IOP Conf. Series: Materials Science and Engineering **724** (2020) 012039 doi:10.1088/1757-899X/724/1/012039

An Experimental Approach to Predict the Behaviour of EHD Contacts under Harmonic Loading

X Zhang, R Glovnea

Department of Engineering and Design, University of Sussex, Brighton, BN1 9QT United Kingdom

E-mail: Xingnan.Zhang@sussex.ac.uk, R.P.Glovnea@sussex.ac.uk

Abstract. Rolling element bearings, gears and other machine components operate in the lubrication regime known as elastohydrodynamic (EHD), where lubricant film thickness is governed by the hydrodynamic action of the converging surfaces, the elastic deformation of the non-conforming surfaces and the increase of lubricant's viscosity with pressure. Classic EHD theory indicates that under the assumption of fully flooded conditions in the contact inlet zone the central film thickness increases with the product of entrainment speed and dynamic viscosity and is very little dependent of load variations. EHD lubricating films most often work under transient conditions of load, geometry or speed. These make the behaviour of the lubricant film different from steady-state conditions. Previous studies showed that the squeeze effect generates film perturbations due to entrapment of lubricant inside the contact. This phenomenon becomes significant when both entrainment and squeeze are presented. In practical applications, this type of film perturbation will generate pressure fluctuations, which in turn may influences the fatigue life of the contact. In the present paper the results of a systematic experimental study for predicting the occurrence of film thickness perturbation phenomenon under variable load condition are shown. In the case of a mean load larger than the amplitude of the load variation, it was found that the film perturbation depends of the frequency of the load cycle, the entrainment speed of the lubricant and the overall lubricant film thickness; it also depends of the ratios between the mean load and the amplitude. Film perturbations occur in contacts for which the ratio between half the load cycle period and the average time of transit of the lubricant through the contact in the loading phase of the vibration is less than 2. In the case of mean load smaller than the amplitude, film thickness perturbation has been observed in every single test regardless of entrainment speed, frequency and lubricant viscosity.

1. Introduction

The regime of EHD lubrication under steady-state conditions has now been well understood for more than six decades. Many experimental and numerical studies have been carried out to predict EHD film formation. In reality, EHD-lubricated contacts rarely operate in steady-state conditions; in rolling bearings, it is known that the contacts between the rolling elements and raceways are cyclically loaded/unloaded as the former pass through the loaded zone of the bearing, while in gears, the geometry and operation of these elements makes them prone to cyclic load variation, shock loading and vibrations.

IOP Conf. Series: Materials Science and Engineering **724** (2020) 012039 doi:10.1088/1757-899X/724/1/012039

It is well known that the load change has small influence on steady state film thickness. Probably this is why the number of experimental studies carried out on the aspect of vibrating EHD films is much lower than the other transient effects on EHD films. However, load variation due to vibrations of EHD contacts may be more relevant to practical applications. The experimental studies carried out in the past on the effect of dynamic variation of load on the behaviour of EHD point contact can be divided into studies on, pure squeeze motion, pure squeeze motion combined with sliding motion, free vibration with pure rolling motion and forced sinusoidal vibrations.

