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STUDY ON FRICTION TORQUE MODELS IN GREASE LUBRICATED BEARINGS

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Abstract. *Rolling bearings need to transmit load at a very low friction, therefore understanding internal friction losses in these elements is relevant for energy saving. The behavior of grease lubricated rolling bearings is not yet well understood, which is observed by the significant number of different models aiming to predict film thickness and friction torque. The main differences among these models are the assumptions related to the grease lubrication mechanisms, grease properties in the contact and lubrication regimes. As consequence, different friction torque predictions are found for the same input arguments. This indicates that new approaches to evaluate grease lubricated rolling bearings should be researched.*

Keywords: *lubricating greases, rolling bearings, friction torque*

1. INTRODUCTION

Energy consumption in machine design has become ever more important since these machines are required to be economical and have high productivity. Because friction is a major component of power loss, controlling and reducing it becomes significant. One type of machine element that is present in many mechanical systems is the rolling bearing. These elements have the function to transmit load at very low friction, therefore, understanding the lubrication behavior under different conditions contributes to evaluate their overall efficiency.

The majority of rolling bearings use grease as a lubricant because its formulation, base oil and thickener, provides some benefits over lubricating oils, such as its consistency, which minimizes leakage. In a rolling bearing, the primary role of grease is to lubricate the contact between the rolling elements and the raceway, since it generates a large portion of the overall friction (De Laurentis *et al.*, 2017). Lugt (2012) states that grease lubricating mechanisms are not well understood in comparison to oil lubrication mechanisms due to the complex composition of greases. Therefore, film thickness and friction prediction remains a challenge.

Since the coefficient of friction depends on the lubrication regime, most of the efforts have been made to understand film thickness. For oil lubrication, the lube films can be reasonably well predicted using classical EHL (Elasto-Hydrodynamic Lubrication) theory. However, for greases, there are several aspects to be considered, such as rheology, thickener type, bleeding characteristics, starvation and others.

Film thickness is reasonably well understood if the grease is abundant and at relatively high speeds. In this case, it depends mostly on the grease oil viscosity. Below a certain transition speed, it depends primarily on the grease thickener properties. Similarly, De Laurentis *et al.* (2017) suggested that both grease thickener and base oil properties have a significant influence on grease friction depending on the operating conditions.

In the following sections, a summary of grease lubrication mechanisms and frictional moment will be presented and discussed.

2. GREASE LUBRICATION MECHANISMS

Grease lubrication mechanisms are relatively well studied for new greases and in fully flooded conditions. For this case, Fig. 1 is an example of the behavior of film thickness on a grease lubricant versus entrainment speed.

There is a transition speed, called U_{crit} in Fig. 1. For speeds over this transition speed $U > U_{crit}$, the film thickness can be predicted using grease oil properties, that is, it is an oil-dominated region. There is a typical increase on film thickness at a rate of approximately $U^{0.67}$ for all lubricants. In this case, the oil viscosity is the main property needed to evaluate film thickness, although some particular greases do not follow this trend (Cousseau *et al.*, 2015). There is no consensus in the literature that explain such observations.

For speeds under the transition speed $U < U_{crit}$, there is a thickener-dominated region. That means that film thickness is primarily dominated by grease thickener as suggested by De Laurentis *et al.* (2017), and not by the grease oil.

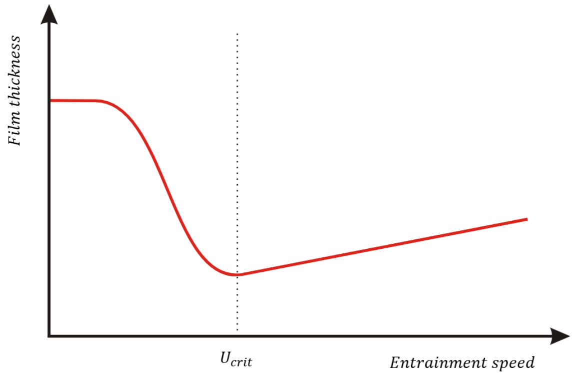

Figure 1. Log-log plot of lubrication mechanisms for greases

If the fully flooded condition is not maintained the film thickness is reduced due to contact starvation. Starvation occurs because grease is a fluid with yield stress. This means that once the rolling elements push the grease aside, it will not easily flow back to replenish the contact (Cann, 2007).

