

# The effect of lubricant supply and frequency upon the behaviour of EHD films subjected to vibrations

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**Abstract.** Machine elements such as rolling element bearings or gears often experience vibrations due to for example geometrical inaccuracies, shock loading, rotating unbalanced masses, and others. These machine elements rely on a very thin lubricant film to protect the metallic surfaces from direct contact and eventual damage. During rapid variation of load the elastohydrodynamic contact is influenced by the so-called squeeze film effect, however, when both entrainment and squeeze are present, the conditions of film formation are more complex. It is expected that the lubricant film thickness is influenced by the amplitude and frequency of the vibrations. At the same time, as it is known that the film thickness is established in the inlet of the contact, it is equally important to evaluate what is the role played by the supply of lubricant to the contact under oscillatory conditions. To date there are not many studies on the effect of the oscillatory motion parameters upon the behaviour of the lubricant film. In this study the focus is on the effect of the frequency of vibrations and the supply of lubricant upon the film thickness.

## 1. Introduction

### 1.1. Starved elastohydrodynamic contacts

When two non – conformal surfaces are in relative motion in the presence of a lubricant, the later is dragged within the convergent conjunction generating the so – called hydrodynamic action which permits the complete separation of the surfaces by a thin lubricant film. It has been established that the thickness of this film depends of the conditions in front of the contact, and once the lubricant enters the Hertzian contact area it travels almost unchanged until near the exit of the contact, where a constriction is formed, to accommodate the rapid drop in pressure [1]. When there is plenty of lubricant in the inlet zone the film thickness can be predicted with a good level of confidence if the properties of the lubricant are known. Very often though, lubricated contacts, including elastohydrodynamic contacts, are forced to work in starved conditions. This means that there is not enough lubricant in the inlet zone to feed properly the contact and allow a full film to be formed. Starved lubrication occurs routinely in rolling element bearings, especially those operating at large rotational speed. This is because the passage of one rolling element pushes the lubricant aside and the next element finds its inlet almost depleted of lubricant. This phenomenon is also frequently encountered in grease lubricated bearings, where the liquid lubricant needs some time to bleed from



the structure of the thickener. In starved lubrication conditions the oil film thickness cannot be accurately predicted by full film formulas.

Important research effort has been done in the past for analysing the conditions in which EHD contacts work in starved conditions and evaluating how these conditions affect the lubricant film thickness. Wedeven and co - workers [2] have studied starvation in EHD contact by measuring the central film thickness for various distances in front of the contact where the inlet meniscus is formed. They have found that when the meniscus is located at a distance corresponding to a separation between surfaces  $h_b$  larger than nine times the central film thickness, the contact is in fully flooded condition. On this basis they suggest that the degree of starvation can be evaluated by the inlet distance  $S_f$  which corresponds to the fully flooded condition.

$$S_f = \frac{3.52(Rh_0)^{2/3}}{a^{1/3}}, \quad (1)$$

where  $R$  is the reduced radius of curvature of the surfaces,  $h_0$  is the central film thickness, and  $a$  is the radius of the contact. This is actually the distance where most of the pressure build – up in the inlet takes place. They have found that for zero  $S_f$  the film thickness is null, so for values of this distance between zero and that given by equation (1), the contact is in a greater or lesser degree of starvation.

If the inlet distance of the meniscus is known that Wedeven et al. also suggest an equation for the film thickness, which accounts for starvation effects.

$$\frac{h_0}{(h_0)_f} = \left[ \frac{S}{S_f} \left( 2 - \frac{S}{S_f} \right) \right]^{1/2} \quad (2)$$

As the authors notice it is difficult to get the inlet distance  $S$ , so for many practical applications this equation is not really useful, but for laboratory studies, especially those employing optical interferometry, as it is the case of this paper, this can be used to study the effect of lubricant supply upon elastohydrodynamic contacts.