Larson and Lundberg [1] carried out an experimental study of squeeze films resulted by the impact between a steel ball and a flat glass surface. Dimples observed at the centre of the contact were analysed with a test rig based on optical interferometry technique. A detailed discussion regarding the effect of various parameter on dimple's geometry was given. Kaneta et al [2] also applied optical interferometry technique to directly observe the effect of impact loads on point EHD contact films in two experimental working conditions, that is pure impact to an oily Hertzian contact and impact load under pure rolling conditions. For pure impact conditions, a central dimple was formed, and the maximum film thickness was found at the center of the contact region. For impact under pure rolling condition, a crescent-shaped oil entrapment formed at the inlet of the contact region, which subsequently passed through the contact at approximately the entrainment speed. Sanborn and Winer [3] carried out an experimental investigation to measure of film thickness profile of an EHD point contact during transient loading under pure sliding condition. During transient loading, Hertzian pressure of the EHD contact varied from zero to maximum of 1.03 GPa in about 45 ms. The results showed that there was a negligible effect of transient loading on the lubricant film thickness profile. Wijnant et al. [4] experimentally studied the effects of structural vibrations on the EHD film thickness in pure rolling conditions. Experimental results of film thickness were qualitatively compared with theoretical contact predictions obtained by numerical simulations. The initial load applied was 45 N and transiently increased to 165 N. Results showed that the sudden increase of the load lead to an expansion in contact region consequently inducing film thickness changes propagated along the entraining direction. Kilali et al. [5] developed an optical based EHD rig to study the dynamic response of the contact under harmonic loading. For pure rolling contact conditions, after a shock load, a disturbance of film thickness was observed travelling along the direction of rolling. Sakamoto et al. [6] studied the effect of pulsating and impact loads on EHD point contact under pure rolling condition by optical interferometry technique. More recently, the work carried out in [7] was the only one regarding the effect of sinusoidal variable loading on EHD film, however, the experimental described was rather limited. Fryza et al. [8] experimentally studied the effects of lubricant rheology and impact speed on EHD film thickness at pure squeeze action. Result showed that the entrapped film shape directly depends on loading speed and the central film thickness is mainly determined by the approaching speed.

In the present paper, a systematic experimental study for predicting the occurrence of film thickness perturbation phenomenon under variable load condition has been carried out. The range of frequencies applied in this paper is between 10 Hz and 100 Hz. A summary of occurrence of film thickness perturbation based on results of various types of lubricant is given.

2. Experimental setup and testing conditions

The experimental rig employed in this paper of measuring lubricant film thickness and observing film thickness perturbation phenomenon was built based on optical interferometry technique. The principle of optical interferometry is widely known by the current research field, which can be found from papers such as [9-11]. Spacer layer imaging technique (SLIM) [12] as showed in figure 1(a) was applied to evaluate EHD film thickness during vibration motion which takes advantage of the high precision of another method of measuring lubricant film thickness called Ultra-Thin-Film Interferometry [13]. The schematic of the employed experimental rig is showed in figure 1(b). For the detailed film thickness calibration procedure accuracy, test equipment information and dry contact dimension analysis during vibration can be found in [14]. In brief, the contact was formed between a glass disc and a 19.05 mm diameter steel ball.

Table 1 shows all the performed experiments regarding EHD film subjected to harmonic loading with different lubricants, entrainment speed between 0.05 m/s and 0.5 m/s, frequency range from 10 Hz to 100 Hz. In road vehicles, the IC engine most often runs at its peak efficiency and performance at speed between about 2700 rpm and 3000 rpm. This means that loading/unloading cycles of the shaft supporting the bearings as well as vibrations due to unbalanced masses have most often frequencies anywhere between 5 Hz and 100 Hz, which justifies the choice of the frequency range employed.

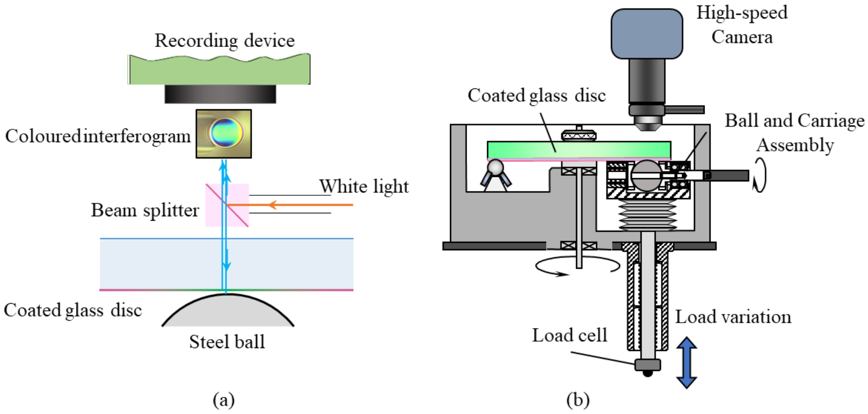


Figure 1. (a) SLIM technique (b) Schematic of experimental rig

Table 1. Performed experiments of EHD film subjected to harmonic loading.