Figure 2 is an example of measurements under starved conditions for a grease lubricant. In general there is a quick film thickness decay followed by a stabilization of film thickness with time. The high standard deviation on the starvation measurements is attributed to grease materials crossing the contact (Cousseau *et al.*, 2015).

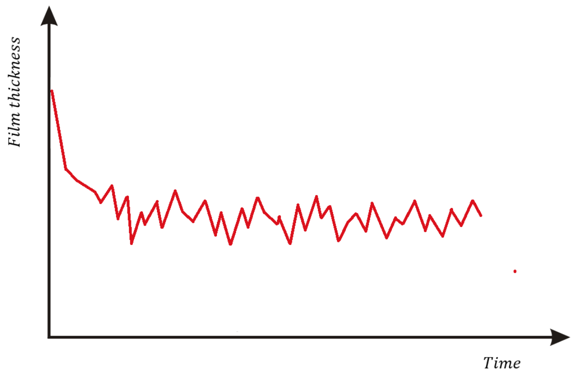

Figure 2. Starved lubrication for greases

There has been a large effort to understand the lubrication mechanisms of grease lubricated rolling bearings, since it rules film formation. However, there is just a few published literature on the evaluation of frictional moment, which are described below.

3. FRICTION MODELS

Some friction models have been developed to attempt to predict friction losses on rolling bearings. Most of them have been developed for lubricating oils, and the ones that consider greases, only take into account grease's base oil viscosity, not accounting for other grease components (thickener, co-thickener). Usually, the estimates are used by partitioning the total friction according to different friction mechanisms in rolling bearings. Also, the coefficient of friction at the operating conditions have to be known, which rarely happens.

Bearing companies' models were developed so they can better understand their products behavior. The most complete ones are the SKF (2016) and Fujiwara (2014) models. The SKF model for calculating frictional moment considers different effects: the rolling frictional moment, the sliding moment, the frictional moment from seals and the frictional moment from drag losses, churning, splashing and others. The NTN Fujiwara model calculates the friction torque by considering differential slip, spin, rolling viscous resistance and shear resistance of the oil film between the rolling element and the cage.

Other theoretical models were developed recently. Most of them take into account rolling bearing kinematics, but in general consider the friction coefficient as a constant in their calculations. Some of these articles are Damian and Paleu (2014), Bălan *et al.* (2015), Jin *et al.* (2012) and Houpert (1999).

Bălan *et al.* (2015) studied the contact with and without lubrication on a modified three ball thrust bearing, considering the frictional torque provided by the rolling frictional moment and the curvatures additional torque. Jin *et al.* (2012) evaluated friction torque indirectly by calculating the heat generation on a ball screw system.

Houpert (1999) made the assumption that the coefficient of friction is constant over the ellipse contact, but acknowledges that to determine it would be necessary to evaluate lubricant rheological behavior at high pressure. Also, that the friction coefficient is a function of the pressure and sliding speed distribution. Brecher *et al.* (2013) considers the coefficient of friction as a function depending on the operating conditions.

The most relevant models found are further explained in the following subsections.

3.1 SKF model

The SKF model (SKF, 2016) is derived theoretically and experimentally to evaluate the frictional moment for a wide range of rolling bearings and lubricant types, considering internal and external influences. But for greases, there are some restrictions, such as only steady state conditions, lithium soap grease with mineral oil at ambient temperature or higher.

Equation (1) presents the parameters considered for calculating the frictional moment for the SKF model.

$$M = M_{rr} + M_{sl} + M_{seal} + M_{drag} \quad (1)$$

Where M_{rr} is the rolling frictional moment, M_{sl} is the sliding frictional moment, M_{seal} is the frictional moment of seals and M_{drag} is frictional moment of drag losses, churning, splashing and others.