Studying the transition between fully flooded and starved condition, Cann et al [3], suggest the use of a non-dimensionless parameter, called starvation degree (SD). They observe that the degree of starvation is established by the balance between the oil being removed by the action of the rolling element and replenished by surface tension.

$$SD = \frac{\eta_0 u a}{h_{oil\infty} \sigma_s}, \quad (3)$$

In this equation  $\eta_0$  is the base oil viscosity,  $u$  is the velocity,  $a$  the radius of contact, and  $\sigma_s$  is the surface tension of the metal, oil and air interfaces. As seen this equation does not contain the inlet meniscus distance, but comes with another parameter, even more difficult to obtain, that is the thickness of the oil “ridges” at the sides of the rolling element track,  $h_{oil\infty}$ . The theoretical analysis indicates onset of starvation for degree of starvation  $SD = 1$  however, experimental results show that the transition between fully flooded and starvation occurs for values of  $SD$  between 1.5 and 2. Cann and co – workers suggest that once starvation has occurred (that is for  $SD > 1.5$ ) the film thickness can be evaluated by:

$$\frac{h_c}{h_{eff}} = \left( \frac{1.5}{SD} \right)^{1.67} \quad (4)$$

where  $h_{eff}$  represents fully flooded central film thickness. Peper [4] uses equation (4) to evaluate the lubrication in a regime which he calls ultrastarved. He conducts experiments in which friction coefficient is measured in a contact lubricated with very precisely measured quantity of lubricant of

the order of nano – litres. Somehow surprising he finds that the fully flooded coefficient of friction has the same values as that obtained in ultrastarved conditions.

Using one version of optical interferometry named colorimetric optical interferometry, Svoboda and co – workers carried out detailed experimental investigations on starved EHD lubrication [5]. They found that their results fit well with earlier theoretical predictions by Chevalier et al [6].

Jiang et al [7] have studied starvation of elastohydrodynamic contacts caused by very large speeds up to 30 m/s. They have found that centrifugal forces play an important role, resulting in an asymmetrical oil reservoir which in turns feeds asymmetrically the contact.

### *1.2. Elastohydrodynamic contacts under oscillatory motion*

There are other studies of starvation in elastohydrodynamic contacts but they will not be mentioned here because the main focus of this paper is on the effect that transient conditions may have when the contact works in starved conditions. It has to be mentioned that transient lubrication occurs frequently and practically any EHD contact experiences regularly or accidentally this condition. A comprehensive review, up to that date, of transient lubrication can be found in reference [8]. There are a number of studies on the effect of oscillatory motion upon elastohydrodynamic contacts, but only two tackle the effect of transient condition upon starvation. The study by Cann and Lubrecht [9] on the effect of loading/unloading of a ball – on – disc contact is one of those studies. They used optical interferometry to measure film thickness during cyclic unloading and loading of the ball. This did not resulted in vibrations, as each, loading and unloading took about 2 seconds, but the authors could still see the beneficial effect of cyclic loading upon track replenishment and recovery of lubricant film thickness. They concluded that cycling loading and unloading can be one of the mechanisms which in practice help the lubrication in rolling element bearings subjected to vibrations.

Nagata et al [10] on the other hand used much larger frequencies, up to 50 Hz, but studied the effect of lateral oscillations upon track replenishment in grease – lubricated starved contacts. They measured the lubricant film thickness of a severely starved contact after the onset of the oscillatory motion and found that the lubricant film recovers completely and maintains full film conditions over long periods of time. They also noticed that, in the conditions of the tests, the inlet meniscus distance is not a true indication of the degree of starvation of the contact.

In the current paper the authors present a research into the effect of vibrations, normal to the plane of the film, upon lubricant film thickness in contacts with restricted lubricant supply.