Lubricant	Viscosity	Speed	10 Hz	25 Hz	50 Hz	100 Hz
Lubricant 1	955.7 mm^2/s	0.05 m/s	•	•	•	•
		0.1 m/s	•	•	•	•
		0.2 m/s	•	•	•	•
		0.3 m/s	•	•	•	•
		0.5 m/s	•	•	•	•
Lubricant 2	484.2 mm^2/s	0.05 m/s	•	•	•	•
		0.1 m/s	•	•	•	•
		0.2 m/s	•	•	•	•
		0.3 m/s	•	•	•	•
		0.5 m/s	•	•	•	•
Lubricant 3	339.8 mm^2/s	0.05 m/s	•	•	•	•
		0.1 m/s	•	•	•	•
		0.2 m/s	•	•	•	•
		0.3 m/s	•	•	•	•
Lubricant 4	135.8 mm^2/s	0.05 m/s	•	•	•	•
		0.1 m/s	•	•	•	•
		0.2 m/s	•	•	•	•
		0.3 m/s	•	•	•	•
Lubricant 5	77.13 mm^2/s	0.05 m/s	•	•	•	•
		0.1 m/s	•	•	•	•
		0.2 m/s	•	•	•	•
		0.3 m/s	•	•	•	•
Lubricant 6	17 mm^2/s	0.1 m/s	•	•	•	•
		0.2 m/s	•	•	•	•
		0.3 m/s	•	•	•	•
		0.5 m/s	•	•	•	•

IOP Conf. Series: Materials Science and Engineering **724** (2020) 012039 doi:10.1088/1757-899X/724/1/012039

Six different types of lubricant were selected and named as Lubricant 1 – 6. The viscosity information of those lubricants can be also found in table 1 just under lubricant's name.

According to the results of the performed tests listed in table 1, the film thickness will respond differently to the variation of load depending whether the two solid surfaces separate completely or not during harmonic loading cycles.

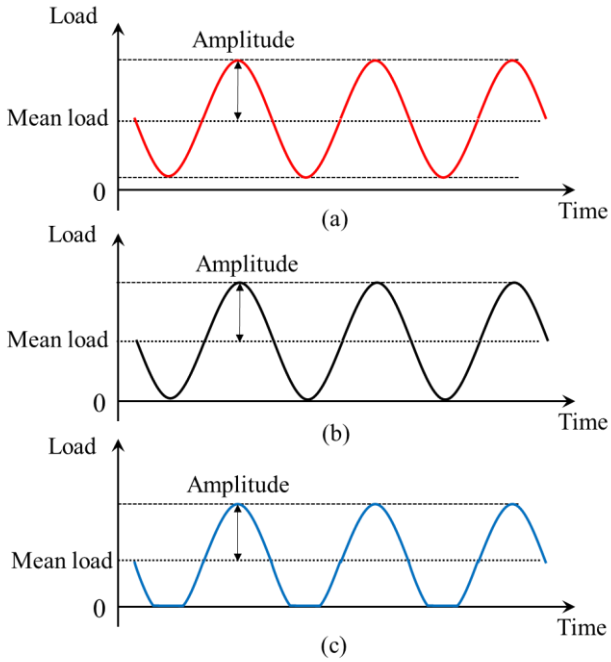
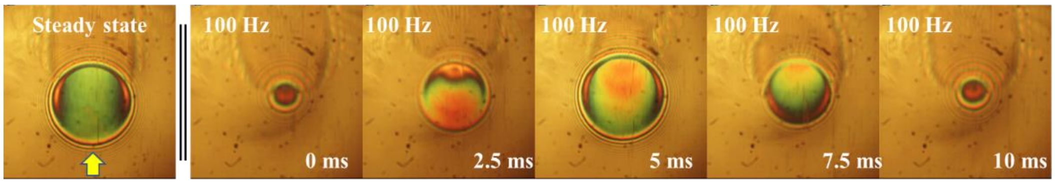


