EXPERIMENTAL OBSERVATION OF ELASTOHYDRODYNAMICALLY LUBRICATED CONTACTS REPLENISHMENT

DAVID KOSTAL, PETR SPERKA,
PETR SVOBODA, IVAN KRUPKA, MARTIN HARTL
Brno University of Technology, Faculty of Mechanical Engineering,
Institute of Machine and Industrial Design, Brno, Czech Republic

DOI: 10.17973/MMSJ.2015_10_201525

e-mail: kostal@fme.vutbr.cz

Starved regime of elastohydrodynamic lubrication (EHL) is usually described by smaller thicknesses of the lubrication film then fully flooded regime. This state can be caused by a number of reasons including operating conditions, lubricant supply or/and its properties. Rolling bearings contain multiple consequent elements which can increase the risk of starvation because the replenishment mechanisms are not able to recover lubricant film after each element passage. One of the main aspects in the rolling bearings is proximity of the rolling elements. Severity of the starvation increases as the mutual elements distance decreases. Lubricant which was squeezed out by rolling element need some time to replenish the gap. This paper presents experimental methods for measuring the time necessary for oil lubricant film recovery. Results obtained by these methods had been compared with existing theory. The theory describes behavior of replenishment of the central film thickness and change in the lubricant distribution across the rolling track. Both of these aspects qualitatively agree. Changes in the central film thickness during replenishment process were theoretically described as very nonlinear process which was confirmed by experiment in this paper.

KEYWORDS
EHL (General), starvation in EHL, ball bearings, replenishment

1. INTRODUCTION

Starved regime of elastohydrodynamic lubrication is usually described by smaller thicknesses of the lubrication film then fully flooded regime. Very often the lubricating film is no longer able to ensure full separation of contact surfaces which leads to their contact, wear, noise, vibration and consequent jamming. If loss outstrips supply this leads to very thin films, which can no longer fulfill their role of separating the surfaces, and thus component failure can result. This state can be caused by a number of reasons including operating conditions, lubricant supply or/and its properties. First who experimentally measured and described starvation were Wedeven [Wedeven 1971], Chiu [Chiu 1974], Pemberton and Cameron [Pemberton 1976]. They observed the film thickness distribution in the starved EHL contact and forming of inlet meniscus.

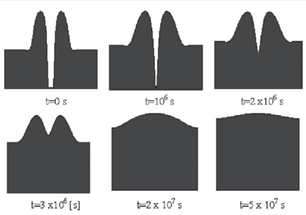

Figure 1. Lubricant film profile during replenishment of the track behind the contact (ball-on-disc) [Gershuni 2008]

Main reason of film thickness decrease in starved regime is insufficient space for pressure build-up in the contact inlet zone. The area in front of the contact where inlet meniscus is formed is considered as the start boundary of the pressure rise. Film thickness profile is approaching hertzian distribution, when meniscus is closing to the contact.

$$R = \frac{h_c}{h_{cff}} \in < 0;1 > \qquad (1)$$

Measurement of the inlet meniscus position is one of the early approaches for quantifying of starvation severity. It was used for example by [Wolveridge 1970] for load capacity assessment of the line contact. This method is however suitable only for mild starvation. Inlet meniscus tends to merge with the pressurized area of the EHD contact when the starvation severity increases. Merging of meniscus and hertzian area prevents exact measuring of the distance. Another approach for such cases can be used. Film thickness reduction parameter R can be obtained when comparing central film thickness of starved contact with the thickness of contact under fully flooded conditions (Eq.1). Value 1 means that contact is fully flooded. Dry contact is represented by value 0. This parameter has advantage against meniscus position approach by means of describing all levels of starvation. Necessity of having fully flooded film thickness could be disadvantage, because it presents needs to conduct another set of experiments to obtain these results.

