CONTROLLING AND MEASURING STARVATION SEVERITY IN EHL CONTACTS

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Starvation is the regime of elastohydrodynamic lubrication which is designated with thinner lubrication films than fully flooded regime. Paper summarizes main aspects of starvation and deals with differences in area of experimental investigation of starved lubrication phenomena in comparison with fully flooded regime. Thinner lubrication film creates obstacles in experiment process and data evaluation. Effect that can be neglected in the fully flooded regime can create obstacles.

Keywords: *elastohydrodynamic lubrication, starvation, replenishment*

1. Introduction

Improvements in the design of mechanical components in the recent times led to the change of distribution of the failures from component body to its surface. Thinner lubrication films are used at the same time which forces engineers to create new designs. They are often required to produce more effective machines with longer life. Therefor it is necessary to make simultaneous progress in understanding of physical phenomena and capabilities in the field of lubrication.

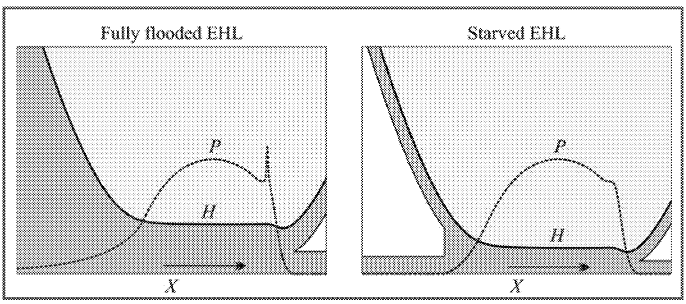

Fig.1: Schematic representation of difference between film thickness and pressure profile in a fully flooded and starved EHL contact [1]

1.1. Elastohydrodynamic lubrication

Elastohydrodynamic lubrication (EHL) is described as contact between non-conformal bodies with very small contact areas and substantial contact pressure. This pressure inflicts elastic deformation of contact surfaces. Increase in the contact pressure also creates positive

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pressure gradient in the lubricant passing through gap between solids which concludes rapid viscosity rise. Increased viscosity of lubricant is positive effect increasing contact capacity. Typical example of EHL contacts can be found in rolling bearings, cam-tappet systems, gears or human joints.

1.2. Starvation

Film thickness in a contact area is determined not only by the contact geometry, velocity, slip ratio, load, temperature, but also by the lubricant supply. Lubricant regime is called fully flooded when all these conditions are close to or ideal. Pressure buildup starts far away from contact area with almost zero pressure gradient (in Fig. 1). This pressure build up provides viscosity rise of lubricant thus creating one of the main conditions for contact capacity. Contacting bodies form meniscus if the inlet is from some reason not filled with the lubricant. Starvation regime is described by closer pressure build up start which can arise only at this boundary. Reduced contact pressure decreases lubricant film thickness in the contact. Film thickness can decrease close to the values of surface roughness heights. Starvation can indirectly inflict additional wear of surfaces which would be completely separated under fully flooded conditions.

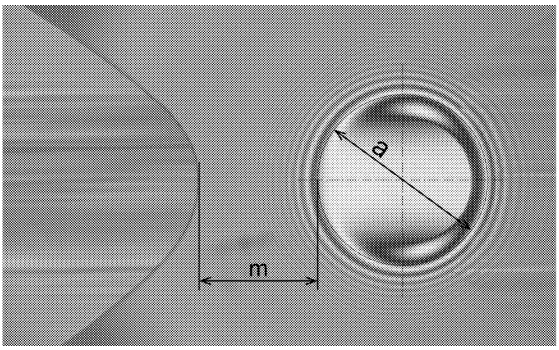

Fig.2: Inlet meniscus position measuring

1.3. Quantifying of starvation

Problems brought by starvation are increasing with starvation severity. Thus one of the important things to help describe starvation is ability to quantify it. There are two main approaches in experimental and analytical area.

Inlet meniscus position is the easiest method. Observing this boundary and measuring its distance from Hertzian area can provide simple method of quantifying starvation. Closer position means shorter pressure buildup and simultaneous increasing of starvation severity. Example of meniscus position can be seen in Fig. 2. More useful than absolute distance can be non-dimensional distance obtained by dividing distance by contact diameter (m/a). Position of inlet meniscus closer than two contact diameters is usually considered as start of starvation. Further position does not influence contact conditions significantly. Position of meniscus is very sensitive method but it can be used only in area of mild starvation and only with combination with optical evaluating methods. This approach cannot be used after point where the meniscus merges with the contact pressure zone.