Figure 2. Variable loading conditions
(a) mean load larger than load amplitude
(b) mean load equal to load amplitude
(c) mean load smaller than load amplitude

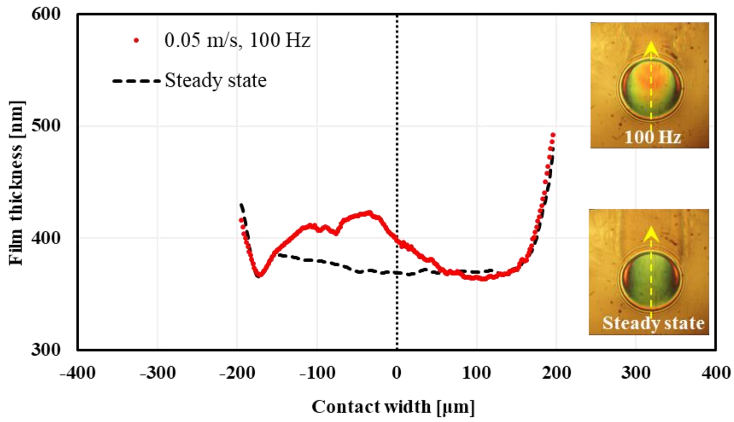
As showed in figure 2, the experimental loading condition in this paper can be classified as: mean value of variation cycle larger than or equal to load amplitude; mean value of variation of cycle is smaller than load amplitude. In the first case, the amplitude of the displacement of the vibrating element is smaller than or equal to the cumulative approach of the solids, while in the second is larger. Evidently the second case also corresponds to impact loading of the contact. The amplitude of the load cycle was about 21 N.

3. Results and discussion

Due to limitation of space of the current paper, only selective and typical results are presented below, based on different harmonic loading type resulting on the corresponding film thickness perturbation phenomenon. The left-most coloured interferogram in figure 3 (a) shows the steady state EHD contact at an entrainment speed of 0.05 m/s, lubricated with *Lubricant 2*. The horse-shoe shape and side lobes of the classical EHD contact behaviour can be clearly viewed. The lubricant entraining direction is from the bottom to the top of the image. Selected interferograms of the EHD contact subjected to 100 Hz harmonic loading (mean load is larger than load amplitude) within a cycle are presented to the right of the interferogram of the corresponding steady state condition. Film thickness perturbation, as seen from the coloured interferogram captured at 2.5 ms of the harmonic loading cycle, is formed at the inlet of the contact region. This crescent-shaped film perturbation travels across the contact region and eventually leaves the contact when the harmonic loading completes a full cycle.

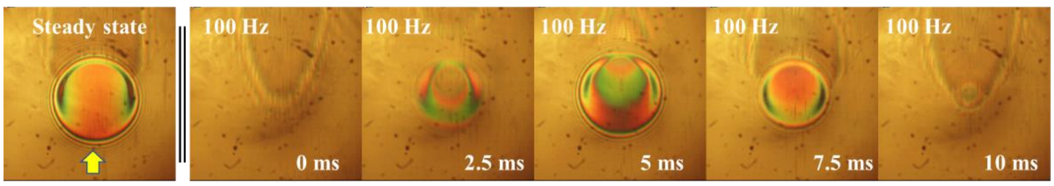


(a)