By neglecting replenishment, the reduction in film thickness is caused by side flow in the contact for which [Zoelen 2009] developed a semi-analytical expression using a thin-film layer model. The side flow from the contact reduces with increasing load due to the rapid increase in viscosity by increasing pressure. As a result of the side flow, the oil layer thickness close to the centerline behind the contact will be thinner than that at the inlet side. However, lubricant that is pushed to the side may flow back into the track. This ability of a lubricant to return to the rolling track is referred as "replenishment" and is very time-dependent. Chevalier [Chevalier 1998] created an equation which describes relative thickness decay according to number of over-rollings. Long-term film thickness decay happens if major volume of lubricant is not able to return to its original position during time between over-rollings. This process leads to gradual increase of the starvation severity and lubrication film failure as the result. First who study replenishment effect was Chiu [Chiu 1974], who showed that main effect is caused by surface tension and speed is decreasing as the lubricant viscosity increases. When time between over-rollings or successive elements spacing in bearing is too short, starvation becomes more severe. The replenishment mechanism need some time to close the gap, which element passage created. The formation of ridges was also observed by Guangteng [Guangteng 1996] in their experimental work. However, they could only get starvation at very high speeds. Gershuni [Gershuni 2008] theoretically showed that replenishment process is extremely nonlinear. There is rapid change of the central film thickness in lubricant layer during replenishment process. This point was called "take-off time" and it can be seen in Fig.1, where major change in the lubricant film profile happens between time steps 2x10e6 and 3x10e6. Steps in this figure represents cross-section of the film profile after passage of the rolling element. It can be seen that times of the steps are extremely long, which could be caused by neglecting of the in-contact-replenishment. Change in the central film thickness as function of time can be seen in Fig.2. There is rapid change of the thickness of the lubricant layer in the center of the track during replenishment process. Gershuni [Gershuni 2008] defined the take-off time as time, where is measurable increase in the central film thickness by 20% in comparison to depleted track which is on the left part of the curve.

Replenishment process can be speed up by artificial channeling of the available lubricant towards center of the depleted track. Ali [Ali 2013] showed that small wiper can significantly enhance replenishment and decrease the starvation severity.

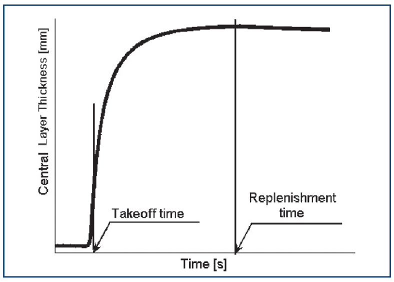

Figure 2. Thickness of the lubricant layer (hc) in the center of the track as a function of time [Gershuni 2008]

The replenishment can be differentiated to the two basic types according to the area where it occurs [Jacod 1999]. In-contact and out-of-contact replenishment provide very different contribution to the combined replenishment effect according to the contact(s) layout.

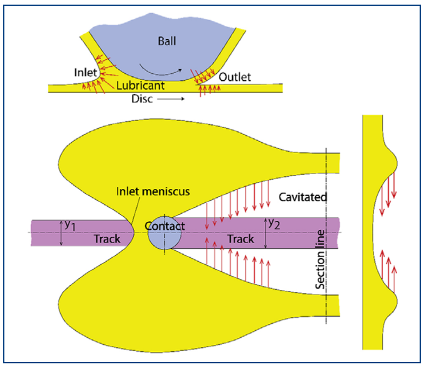

Figure 3. In-contact (top) and out-of-contact replenishment (bottom). Driving forces for each one are illustrated as groups of arrows

As can be seen in Fig.3 in-contact replenishment occurs in the vicinity of the contact in the gap between rolling element close to the contact pressurized region. Main drive force of this replenishment type is capillary action. In-contact replenishment is expected to have similar effect for different delays between over-rollings because the fact that area of its influence is located only close to the contact region. Lubricant behavior in the area close to the contact was observed by Pemberton and Cameron [Pemberton 1976]. They observed separation of the lubricant into two side banks behind the contact. These side banks merges at the contact inlet after one over-rolling in the case of sufficiently low speed. This is however not happening for high speeds which creates further decrease in the film thickness and deterioration of the starvation.

Out-of-contact reflow occurs only between over-rollings in case of single contact or between two subsequent contacts in case of multiple contacts. In Fig.3 which represents layout during common experiment can be seen that track width at the contact inlet is narrower then at the contact outlet. That suggests some kind of reflow in the contact's outer regions. Therefore the dedicated area for this kind is the free lubricant layer and it is driven by surface tension between two side banks [Jacod 1999]. Influence of out-of-contact replenishment on the combined effect can differ significantly. One of the most important parameters is the time between passages of the element through the same place on the opposite surface.

