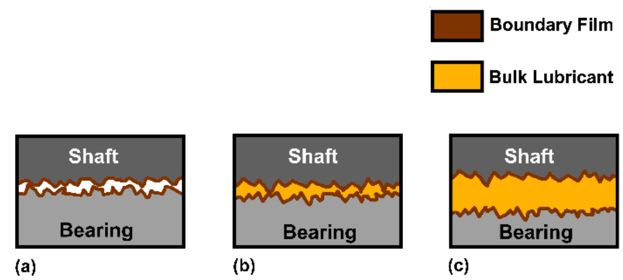

Figure 3. Bearing and shaft surfaces during (a) boundary lubrication, (b) mixed film lubrication, and (c) full film lubrication regimes [2].

When the shaft first begins to turn and at slow speeds, there is very little, if any lubricant between the shaft and bearing. This is known as the *boundary lubrication* regime, shown in **Figure 3a**. During this period, the asperities, or microscopic peaks and valleys on the shaft and bearing surfaces left over from the machining process, come into contact. The coefficient of friction is high in boundary lubrication, and this is where nearly all of the wear occurs in journal bearings [1].

Once the shaft speed begins to increase, the oil film begins to form between the two surfaces. However, at this point the oil film is not thick enough to fully separate the shaft and bearing, as shown in **Figure 3b**. This is known as the *mixed film* lubrication regime. During mixed film regime, as shown in region II of **Figure 2**, both friction and bearing wear reduce considerably. However, there is still contact between the asperities, and the bearing is vulnerable to damage from contaminants that may be larger than the oil film [1].

The final regime is known as *full film* lubrication regime. This is when the fluid film fully separates the shaft and bearing, as seen in **Figure 3c**. During this regime, there is no wear of the shaft or bearing, and the bearing is generally safe from contaminants smaller than the oil film. Once the full film is achieved, friction slightly increases with speed. This is due to an increase in oil shear forces from a thicker film and is usually very minor [2].

However, the Stribeck curve assumes that the bearing operates in the fully flooded condition, meaning that it is being supplied with at least the minimum amount of oil needed to generate a film at the speeds experienced. If a bearing operates in a starved state, then the amount of oil supplied is below the minimum required to support the film. When starved, the bearing can run in boundary or mixed film lubrication regimes for much longer and experience greater wear and reduced life.

Oil Ring Lubrication

Hydrodynamic journal bearings in low-speed (up to approximately 150 FPM) to medium-speed (up to approximately 4000 FPM) applications are often lubricated by one or more oil rings that ride on the shaft and dip into the oil sump below, as shown in **Figure 4**. As the shaft turns, friction between the shaft and the oil rings cause them to turn as well, bringing oil from the sump to the shaft and lubricating the bearing.

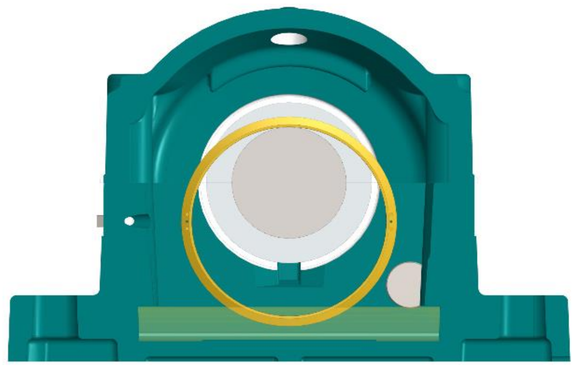

Figure 4. Oil ring lubricated journal bearing.

Like the bearing itself, oil rings operate in three distinct stages. During slow speeds, there is little slip between the shaft and oil ring due to friction between the two surfaces, and the surface speeds of the shaft and oil ring are roughly proportional. However, as the speed increases, drag forces from the oil overcome the friction and significant slip occurs between the shaft and oil ring. Since the surface speeds of the shaft and oil ring no longer match, a hydrodynamic film forms between them, similar to the film between the shaft and the bearing. This film also operates in the mixed-film and full-film lubrication regimes, depending on the shaft speed, oil viscosity, and oil ring diameter [3].

Key benefits to oil ring lubrication are that it is cost effective, allows the bearing to be fully self-contained and, if sized properly to the application, can provide sufficient lubrication to the bearing at the required operating speeds.