More versatile approach is film thickness reduction parameter (R). This parameter is ratio of starved film thickness divided by its fully flooded result. Parameter describes whole range of starved levels, literally from fully flooded regime down to parched or dry contact. Disadvantage is necessity of having fully flooded film thickness for the same conditions as starved (same temperature, speed, lubricant properties, etc.).

1.4. Replenishment

Starvation starts in the contact due to insufficient filling of inlet zone by lubricant. The most of real contact works in repeated overrolling. Example is rolling element in bearings which is passing through the same spot on the bearing ring repeatedly. Each of this pass presents decrease in the lubricant film thickness. Rolling element creates depleted track by pushing lubricant to the sides of the track as can be seen in Fig. 3. This would inevitably lead to contact failure after certain number of overrollings. However this is not observed during the experiments. This suggests some kind of lubricant reflow back to the track. Pushing of lubricant away from the track and surface tension driven replenishment are opposite effects. Severity of starvation is smaller if replenishment process is able to pull enough lubricant back to the track between overrollings.

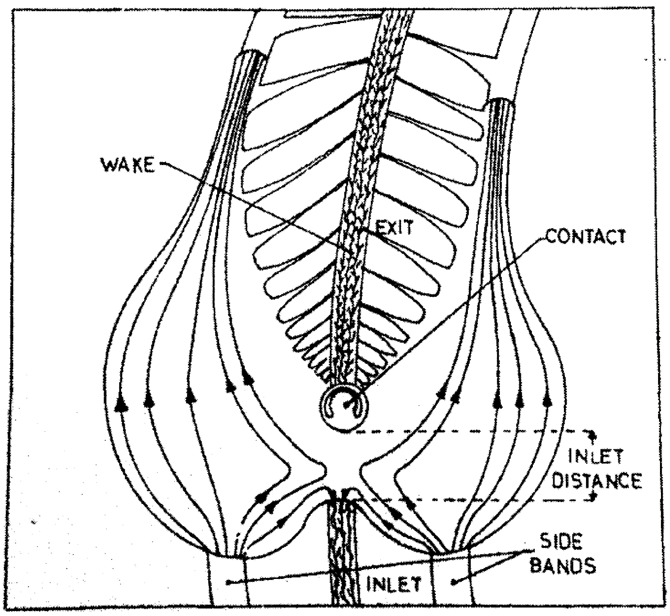

Fig.3: Mechanism of fluid flow around EHL contact [2]

1.5. Current state of knowledge

Study of the fully flooded conditions [3, 4, 5] has already brought fair understanding in modeling and experimental approach. Work on starvation regime is in progress as well. Film thickness and pressure for smooth surfaces can be quite accurately predicted [6, 7, 8]. Some papers has already dealt with the non-smooth surfaces (real or artificial roughness) under starving conditions [9, 10]. Even replenishment process in or outside contact has been considered [11, 12].

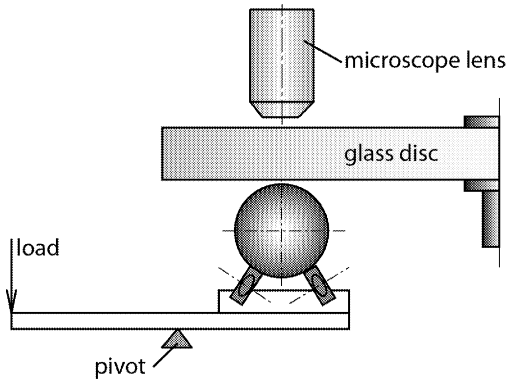

Fig.4: Schematic representation of ball on disc machine

2. Material/Methods

Starvation is usually connected with very thin lubricant films. Therefore optical interferometry [13, 14] is important and useful tool for evaluating lubricant thickness and distribution. Thin film colorimetric interferometry is optical method for evaluating chromatic interferograms in range 0–800 nm with precision of 1 nm.

2.1. Apparatus

Contact simulator equipped with industrial microscope is usually used for obtaining interferograms. This simulator consists of two main parts for creating contact – glass or sapphire disc and rolling element made usually of bearing steel. Scheme of the typical ball-on-disc machine can be seen in the Fig. 4.

Starvation degree in this machine could be controlled by lubricant volume, its viscosity or/and rolling speed. These three parameters influence starvation at most.

2.2. Lubricant volume controlling

When dealing with ball on disc machine and starvation volumes of lubricant are very small. Usual volume varies between 5 and 30 μl. Such volume cannot be dispensed equally to entire track manually. Automatic syringe pump is therefore used and can be seen in the 5. This device is able to dispense continuously volumes at rate from few μl/hour. There is jet at the end of the hose. This jet is injecting lubricant directly in front of the contact inlet. Dispensing can be stopped after reaching certain volume on the track. Method provides very precise control of lubricant volume.