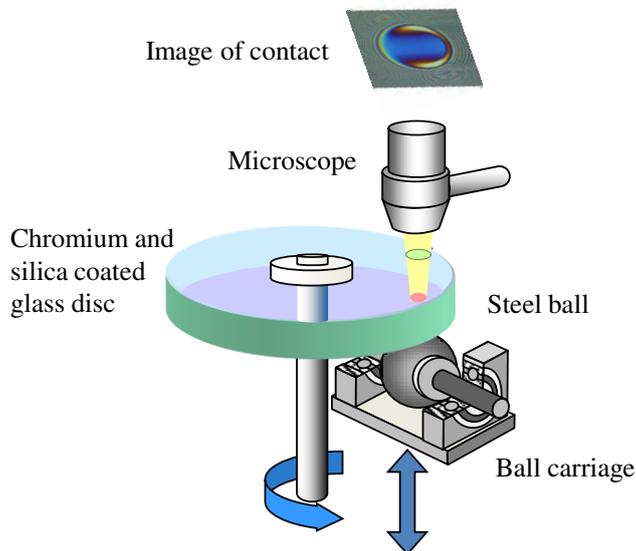
## **2. Experimental method and calibration**

Optical interferometry is the most convenient method for studying elastohydrodynamic lubrication. It can provide film thickness maps of the whole contact so it is best suited for studying starvation as the film is expected to have uneven thickness across the contact. The principles of optical interferometry as it is applied to studying elastohydrodynamic lubrication have been presented in many papers [9, 10]. In the current research white light was used which resulted in coloured images of the contact, which were then converted into film thickness profiles. The EHD contact analysed was formed between a glass disc and a steel ball. The disc is driven at desired rotational speed while the ball moves due to the traction force in the contact, thus the contact is in nominal pure rolling conditions. This allowed the support of the ball to undergo oscillatory motion in a direction perpendicular to the plane of the disc, thus effectively loading and unloading the contact.

A schematic of the experimental method and setup is shown in figure 1. This is not a detailed picture, as in reality the ball shaft is supported by two ball bearings on one side and by a needle bearing on the other. It is done in this way so that the ball support is more rigid than the EHD contact under study, between the ball and the glass disc. As it is custom to the optical interferometry method applied to study of elastohydrodynamic lubrication, the disc is coated by a very thin chromium layer and a silica layer of about 130 nanometres thickness.

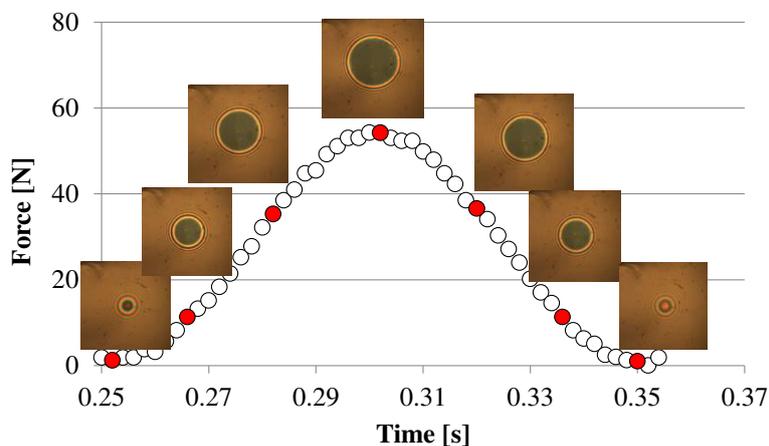
The light is shown onto the contact through a specially built microscope, which also collects the reflected light and directs it towards a high – speed camera. Before the beginning of the tests the

calibration of the colour intensity versus lubricant film thickness was carried out. The procedure of how the calibration is carried out was explained in many other publications [e.g. 10], and will not be repeated here. To note that the calibration is carried out for each oil studied to take into account the difference in refractive index between different fluids.



**Figure 1.** Experimental setup

The load was applied from an electrodynamic shaker through a plunger and lever. In the current experiments the load varied between zero and approximately 50 N. Figure 2 shows the load variation together with the contact diameter in static, dry contact test.

