OIL FILM THICKNESS AND SHAPE IN OSCILLATING ROLLER CONTACTS[1]

Xiaoyang Chen[2]
Tongshu Hua[3]
Xuejing Shen[3]

Abstract

In this paper, the elastohydrodynamic lubrication (EHL) oil film thickness and shape between a roller and a flat rectangular glass in pure rolling oscillated working conditions had been measured based on the principle of optical interferometry. The EHL behavior affected by the applied load, oscillating frequency was investigated. The typical film shape varies of interference pictures on non-steady state motion, such as acceleration and deceleration, stop and start rapidly was obtained. When the velocities of roller decreased to zero and then start in opposite directions, it was found the oil film can remain in a certain thickness for a short time because of the lubricant transient inertia effects, which is weakly viscosity-dependent or load-dependent. These phenomena could reduce wear for oscillating roller contacts. And the side constrictions are always the most severe. They are strongly viscosity and load dependent.

Keywords: EHL; Optical interferometry test; Oil film measurement; Oscillating roller contacts.

---

[1] *Technical contribution to the First International Brazilian Conference on Tribology – TriboBr-2010, November, 24th-26th, 2010, Rio de Janeiro, RJ, Brazil.*

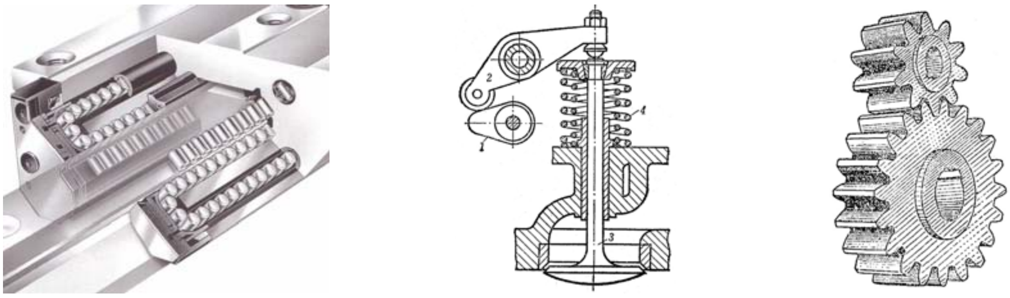
[2] *Professor, Doctor. Research Institute of Bearings, Shanghai University, Shanghai, 200072, China. Fax: 8621-5633 1937, xychen@shu.edu.cn*

[3] *Research Institute of Bearings, Shanghai University, Shanghai, 200072, China*

INTRODUCTION

Line contacts are widely used in engineering components for heavy radial load and high rotational speed conditions, for example, as shown in Figure 1, in roller bearings, cam-followers, linear roller guidance systems, traction drives and gear teeth. But all of the elements mentioned above are of finite length, so most of them are normally profiled at their ends to overcome the problems of edge effects caused by their finite length and by misalignment. In this paper all above finite line contacts are called to roller contacts.

Cylindrical roller bearing Taper roller bearing Needle roller bearing



Lnear guidance systems Cam and roller follower Involute gears

Figure 1. Application of roller contacts.