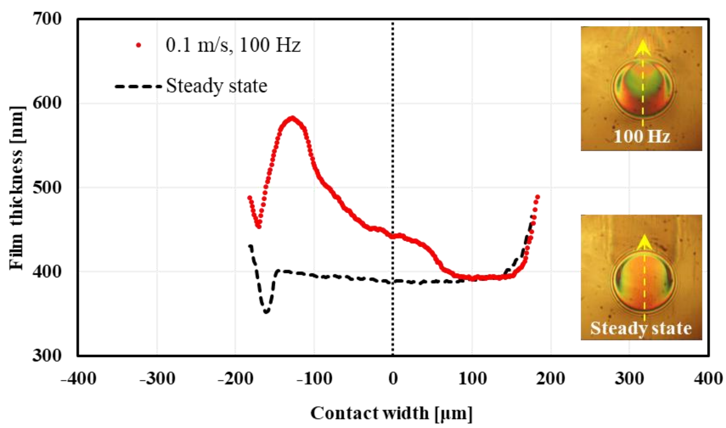


(b)

Figure 3. (a) Interferograms of EHD contact, 100 Hz-harmonic loading.
(b) Steady state and transient film thickness profiles



(a)



(b)

Figure 4. (a) Interferograms of EHD contact, 100 Hz-impact loading.
(b) Steady state and transient film thickness profiles

Figure 3 (b) compares the steady state film thickness profile with film thickness profile of the EHD contact within the harmonic loading cycle under peak load. The film thickness profile is calculated from along the entraining motion. The maximum generated film thickness perturbation is about 53 nm greater than film thickness under steady state condition. Figure 4 (a) shows selected coloured interferograms of the EHD contact subject to 100 Hz harmonic loading (mean load is smaller than load amplitude). This means that shock loading is applied to the contact. It can be observed that a dimple shaped film thickness perturbation has been formed in the central region of the contact and it travels across the contact along the direction of the entraining motion. In Figure 4 (b), the film perturbation has travelled towards the exit of the contact at the point when the load reaches the maximum value. It can be seen that this dimple perturbation is 193 nm greater than the steady state film thickness.

A graphical summary of film perturbation phenomenon on harmonic loading (mean load is larger than load amplitude) is showed in Figure 5.