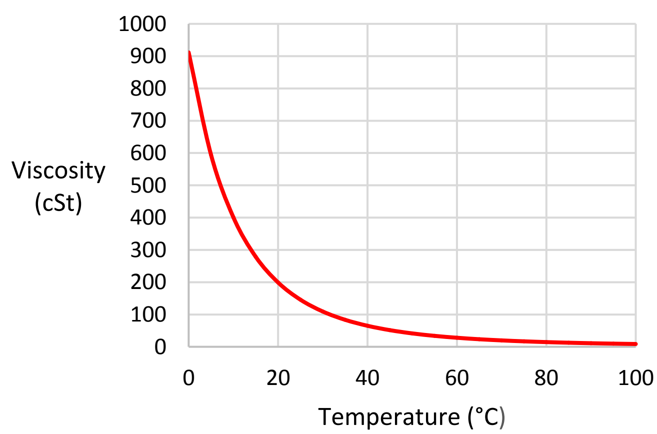

Figure 5. The relationship between temperature and viscosity for a typical ISO VG 68 turbine oil.

However, there are situations where oil ring lubrication alone is not ideal. When the shaft begins to turn, there is no oil available to separate the shaft and bearing. This results in metal-to-metal contact, either as solid friction or boundary lubrication. This is especially problematic if the oil in the sump is too cold, as oil become exponentially more viscous as temperature drops, as shown in **Figure 5** [4]. If the oil is too viscous, the drag forces will outweigh the friction forces, preventing the oil ring from turning or bringing oil to the shaft [5]. Experience has shown that for oil viscosities typically used in oil film bearings, this becomes a risk when the sump temperature falls below 22°C at startup.

A second instance where oil ring lubrication is not ideal is during slow speed operation. On many induced draft, or ID fans, there is a turning gear operation where the shaft speed is significantly slower than normal operation to allow the shaft to cool down. During this time, the oil film between the shaft and bearing will be much thinner than during normal operation, and the bearing may operate in the mixed film lubrication regime. If the speed is low enough, then the oil rings will bring significantly less oil to the bearing, which can cause it to operate in a starved state, and wear in a way more similar to the boundary lubrication regime [3].

As with slow speed applications, high speed applications (approximately 4000 FPM or greater) can be problematic for oil ring lubrication. At high enough speeds, oil rings struggle to deliver enough oil to fully lubricate the bearing. Once a hydrodynamic film forms between the shaft and oil ring, oil delivery rate decreases as the shaft speed increases, which can starve the bearing, resulting in mixed-film or boundary lubrication. Operating in the mixed or boundary lubrication regimes at high speeds can rapidly wear the bearing.

Another issue at high speeds is that vibration in the system, air currents created inside the bearing by the oil rings, and centrifugal forces on the oil can cause the oil rings to oscillate [3]. Oscillations can occur in a pendulum motion, conically, or axially on the shaft, as shown in **Figure 6**, or a combination of the three [6]. This not only reduces oil delivery, but can also cause the oil ring to come in contact with fixed structures in the bearing and cause damage.

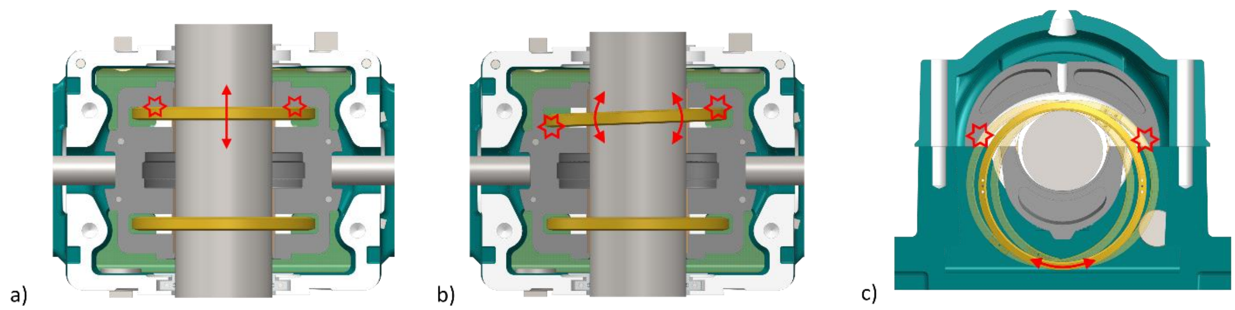

Figure 6. Oil ring oscillation (a) axially, (b) conically, and (c) in a pendulum motion.

Benefits Circulating Oil in Ring Lubricated Bearings

Figure 7 shows a hydrodynamic fan bearing configured with a circulating oil system, also known as a lube skid. There are several benefits to using an external circulating oil system on hydrodynamic bearings that can improve bearing performance and reliability. They include:

Sufficient oil flow at all times – Circulating oil, or force-fed lubrication is where an external pump directs oil directly to the shaft before, during, and after operation. Ideally, the oil flow to the bearing is sufficient for operation at all potential operating speeds, including at startup and in slow-speed turning gear applications. By reducing the amount of time spent in boundary or mixed film lubrication, adding circulating oil can significantly reduce bearing wear.