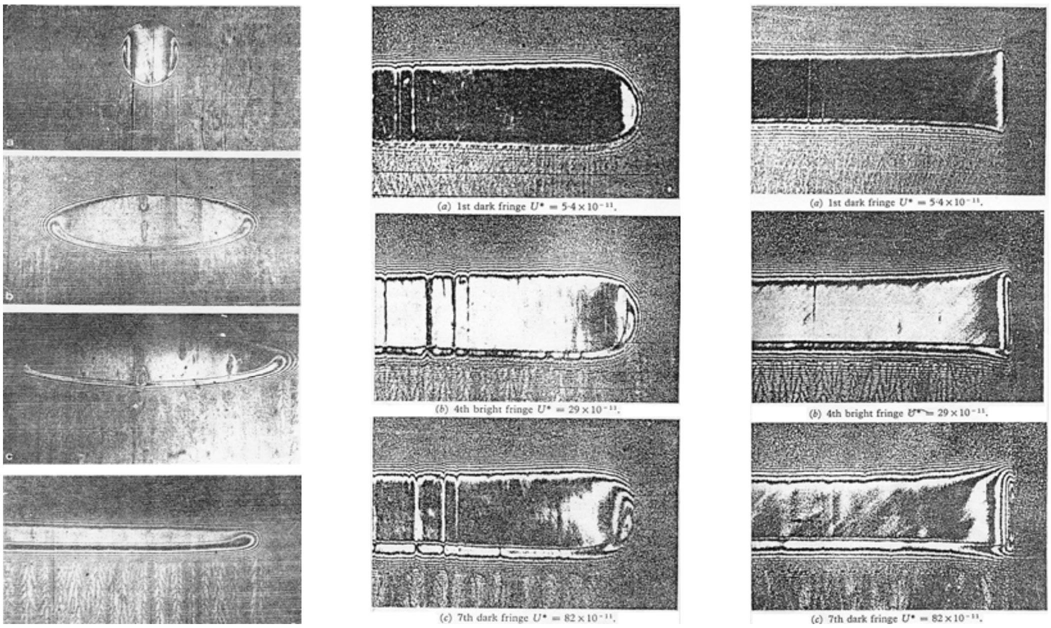
There are many oscillatory applications for above roller contacts where determining the performance of a machine becomes an important engineering component, such as in the Hooke's universal joints which widely used in automotive and mechanical transmissions, or in the linear guidance elements. The operational reliability of the machines depends on the functional dependability of these roller contacts incurporated. So the roller contacts design that meet user demands, together with high quality manufacturing methods, are prerequisites for the satisfactory operation of many sophisticated machines.

It is well known that the roller contacts are separated by a viscous oil film during rolling or sliding, which results in the EHL state. The load-bearing capacity, working velocity and service life of roller contacts is deeply influenced by the film thickness, film shape and pressure distribution of the film. Many researchers have studied the roller contacts EHL problems during the past five decades.

After the first experimental investigation of EHL performance for both blended and unblended roller in sliding contact did by Gohar and Cameron,[1] which gave several important pictures of the effect of roller blending. A series of research on the roller contacts EHL have been done during the past years. Wymer and Cameron[2] developed a very flexible loading system which enabled the optical interferometry usable to study roller contacts EHL under pure rolling and 0.72 GPa contact pressure conditions. They showed clearly that the oil film shapes and thicknesses of blended and unblended rollers were quite different, especially near the edge region of the roller. It was encouraging to the further research works. Several other optical interferometric testing methods was developed for measuring the oil film thickness and shape at different rolling working conditions and roller profiles.[3-8] Glovnea and Spikes,[9] Wang et al.[10] had measured the oil film in oscillation working conditions for point contacts.

A numerical analysis of the roller contacts EHL problem of axially profiled cylindrical roller under flooded, moderate load and material parameter conditions was done by Mostofi and Gohar,[11] Park and Kim.[12] They showed that the minimum film thickness was affected by different radii of dub off and crown profiles, as well as pointed out that the maximum pressure and the minimum film thickness are highly dependent on the local geometry there. Subsequently, several numerical solutions were obtained, and some of complicate factors such as roller misalignment, thermal , transient and oscillating effects have been considered separately in them.[13-18]

Figure 2 shows the behaviour of elliptical contacts of varying aspect ratio. Under increasing load the extent of the contact in the longitudinal direction may exceed the design value in which case the contact may also behave as a finite length contact, presenting the same problem as a finite line contact. But the sideways flow of different profile in finite line contacts is quite different, which can be found clearly in Figure 2 by comparing the interferograms.



Elliptical contact [19]	Blended roller[2]	Unblended roller[2]

Figure 2. Difference between interferograms of elliptical and finite line contacts.