2.3. Rolling speed

Lubricant film thickness is dependent on the rolling speed. According to Hamrock-Dowson's predictive formula, film thickness increasing is with the increase of rolling speed. Starvation is changing the trend of the measured thicknesses when the meniscus reaches the pressure gradient area. At this point, decrease of the thickness even with the simultaneous increase of speed is observed. However, equilibrium between replenishment and starvation process can be seen at some point in the area of severe starvation. Film thickness stabilizes at some small value rather than decrease to zero.

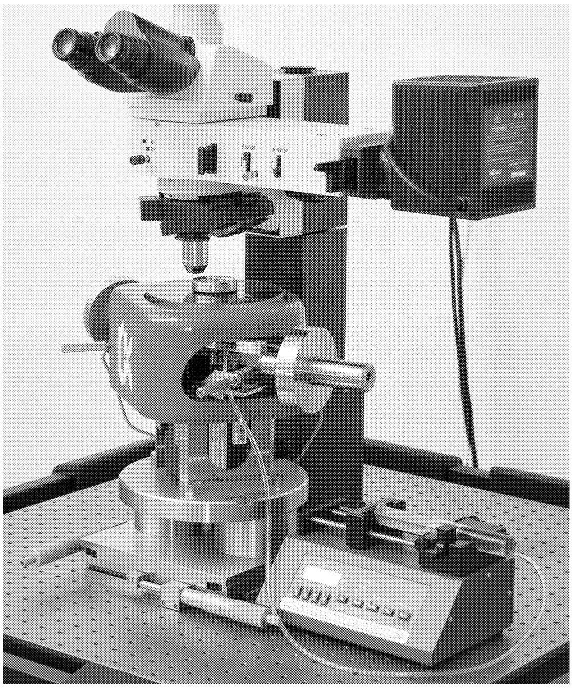

Fig.5: Ball on disc machine with lubricant dispenser (syringe pump in the bottom right part)

3. Results

Obtained interferograms were evaluated by the film thickness colorimetric interferometry [14]. Each color in the picture represents specific thickness of the lubricant. Example can be seen in Fig. 6.

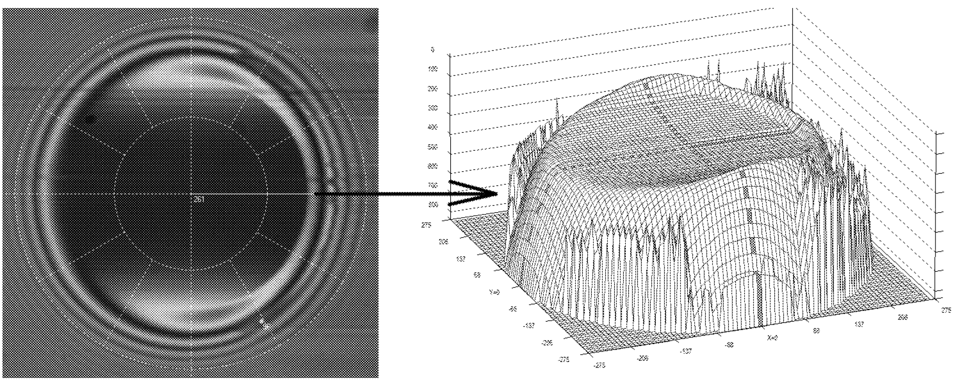

Fig.6: Representation of 2D interferogram in 3D space

Central or minimum vales of the film thickness are studied as a value which depends on speed. The plot with axes central film thickness and speed are shown in Fig. 7. Measured data are represented by points, fully flooded prediction based on Hamrock-Dowson's formula is shown by solid line. The central film thickness follows trend which in log-log axes gives a straight line. Starvation is designated by change of the trend at some point which depends on conditions. After this point the film thickness is decreasing rather than increasing according to the fully flooded prediction.