As were mentioned above Gershuni et al. [Gershuni 2008] verified their theoretical results by experiments on optical profilometer. They stated that there is substantial time delay between taking the disc from test apparatus and measurements (~10 min) and therefore, they only evaluated two profiles relatively between each other.

Aim of this work is to experimentally describe and quantify out of contact replenishment behavior by means of different time delays. Compared with the previous study the advantage of this experimental work is based on in-situ measurement which is more reliable and can be used for much shorter times and as zero time can be taken rolling element passage.

2. MATERIAL AND METHODS

The lubricant layer thickness of EHL contacts was observed using an optical ball on disc rig with two rolling elements (Fig.4) because the fact that only device capable of changing two contacts mutual distance allows to study of out-of-contact replenishment.

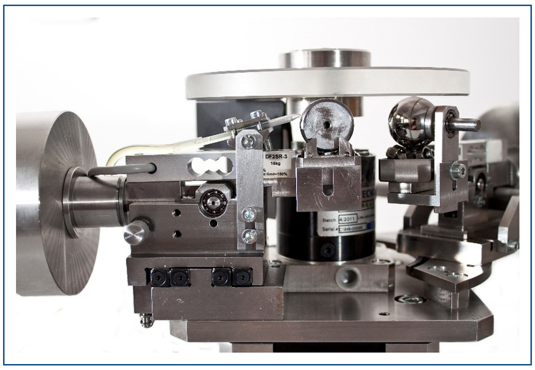

Figure 4. Ball on disc rig with two rolling elements

Each element can be loaded independently and distance between them can be adjusted in order to regulate the mutual spacing. Moreover second element can be moved perpendicularly to the rolling direction by micrometric screw in order to precisely align with the first element's track. The experimental device is expected to operate close to pure rolling conditions. Despite the fact that only the glass disk is driven by a servomotor (Fig.5), measured surface velocities difference was up to 4 % which can be neglected. Spherical roller or ball can be used as rolling element at both levers. Applied load is measured by embedded strain gauge sensors. Entire rig can be turned around disc rotational axis. This ability allows us to observe both contacts by one fixed microscope system in rapid sequence. See [Svoboda 2013] for more detailed description of the experimental rig and method.

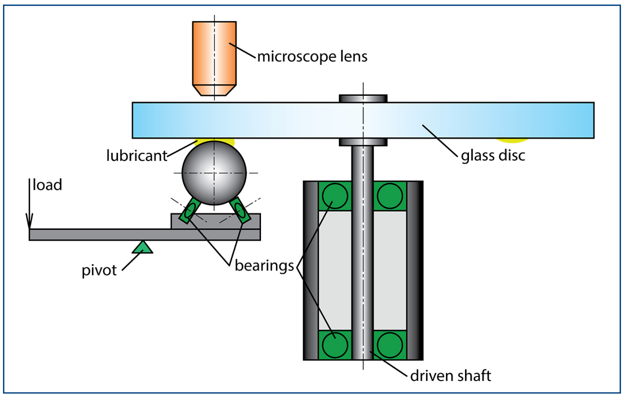

Figure 5. Contact simulator scheme

	Modulus of elasticity [GPa]	Poisson ratio [-]
Ball / spherical roller	210	0.3
Disc	81	0.208

Table 1. Mechanical properties of contact couple

Contacts were examined by microscope imaging system based on the industrial microscope. The change of film behavior was captured by high speed camera. The thin film colorimetric interferometry was used for film thickness evaluation [Hartl 1997, Hartl 2001]. This technique enables film thickness evaluation in the range between 1 and 800 nm with an accuracy of 1 nm. It is based on colorimetric analysis of chromatic interferograms using appropriate color matching algorithm and CIELAB color film thickness calibration. All experiments were carried out with steel spherical rollers or balls and glass disc. Mechanical properties of contact materials are in Tab.1. Surface roughness (Ra) was always less than 10 nm for both surfaces. Diameter of rolling elements is 25,4 mm for both ball and spherical roller in rolling direction. Contact were loaded with force of 27 N in all cases.

As a lubricant for all experiments was used mineral base oil R834/80 with ambient viscosity of 0.19 Pa·s at 22 °C and volume of 10 μl. Temperature in the room was maintained at 22°C all the time during the experiments by air condition. Device is of very open construction and it is assumed that it works at very similar temperature as room temperature. This paper is limited on the description of oil replenishment, therefore no greases were applied.