Continuous oil filtration – A second benefit of using circulating oil lubrication is that the system is being continuously flushed, and

Figure 7. Hydrodynamic fan bearing configured for circulating oil.

harmful contaminants are removed. This is critical, because contaminants can cause damage to both the shaft and bearing, especially during boundary lubrication. Another concern is that contaminants can partially embed into the oil rings, which are usually a semi-soft metal such as brass or bronze. At slower speeds where there is no film between the oil ring and shaft, these partially embedded contaminants can damage the shaft, as shown in **Figures 8 and 9** [7].

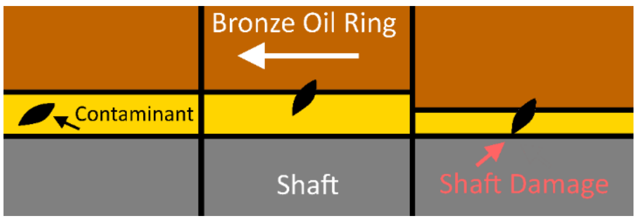

Figure 8. Solid contaminants can partially embed into bronze oil rings and cause damage to the shaft.

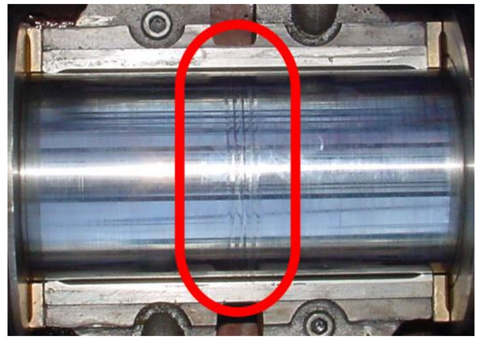

Figure 9. Shaft damage due to contaminants in the oil rings.

Easy to monitor the oil quality and temperature –With a circulating oil system, there is a steady flow of oil into and out of the bearing, and the circulating oil system usually has a significantly larger reservoir than the oil sump. This makes it easy to safely take live samples of the oil going into and coming out of the bearing. While it is possible to take a live oil sample directly from the bearing, this would require getting very close to spinning, potentially hot machinery and is not recommended.

Cooling – In lightly loaded and low-speed applications, hydrodynamic bearings can operate without any external cooling. However, many applications generate too much heat for either the bearing material or the lubricant to and require external cooling. Bearing manufacturers have used water, either through a jacket around the bearing surface or through cooling coils in the oil sump, compressed air, and sometimes air over the bearing housing to remove heat.

Another option to cool hydrodynamic bearings is to use a circulating oil system with a heat exchanger. By delivering cooled oil directly onto the shaft and bearing surface, where the heat is generated, a very significant amount heat can be removed. In existing applications, circulating oil can be used to significantly reduce or eliminate the need for external cooling.

Redundant lubrication – Due to the nature of hydrodynamic bearings, loss of lubrication (which can be caused by an oil leak or by failure of the oil rings) causes the bearing to instantly begin operating in the boundary lubrication regime, followed quickly by total bearing failure. For this reason, it is very important to have redundant lubrication systems for the bearings in critical applications.

When used in conjunction with oil rings, a circulating oil system provides redundancy that can allow an operator or automatic system to shut down equipment before the lubrication failure becomes a catastrophic bearing failure.

Conclusion

The use of circulating oil is always beneficial for hydrodynamic bearings. Bearings in both new and existing applications can see improvements in performance and reliability with the addition of circulating oil, reducing the risk of unplanned downtime. A brief overview of the benefits of circulating oil are shown it **Table 1**.

Table 1. The Benefits of Circulating Oil in Hydrodynamic Bearings

Benefit	Oil Ring Lubrication with Circulating Oil	Oil Ring Lubrication Alone
Lubrication	Sufficient lubrication at all operating speeds.	Sufficient lubrication at primary operating speed. Potentially oil-starved at turning gear speed.
Filtration	Continuous oil filtration	No filtration. Regular sump oil flush required.
Condition Monitoring	Ability to monitor oil quality while in operation.	System should be shut down to safely sample sump oil.
Cooling	Cooling provided in addition to or in replacement of external cooling.	Provides little cooling. External cooling may be required.
Lubrication Redundancy	Redundant lubrication if the circulating oil system or oil rings fail.	(1) Oil ring: No redundancy (2+) Oil rings: Partial redundancy, bearing may operate in starved condition of one ring fails.

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