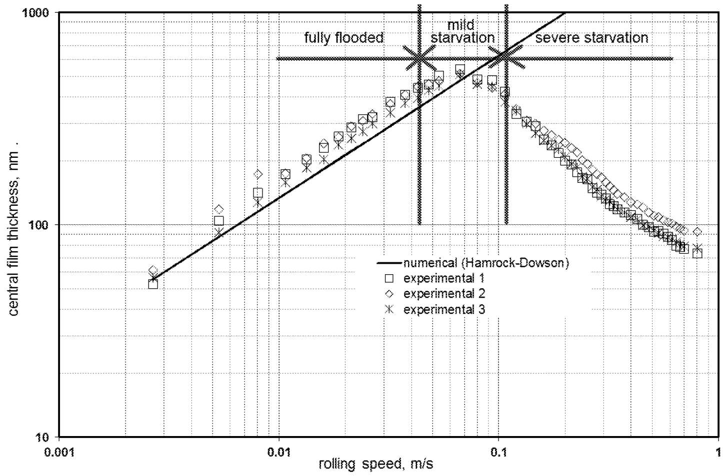

Fig.7: Example of starvation plot

Example of the interferogram from the transient point between fully flooded conditions and starvation can be seen in left Fig. 8 where can be seen distinguishable inlet meniscus approaching contact area. Film thickness starts to decrease rapidly when the inlet meniscus merges with the contact area. This example of severe starvation can be seen in the right Fig. 8.

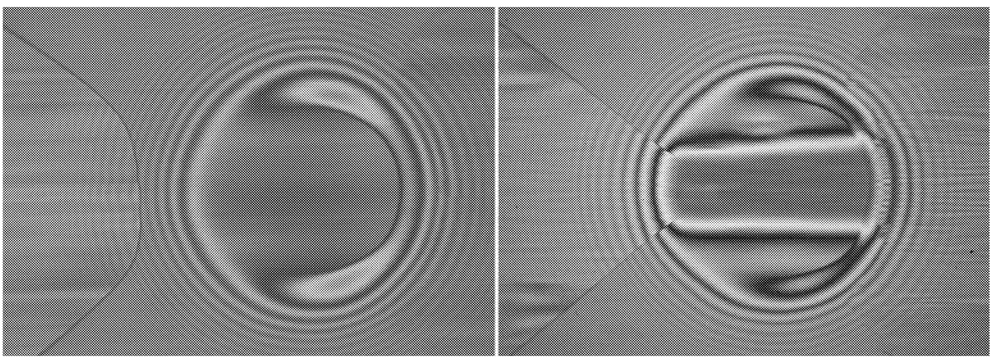

Fig.8: Transition between fully flooded and starving regime (left) and severe starvation (right)

Replenishment process has to be also considered when dealing with the starvation regime of lubrication. Depleted track is continuously supplied by the lubricant from the side banks between overrollings. This effect depends on the lubricant properties and conditions of the experiment. Replenishment can however influence film thickness distribution greatly for some conditions. There is an example of replenished track in front of the contact in the Fig. 9. White arrow on the right represents width of the track at the contact outlet. Size of the arrow on the left at the contact inlet should be the same with no replenishment action. However arrow is significantly shorter. This means relatively strong replenishment action which creates heterogeneous distribution of film thickness across the track. Centre part (bright one) of the contact is severely starving when outer parts are fully flooded at the same time. Complete replenishment of track and fully flooded regime can be expected in the case of further increase of the distance between rolling elements or time between overrollings.

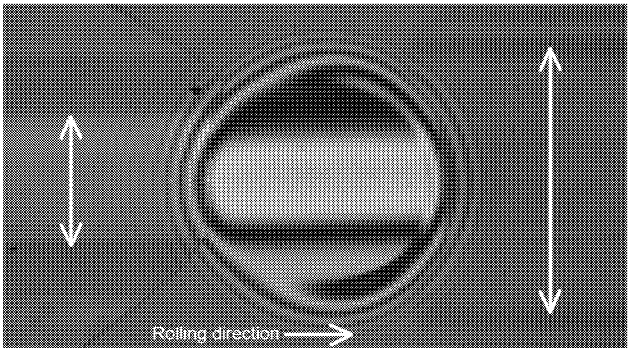

Fig.9: Example of replenishment process

4. Conclusions

This article's introduction provided explanation and summarization of principles necessary to successfully understand starvation phenomena. Starvation and replenishment presents opposite effects in elastohydrodynamically lubricated contacts. Starvation is decreasing the film thickness and replenishment creates positive effects by providing lubricant to the depleted track. Process of starvation is influenced mainly by contact geometry, rolling speed, lubricant viscosity. However, these parameters can be used for controlling it during the experiments.

Two the most used ways of experimental starvation quantifying were presented – the inlet meniscus position and R parameter. Thin film colorimetric interferometry method and ball on disc machine were suggested as the most convenient method to measure starvation.

The results can be divided into three main groups. Not influenced area is designated as fully flooded regime with sufficient amount of lubricant. Transition to starved regime is called mild starvation and is designated with inlet meniscus approaching the contact pressure area. Onset of severe starvation is at point, where the inlet meniscus merges with this area and the film thickness starts do decrease rapidly. Film thickness under severely starved conditions tends to stabilize at some value rather than decrease to zero. This point is the equilibrium of replenishment and starvation effects.

Acknowledgement

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