3. RESULTS AND DISCUSSION

Results are split into two groups by the severity of starvation. The easiest division is to mild and severe starvation. Mild starvation is usually described by recognizable inlet meniscus which is not yet merged with hertzian pressure area. Onset of severe starvation is from the point where meniscus merges with the contact zone and rapid film thickness decrease starts.

3.1 Mild starvation – meniscus position

In the mild starvation area the meniscus is separated from contact and this separation is decreasing with progressing starvation. The effect of this is reduction of the lubricant film thickness. Therefore, meniscus position can be used as a tool for starvation severity evaluation. Change in the position of the meniscus is however very sensitive to change of the central film thickness. It means that change in the meniscus position can lead to almost non-measurable change in the central film thickness which provides conveniently sensitive tool for evaluating small change in the starvation severity caused by operating conditions (Fig.6). Experimental setup shown in Fig.7 with constant distance of two balls (marked as track length) in one rolling track was used. Distance between elements was 35 mm. Entire rolling track length (circumference) is 330 mm. Therefore the time between first and second contact was approx. nine times shorter than time between second and first contact.

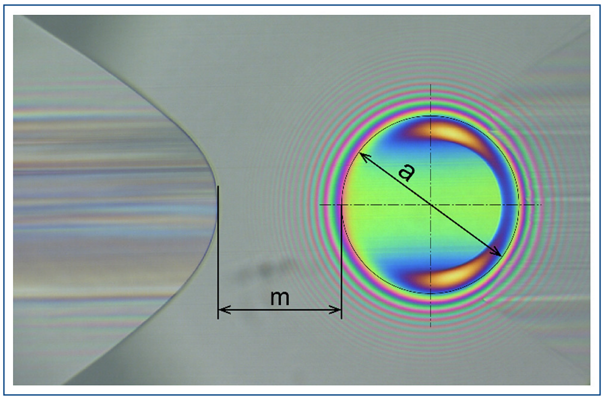

Figure 6. Meniscus position measurement

Different levels of starvation in area of mild starvation were obtained by change of rolling speed. This provided the desired change in the meniscus distance for both contacts. From the results in Fig.8 can be seen that meniscus position for the first element is further from contact then for the second element under same conditions. This could be explained by the track length in front of the contact. Longer length means longer time thus higher replenishment action. This action delivers more lubricant further to the center of the rolling track. More lubricant in the track means increase of inlet film thickness, which causes retrieve of the meniscus further from the contact zone. Therefore, lower meniscus position value can be represented as higher starvation level.

However this method can be used only for mild starvation. In Fig.8 can be seen that as rolling speed increases, difference in the meniscus positions is decreasing. Difference for values of rolling speed higher than 0.05 m/s (starvation parameter R<0.5) cannot be evaluated because insufficient system sensitivity. Starvation level is increasing with increasing speed and meniscus is closing to the contact zone. Speed of 0.05 m/s presents transition between mild and severe starvation for this conditions, when meniscus starts to merge with Hertzian area. Therefore meniscus position cannot be used as tool for higher speeds.

Evaluation of meniscus position for two contacts however showed that there is some influence of out-of-contact replenishment to starved film thickness. Next chapters describe attempt to experimentally obtain film thickness replenishment curve from Fig.1.

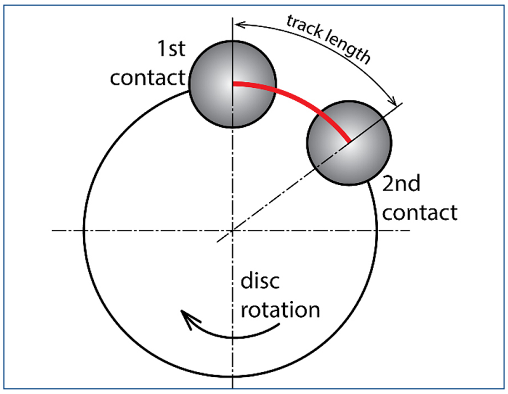

Figure 7. Double contact configuration for mild starvation

3.2 Severe starvation – double contact

Instead of inlet meniscus position method, the film thickness reduction parameter R according to Eq.1 as function of time was used. This ratio was obtained for different times by changing contacts mutual distance at fixed rolling speed of 0.4 m/s. This speed was chosen as optimal to achieve starvation which is necessary to obtain track in lubricant and contrary to previous method can be quantified by R parameter without issues. Changing the distance from 30–300 mm (0.05 – 0.7s) showed almost the same film thickness reduction of R=0.2. This could mean that time for replenishment action is too short. From this we can conclude that data may be well placed in a part of the curve in Fig.2 before the take-off time because there is no change either in this part of plot. Another experimental approach was used to obtain longer distance and confirm replenishment process illustrated in Fig.1.