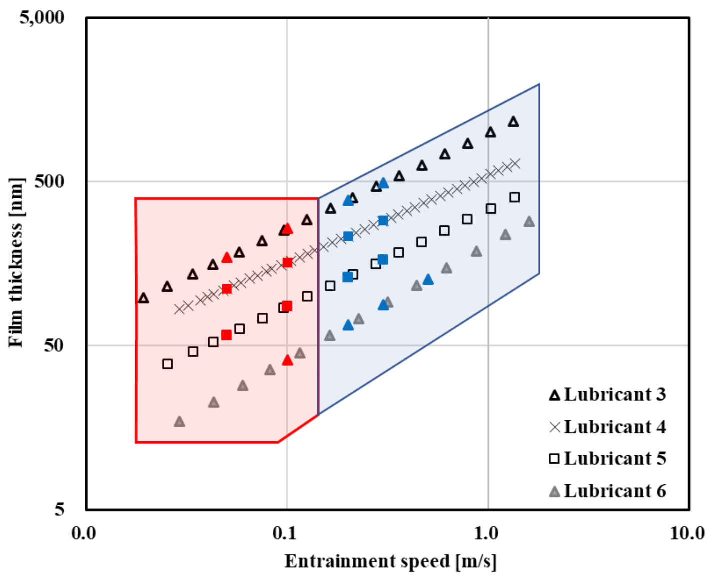


Figure 5. Film thickness perturbation map- harmonic loading

Steady state film thickness is shown for four different lubricants, which appear as four straight marker lines in the logarithmic graph. The grey markers indicate steady state values. Coloured symbols marked within the steady state values, indicating the conditions where vibration tests were performed at any of the working frequencies 10, 25, 50 or 100 Hz. The red markers show the tests when film perturbations occurred, while for the conditions corresponding to the blue markers no significant perturbations occurred. Based on previously discussed results, film thickness perturbation phenomenon is most significant at maximum frequency studied (100 Hz) in the red region, and it is less pronounced at lower test frequencies of 10 Hz and 25 Hz. In the blue region, film thickness perturbation was not observed even at the largest frequency employed in these tests. As a note, this is not a guaranty that film perturbations may not occur at frequencies larger than 100 Hz. Anyway, as seen in these experiments film thickness perturbations do not extend to entrainment speeds higher than approximately 0.1 m/s. This is marked by the blue region in the graph. It thus seems that film perturbation depends on the ratio between the average transient time of the lubricant through the contact and the period of the oscillatory cycle.

Parameter τ, defined as the ratio between the half period of oscillation $T/2$ and the average lubricant transit time t_{av} in the loading phase of vibration cycle is therefore used to provide a guideline for the occurrence of film thickness perturbation.

$$\tau = \frac{T}{2t_{av}} \tag{1}$$

Analysis of the results shown indicates that if τ is greater than 2 no film perturbation occurs, while for smaller values it does. For instance, in the 100 Hz cycle test, the load applied to the EHD contact varied from 1 N to 55 N and the entrainment speed was 0.1 m/s. The diameter of Hertzian contact, in this case, varied between 100 µm and 392 µm and the average lubricant transit time is 2.46 milliseconds. Parameter τ for this case becomes 2.03 which can be taken as 2. For the entrainment speed of 0.2 m/s, τ is obviously double to 4.06 thus results show no film thickness perturbation. Obviously, the value of 2 for parameter τ is only approximate as no tests were carried out at every possible speed in the interval between 0.1 m/s and 0.2 m/s.

More vibration tests are required to be carried out for shaping a more accurate boundary location of the red-blue regions in figure 5.

Figure 6 shows film thickness versus entrainment speed in the same steady state as in Figure 5. Results of transient experiments are again marked over the steady-state values. The transient tests were performed at speeds marked by coloured symbols at 10 Hz, 25 Hz, 50 Hz and 100 Hz for values of the amplitude of the load larger than the mean value of the cycle. As seen, there are no blue symbols, which means that film thickness perturbations occurred in every single test, no matter the speed and frequency

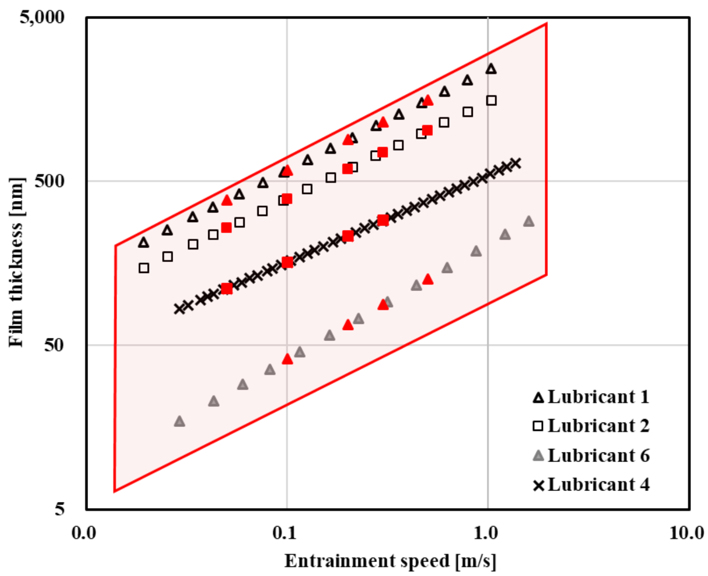


Figure 6. Film thickness perturbation map-impact loading

The red region can now be shaped as shown in figure 6. Only film thickness values at the maximum load in the cycle are shown in these graphs. It should be speculated that in case of cyclic application of load with impact, film thickness perturbation is generated in any condition of speed even for those larger than the speeds employed in these tests, however it may exit the contact before the load has reached the peak value in the vibration cycle.