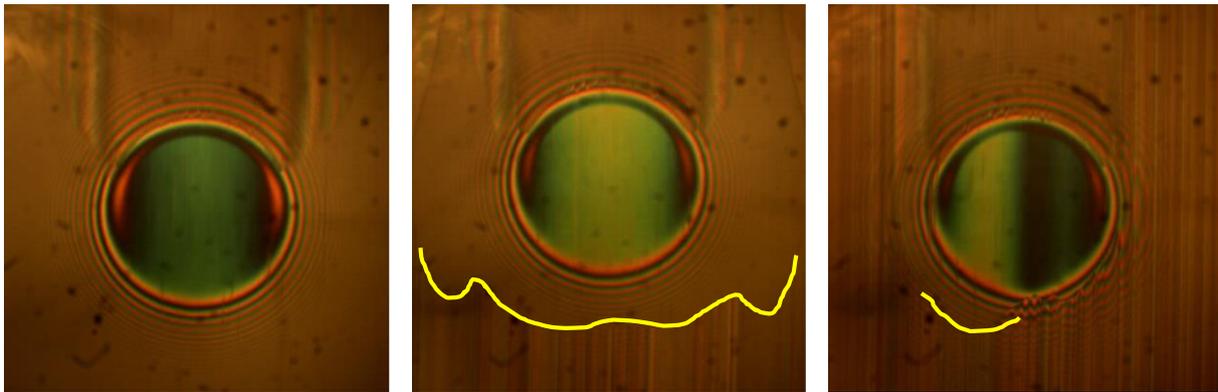


**Figure 2.** Load variation for 10Hz, dry contact.

In the present study the tests were carried out at frequencies of 10 Hz, 25 Hz and 50 Hz. The lubricant used was a synthetic lubricant, poly – alpha – olefin with viscosity 0.396 Pas at 40°C and 0.039 Pas at 100°C. The temperature of the tests was set at 40°C. The ball was about one third immersed into the oil bath and in normal conditions drags the oil into the inlet of the contact ensuring fully flooded conditions. Starved lubrication was obtained by placing wipers in front of the ball and disc. The wipers were flexible, straight – profile sheets of plastic which rubbed against the surfaces of the disc and ball respectively. This was not intended as a method to control the exact quantity of lubricant, but just to make sure that there is little lubricant supply in the inlet. The speed for all tests was 0.1 m/s.

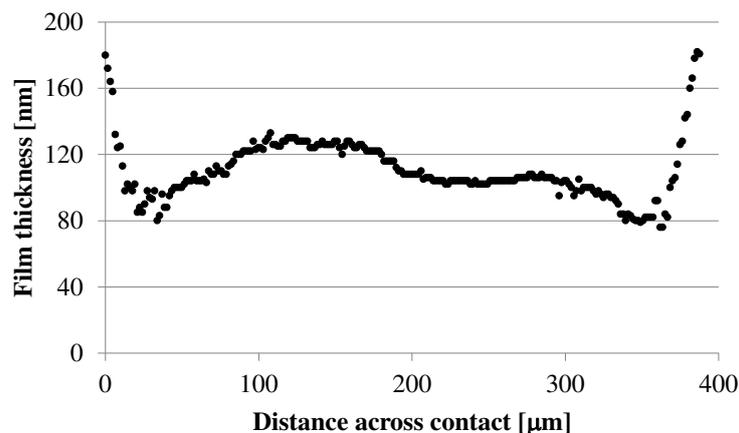
### 3. Results and discussion

Figure 3 shows images of a steady – state contact in three different conditions: fully flooded, partially flooded and starved. In the image on the left hand side the oil fills completely the inlet region and no inlet meniscus boundary can be seen. In the middle image the inlet meniscus boundary is marked by a yellow line for better visibility. This result was obtained with wiper only on the ball. As it can be seen the meniscus is continuous around the contact however, the distance from this boundary to the contact edge is about 59 percent of the contact radius at 109 micrometres. This continuous meniscus ensures a uniform thickness film throughout the contact however the film thickness is smaller than that corresponding to fully flooded conditions. According to equation (2) the film thickness in this case should be approximately 94 percent of the fully flooded condition. The measurement shows values of 214 nanometres for fully flooded and 130 nanometres for limited supply case.