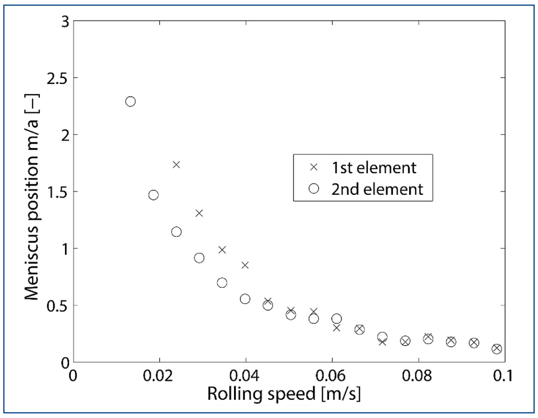

Figure 8. Meniscus position as function of rolling speed for two contacts in one rolling track

3.3 Severe starvation – single contact

Maximal possible length of the rolling track was already used in previous chapter however still with no change in starvation level between elements. Lowering the speed is not an option because starvation, which is necessary for creating of the track in the lubricant, cannot be achieved under lower speed. Another approach is to measure only with one element. Increase of the track length (or time) is virtually possible by retracting rolling element from the contact through lever system and reconnecting it back after selected time or number of disc over-rollings. Time with disconnected element can be considered as time reserved for replenishment action. The track is left without over-rolling element and it has time to recover due to replenishment. Interferograms were then captured in rapid sequence (4000 frames per second) by the high-speed camera. The one evaluated interferogram was selected from the time corresponding to half of the ball rotation after reconnecting back to the rolling track. This method provides possibility to neglect slip of the ball in the first milliseconds after ball reconnecting and fully loaded state. However this short time of slippage is probably the reason that interferograms are showing low level of starvation in the form of meniscus on the edge of the visible area. Another reason to wait for half rotation of the ball is to avoid oil shape features on the ball surface which could be created during disconnecting due to surface tension. The same features can be expected on the disc surface, but disc is still rotating, so this features moves to different position and the ball connects back to different spot in the track. The values of central film thickness from interferograms are then plotted in the same graph together with results from previous chapter. This plot can be seen in Fig.9. Similarity with the shape of the curve in Fig.2 is clear. Area close to the take-off time is not so steep in comparison with the one from Fig.2 but this is probably caused by the smaller number of points. It can be expected that more experiments would refine line to the shape presented in Fig.2. Reason for the maximum value of R<1 are probably the mentioned unsteady conditions during the reconnecting of the rolling element which made the evaluation difficult. However more important is that they can cause the prevailing starvation.

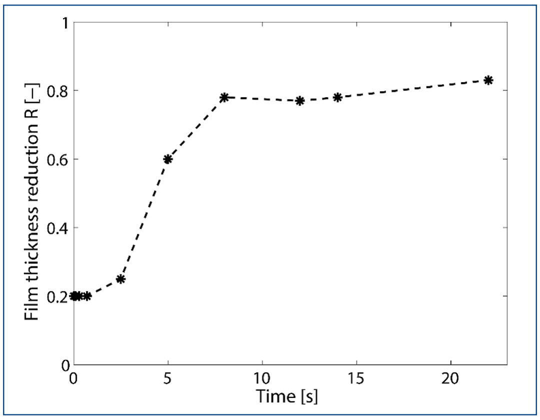

Figure 9. Replenishment caused change in the central film thickness for different delays

3.4 Film thickness profiles

Central film thickness behavior is extremely nonlinear around take-off time. This is usually explained by following process. Depleted track in the lubricant film is created after passage of the rolling element. Replenishment action starts to move the side banks of the lubricant closer together in the direction perpendicular to the rolling track. However central part of the track is still depleted. This is main cause of the short time with no change in central film thickness. Narrow groove is created when the side banks meet in the center of the track. Surface tension causes increasing speed in closing of this gap thus rapid change in the behavior (take-off time) can be observed. There is only slow equalization of the lubricant distribution on the disc after this point. This process is briefly illustrated in Fig. 10. Arrows and their relative sizes in the each step represents resulting forces and their magnitudes acting on the surface of the liquid during key steps in the replenishment process.