The first parameter M_{rr} on Eq. (1) depends on bearing geometry, type and operation conditions. It also takes into account starvation through a constant replenishment factor, which is different for lubricating oils and greases. The parameter M_{sl} depends on the bearing type, bearing geometry, loads and sliding coefficient of friction μ_{sl}. This coefficient of friction varies between its highest value at boundary lubrication conditions (usually about 0.15) to its minimum value of 0,05 for full film lubrication with mineral base oils, as shown in Fig. 3.

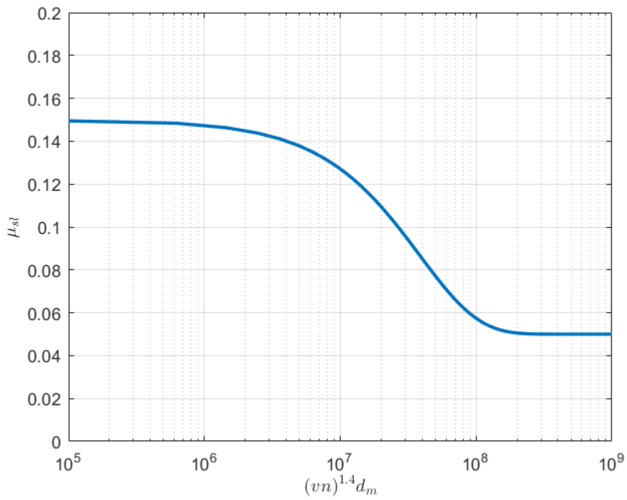

Figure 3. Sliding friction coefficient for SKF model

For full-film lubrication the value of the weighting factor for the sliding friction coefficient φ_{bl} tends to zero, so μ_{sl} tends to its minimum value. For mixed lubrication, which can occur when lubricant viscosity or the bearing speed is low, the value of φ_{bl} tends to 1, as occasional metal-to-metal contact may occur and friction μ_{sl} increases.

The SKF model only takes into account the kinematic viscosity at operating temperature of the base oil of the grease, and differentiate grease from oils through the replenishment factor. However, it is not possible yet to differenciate lubricating greases with the same base oil viscosity.

3.2 Fujiwara model

The Fujiwara model (Fujiwara, 2014) provides an estimation for the friction torque of air-oil lubricated angular contact ball bearings. The friction torque considers differential slip, spin, rolling viscous resistance, elastic hysteresis loss and friction between cage and rolling element.

It evaluates the tangent friction force by multiplying the pressure at the observation point by the coefficient of friction μ. The coefficient of friction is given as a function of slip ratio and can be written by Eq. (2).

$$\mu = \frac{s/s_m}{\sqrt{1 + (s/s_m)^2}} \quad (2)$$

Where s is the slip ratio and s_m is the slip ratio that provides the maximum friction coefficient μ_{max}. The values of s_m and μ_{max} have to be assumed for the condition proposed.

3.3 Brecher *et al.* model

The frictional forces in Brecher *et al.* (2013) are considered as one entity, not partitioning them into separate sources. The model intends to determine ball kinematics by taking into account the resulting friction forces on the ball.

A friction experimental function is used to approximate coefficients of friction needed instead of determining coefficient of friction at the EHL contact point using the height of the lubricant film, and shear-related properties of the fluids.

The coefficient of friction is a function of local conditions at the contact point and is determined by Eq. (3).

$$\mu = \mu_0 S \tag{3}$$

Where, μ_0 is the maximum friction coefficient and S is the slip function. The friction coefficient μ is based on analysis of an EHL point contact while varying the slip, pressure and surface velocity independently. The results for these parameters are shown in Fig. 4 for a specific mineral lubricant oil.