4. Conclusions

In the present paper, a systematic experimental study for predicting the occurrence of film thickness perturbation phenomenon under harmonic loading condition has been carried out. The range of frequencies of the harmonic load employed in these tests ranges between 10 Hz and 100 Hz which has strong practical relevance.

In the case of a mean load larger than the amplitude of the load variation, it was found that the film perturbation depends of the frequency of the load cycle, the entrainment speed of the lubricant and the overall lubricant film thickness; it also depends of the ratios between the mean load and the amplitude. Film perturbations occur in contacts for which that ratio between half the load cycle period and the average time of transit of the lubricant through the contact in the loading phase of the vibration is less than 2. In the case of mean load smaller than the amplitude, film thickness perturbation has been observed in every single test regardless of entrainment speed, frequency and lubricant viscosity.

5. References

[1] Larsson. R and Lundberg. J, 1995, "Study of Lubricated Impact Using Optical Interferometry", *Wear*, **190**, pp 184-189.
[2] Kaneta. M, Ozaki. S, Nishikawa. H and Guo. F, 2006, "Effects of Impact Loads on Point Contact Elastohydrodynamic Lubrication Films", *Proc. I. Mech. E.*, **J221**, pp 271-278.
[3] Sanborn, D. M. and Winer., W. O., 1971, "Fluid Rheological Effects in Sliding Elastohydrodynamic Point Contacts with Transient Loading: 1- Film Thickness", *Trans. ASME, J. Lub. Tech*, **93**, pp 262-271.
[4] Wijnant., Y. H, Venner, C. H, Lassron. R and Eriksson. P, 1999, "Effects of Structural Vibrations on the Film Thickness in an EHL Circular Contact", *J. Trib*, **121**, pp 259-264.
[5] El Kilali. T, Perret-Liaudet. J and Mazuyer. D, 2003, "Experimental analysis of a high pressure lubricated contact under dynamic normal excitation force", *Transient Processes in Tribology*, Elsevier, **43**, pp 409-418.
[6] Sakamoto. M, Nishikawa. H and Kaneta. M, 2003, "Behaviour of Point Contact EHL Films Under Pulsating Loads", *Transient Processes in Tribology*, Elsevier, **43**, pp 391-399.
[7] Kalogiannis. K, 2013, "Behaviour of Elastohydrodynamic Films Subjected to Oscillatory Motion", Ph. D. Thesis, University of Sussex, United Kingdom.
[8] Fryza. J, Sperka. P, Kaneta. M, Krupka. I and Hartl. M, 2017, "Effects of Lubricant Rheology and Impact Speed on EHL Film Thickness at Pure Squeeze Action", *Trib. Int*, **106**, pp 1-9.
[9] Gohar. R and Cameron. A, 1967, "The Mapping of Elastohydrodynamic Contacts", *ASLE Trans*, **10**, pp 215-225.
[10] Foord, C. A., Hammann, W. C. and Cameron. A, 1968, "Evaluation of Lubricants Using Optical Elastohydrodynamics', *ASLE Trans*, **11**, pp 31-43.
[11] Wedeven, L. J., 1970, "Optical Measurements in Elastohydrodynamic Rolling Contact Bearings", PhD. thesis, London University, London.
[12] Cann, P. M., Spikes, H. A. and Hutchinson. J, 1996, "The development of a Spacer Layer Imaging Method (SLIM) for Mapping Elastohydrodynamic Contacts", *Trib. Trans*, **39**, 4, pp 915-921.
[13] Johnston, G. J., Wayte. R and Spikes, H. A., 1991, "The Measurement and Study of Very Thin Lubricant Films in Concentrated Contacts", *Trib. Trans*, **34**, 2, pp 187-194.
[14] Zhang. X, 2017, "The Effect of Vibrations on the Behavior of Lubricated Elastohydrodynamic Contacts. PhD thesis, University of Sussex.