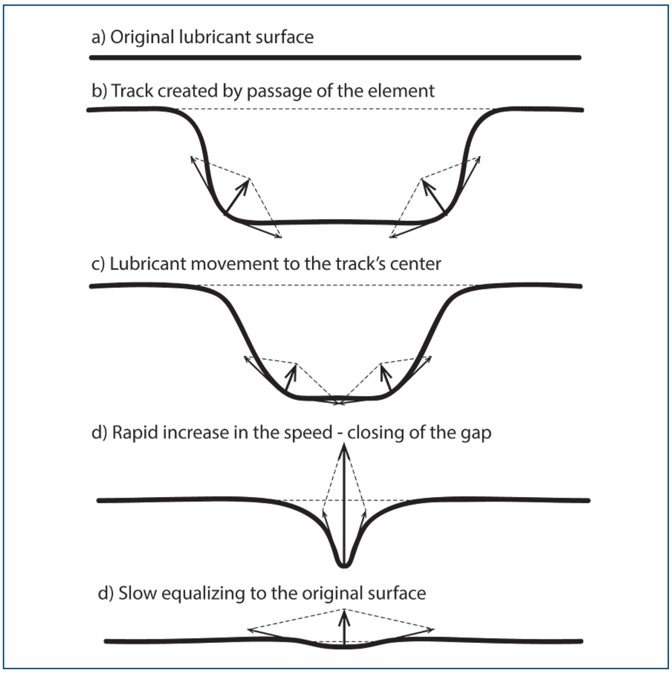

Figure 10. Description of the steps during film recovery due to surface tension

Improved way for complex description of this behavior is evaluation of entire film thickness profile – not just the central thickness. Spherical roller instead of the ball was used in this experiment. Depleted track was created not by the ball as in previous, but rather spherical roller was used as a reconnecting element after specific time delay. This type of element creates significantly wider contact area thus provides better visualization of film thickness profile, especially on the sides. Reconnecting of the same element can lead into small change of the contact position and the element can be slightly eccentric to the track. This misalignment is insignificant due to wider track of the spherical roller. Interferograms of the film thickness distribution are shown in Fig.11. There is recognizable track created by the ball on the left side of the each interferogram (inlet). This track is represented by slightly brighter area in comparison with the rest of a contact vicinity. Starving area is on the other hand represented by dark region in the center of the each contact. It is clear that this area is smaller for longer times. Replenishment progress can be seen in the interferograms or better in Fig.12. This figure provides vertical sections through the center of the contacts from Fig. 11. These sections could be compared with those showed in Fig. 1. There are no side banks on the evaluated section because only contact geometry can be evaluated. However there are obvious similarities of the shape in the profiles.

Only shape of the profile can be considered because there is inconsistency between ball profile and the spherical roller profile, which was used. Spherical roller creates lower contact pressure in comparison with the ball, which results in higher lubricant film thickness. Curve from Fig. 2 cannot be therefore created by this method, because profiles of the ball and the spherical roller are not comparable, but it is still useful to see profiles shapes.