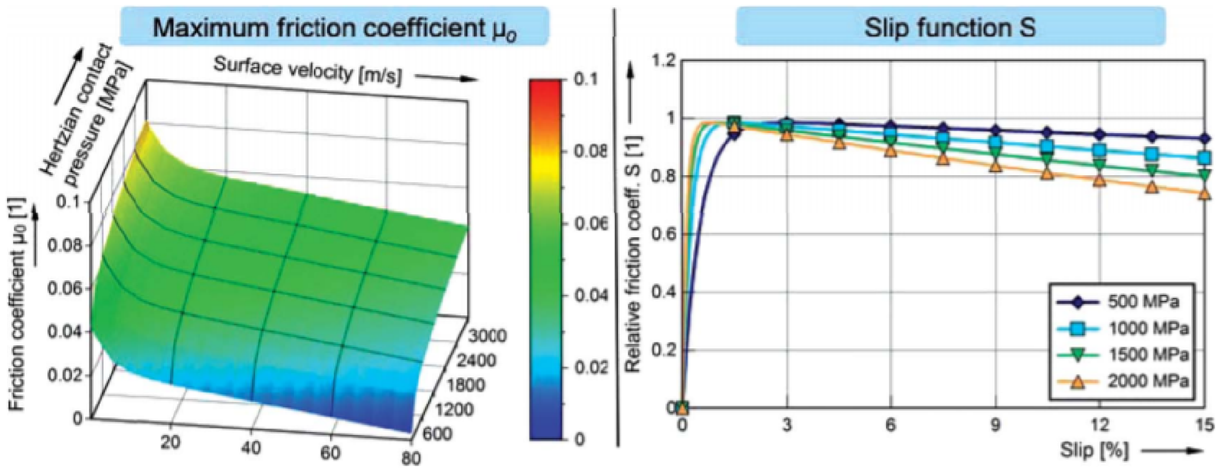

Figure 4. Friction coefficient parameters for Brecher *et al.* model. Source: Brecher *et al.* (2013)

Formulas for the μ_0 and slip function S were derived to map the overall friction behavior in the proposed application. Cage friction was also taken into account, and experimental results validated the friction torque model proposed.

4. DISCUSSION

The complexity of grease and the internal bearing geometry makes it difficult to study the mechanisms of grease lubrication and friction generation. Therefore, several models were developed to attempt to predict film thickness and friction torque.

All the friction models presented were validated for the proposed conditions and assumptions. However they lead to different predictions for the same inputs and operating conditions.

Bearing kinematics have been studied in several articles. But when it comes to friction coefficient, most of them (Damian and Paleu (2014), Bălan *et al.* (2015), Jin *et al.* (2012) and Houpert (1999)) only consider a constant friction value, instead of calculating it for a given operating condition. And when the friction coefficient is calculated, such as in SKF (2016), it does not consider the effect of the other grease components, such as thickener and additives.

As suggested by De Laurentis *et al.* (2017), the friction coefficient for greases does not always behave as shown in Fig. 3. For some greases types, the friction coefficient at lower entrainment speeds is smaller than the ones at higher speeds even for lubricating greases formulated with mineral base oils, which is taken into account at the SKF model. This behavior is typical for oil lubricants as shown by Brandão *et al.* (2012).

The opposite behavior experienced by some greases has not yet been modeled in terms of friction. However, the influence of thickener type and percentage on film thickness has recently been modeled by Cyriac *et al.* (2016). Experimental results showed that grease film thickness was found to be higher than the bled oil film thickness because of the presence of thickener particles in the inlet of the contact. This increase in film thickness found is a function of thickener concentration and grease particle dimensions. A similar approach could be used to model friction torque.

Also, Morales-Espejel *et al.* (2014) evaluates the effective viscosity of the grease in the condition, since the base-oil viscosity does not always represents the grease behavior.

To improve these models, it would be necessary to be able to better understand friction in full film and under starved conditions as well as temperature effects and aging effects in lubricant properties.

5. CONCLUSIONS

The evaluation of friction in grease lubricated rolling bearings is still being developed. There has been efforts by Cyriac *et al.* (2016) and Morales-Espejel *et al.* (2014) to understand the influence of grease thickener on film formation since most of the models developed only consider the base-oil viscosity.

A similar approach could be developed by experimentally studying the effect of grease thickener and additives on the friction torque. By incorporating the effect of grease thickener concentration and particles geometry, it is possible to predict an effective grease viscosity that is supposed to better predict friction coefficient and therefore friction forces. These results could be included on the available friction torque models, so they can better represent grease behavior on rolling bearings.

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