**Figure 3.** Images of the contact showing three different inlet supply conditions.

Finally the image on the right hand side shows a contact with even less lubricant supply, obtained from tests with wipers on both the ball and the disc. The inlet meniscus only covers a small fraction of contact diameter and it is close to the inlet edge of the contact. As seen on the left hand side of the contact inlet the meniscus is located at about 61 micrometres in front of the contact edge. Using again equation (2) the resulted film thickness is 78 percent of fully flooded value. On the right hand side the meniscus disappears almost completely; from the ripples in the Newton's rings the inlet distance can be approximated at less than 25 micrometres. Even for such short inlet meniscus distance the film thickness calculated in this case is about 50 percent of the fully flooded thickness.

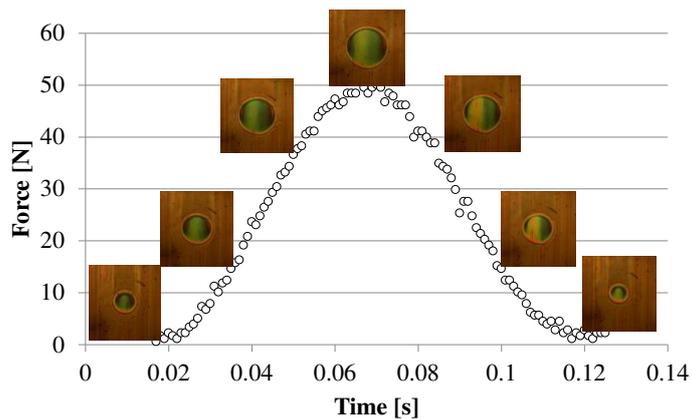


**Figure 4.** Film thickness profile for low lubricant supply (steady – state conditions).

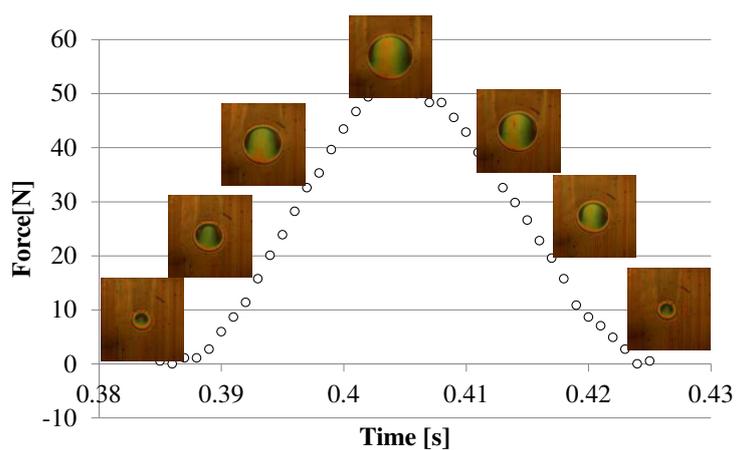
The film thickness profile across the rolling direction, extracted from the right hand side image is shown in figure 4. As seen the film thickness in the central region of the contact varies between 100

and 128 nanometres. These values are less than those predicted by equation (2). Note that  $S_f$  in equation (2) was calculated using the measured central film thickness in fully flooded condition and equation (1).

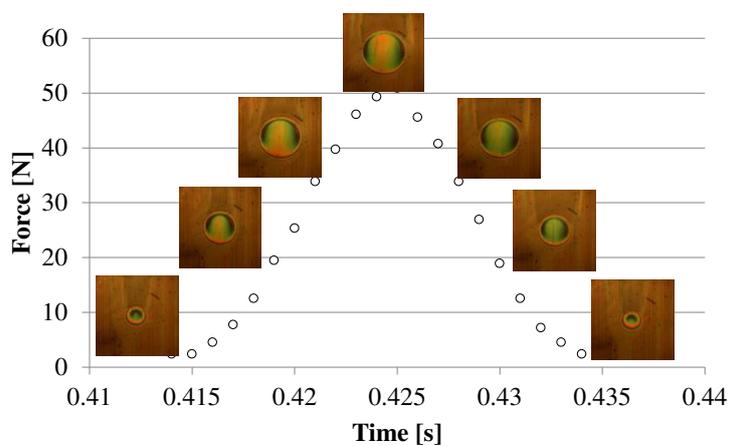
Figures 5 to 7 show the load variation for 10 Hz, 25 Hz and 50 Hz frequency of vibrations respectively. One overall view of these images shows that film thickness is more uniform over the whole contact area, unlike the steady state case. This means that vibrations of the contact have an effect of levelling somehow the quantity of lubricant in the inlet.