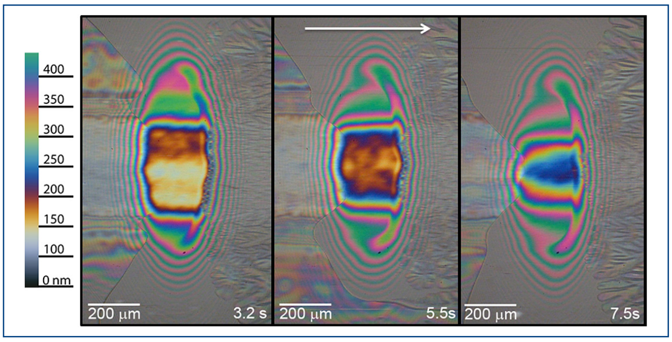

Figure 11. Distribution of film thickness for three different delays

4. SUMMARY AND CONCLUSION

This paper presents three different experimental approaches to study out-of-contact replenishment. The aim was to experimentally obtain theoretical curve shown in Fig.2. Used experimental approaches enables measurements of take-off time and replenishment time. Take-off time for the current configuration of experiment was 3 seconds and full replenishment time roughly 8 seconds. Behavior of the central film thickness change during replenishment action was measured experimentally and discussed. Results of these experiments are presented in Fig.9 and they qualitatively agree with theory. Explanation of the behavior was moreover confirmed by measuring full profile of the lubricant film thickness. These measurements proved the assumption about the movement of the side banks to the center of the track.

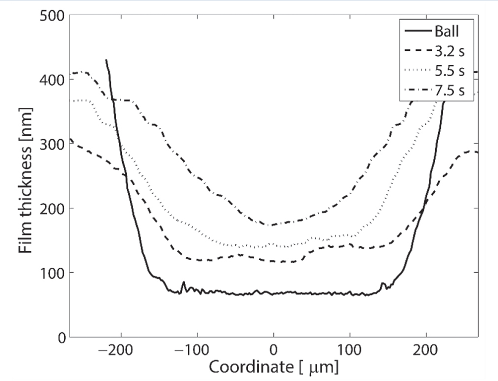

Figure 12. Film thickness profiles of the contact between disc and spherical roller for different time delays (Full line is the film thickness profile between the disc and the ball and can be interpreted as initial track)

Behavior of the out-of-contact replenishment could be summarized to three main area:

- Before take-off time is central film thickness constant. There is change in the film thickness only on the sides of the track. Side banks created by passage of the element are moving closer together.
- Rapid rise of the central film thickness occurs when they meet in the center of the track. Mainly surface tension driven replenishment in this moment causes fast closing of the gap in lubricant layer. This is designated as take-off time.
- This point is followed by slow leveling of the surface layer into flat and there are no substantial variations at this moment.

Conclusion for the practical application is, that duration between the over-rollings longer than the take-off time, will produce the progressing starvation of the contacts. Rolling bearing is however more complicated geometry in comparison to the experimental apparatus used in this study therefore, results cannot be applied simply. There is for example influence of the cage, which can cause redistribution of the lubricant during element's rotation, effect of the ball's spin, or the extremely high body forces perpendicular to the lubricant's surface caused by rotation at high speeds. All of these effects are not considered in this work and should be studied as next step.

Measured time of 3 seconds is however extremely high considering for example operating conditions of rolling bearings. Over-rollings in the bearings can be in orders of milliseconds, which, without any other effect that could speed-up replenishment process, suggests operating regime as severe starvation and starvation presents risk of surface damage due to insufficient film thickness. As conclusion of this work can be stated, that out-of-contact replenishment itself is very slow process to provide sufficient reflow of the lubricant in the rolling bearing.

5. NOMENCLATURE

h_c – measured central film thickness of starved contact

h_{cff} – central film thickness of fully flooded contact under equivalent conditions to starved contact

R – central film thickness reduction parameter, also called as level of starvation (h_c/h_{cff})

a – contact Hertzian area diameter (Fig. 6)

m – distance of inlet meniscus from contact area (Fig. 6)

ACKNOWLEDGMENT

The research leading to these results has received funding from the Ministry of Education, Youth and Sports under the National Sustainability Programme I (Project LO1202).

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CONTACTS:

Ing. David Kostal
Ing. Petr Sperka, Ph.D.
Ing. Petr Svoboda, Ph.D.
prof. Ing. Ivan Krupka, Ph.D.
prof. Ing. Martin Hartl, Ph.D.

Brno University of Technology, Faculty of Mechanical Engineering
Institute of Machine and Industrial Design
Technicka 2896/2, 616 69 Brno, Czech Republic
tel.: +420 54114 3227, email: kostal@fme.vutbr.cz
tel.: +420 54114 3238, email: sperka@fme.vutbr.cz,
tel.: +420 54114 3215, email: svoboda.pe@fme.vutbr.cz,
tel.: +420 54114 2723, email: krupka@fme.vutbr.cz
tel.: +420 54114 2769, email: hartl@fme.vutbr.cz
http://uk.fme.vutbr.cz/