**Figure 5.** Load variation and images of contact for 10 Hz.



**Figure 6.** Load variation and images of contact for 25 Hz



**Figure 7.** Load variation and images of contact for 50 Hz.

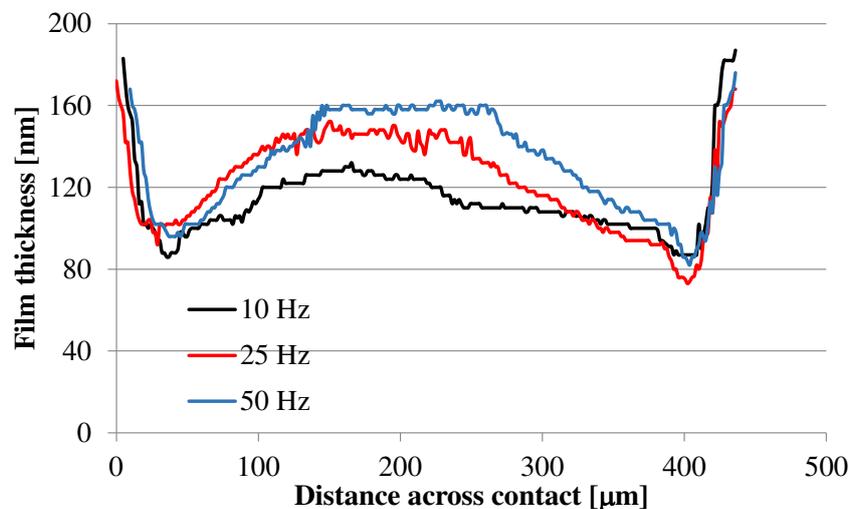
A closer look at the image obtained for the largest loads, for all three frequencies, indeed show that the inlet of the contact is better covered by the inlet meniscus for larger frequencies. Compared with

the steady state meniscus, shown in figure 3 it is clear that vibrations have a beneficial effect upon the lubrication mechanism in limited oil supply conditions.



**Figure 8.** Inlet menisci for three frequencies at peak load.

Film thickness profiles extracted from the images in figure 8 are shown in figure 9. As seen the central film thickness increases with the frequency. It is thought that during the unloading of the load a suction action takes place which enlarges the meniscus of lubricant around the contact, which in turn leads to thicker film thickness. The maximum thickness is about 33 percent larger for 50 Hz than it is for the 10 Hz test.



**Figure 9.** Film thickness profiles for different frequencies.

#### 4. Conclusions

An experimental study on the effect of vibrations upon elastohydrodynamic films behaviour when limited supply of lubricant is available was carried out. High – speed optical interferometry allowed capturing of interferometric images of the contact during rapid variation of the force applied.

The results showed that vibrations have a beneficial role in the formation of the EHD film. It is thought that the a suction action takes place during the load decrease phase, which helps supply the contact inlet, lowers the degree of starvation and results in larger film thickness.

The supply of lubricant to the contact was restricted by placing wipers in front of the ball and disc. The intention was not to achieve severe starved contacts, but to limit the quantity of lubricant in the contact inlet. It is thought that severely starved contacts subjected to vibrations would destroy the

silica layer very quickly, so these conditions were not sought in this study. The authors intend to continue this work at larger frequencies, with different lubricants and at thinner films.

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