This paper presents some of our recent measured results for EHL oil film thickness and shape between a roller and a rectangular glass in pure rolling oscillated working conditions based on the principle of optical interferometry. The influences of applied load and lubricant on the oil film thickness had been investigated.

TESTING APPARATUS

Figure 3 gives the photograph of an overall view of the apparatus and the sectional view of it is shown in Figure 4. In this test rig, the cylinder specimen, with a 10.0 mm diameter and 10.5 mm length, rolls against two cylinders with 15 mm diameter and 20 mm length. The steel specimen is held by a fixed cage for remain the position in axis direction and saving a little lubricant oil. The tested roller runs between an upper flat rectangular glass, which is mounted on linear double rail guidance systems with high rigidity and load carrying capacity.

Figure 3. Overall view of the apparatus.

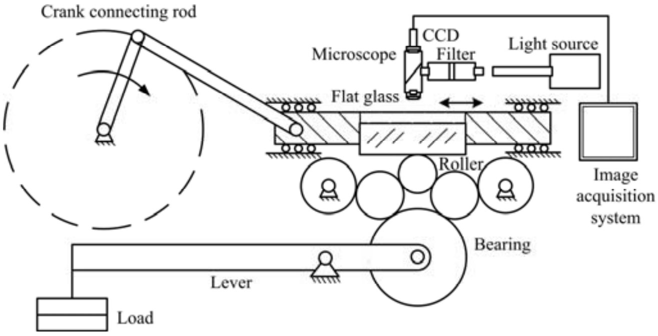


Figure 4. Sectional view of the apparatus.

A standard microscope MZDH1065TC with a 82 mm working distance with a 1X～6.5X objective and 25×eyepiece is mounted above the rectangular glass. A xenon lamp source is used as side illuminator. The wavelength of it is 600 nm. And a Hopkins collimator[20] of below-the-lens system is used. The oscillating frequency of the rectangular glass is measured by a digital tachometer. And the temperature is obtained through a thermometer.

PRINCIPLE OF OPTICAL INTERFEROMETRY AND CALIBRATION

The optical interferometry test about EHL properties of roller contacts is based on the wave optics theory, that is, interferometric phenomenon will occur when two coherent lights meet at one position. When parallel light pencil emit contact area of the rectangular glass and the roller along the direction of the oil film thickness, the reflected rays coming from two interfaces form coherent light. By the microscope and the CCD camera, the interference fringe picture is observed and recorded. Then, oil film thickness values at every point can be calculated according to shape, position and order of the interference fringe.

Figure 5 shows the principle of optical interferometry EHL oil film measurement. The space between the roller and the rectangular glass is brimming with lubricating oil. If a beam of collimated monochromatic incident light falls onto upper surface of the glass, it splits so that partial reflections occur at the top and bottom surfaces of the oil film. Between the reflected ray 1 which occurs when a beam of incident light goes through the glass to the bottom surface of the glass and the reflected ray 2 that occurs when the beam of incident light continually goes through the film to the roller's surface, the interferometry light is formed.

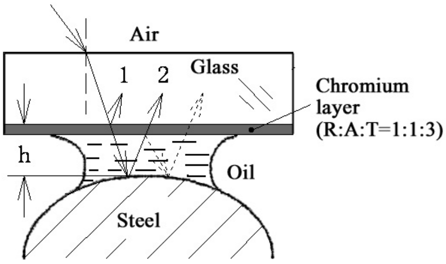


Figure 5. Two-beam interference.

The path difference between the two reflected rays is $\Delta = 2h\cos\theta + \lambda'/2$, where h is the oil film thickness, θ is the reflected angle, λ' is the wavelength of light in the oil film. When the reflected ray 1 and 2 form the interference phenomenon, if $\Delta = 0$, the two emergent rays reinforce so that the eye will see a light area or a bright interference fringe. The general condition for a bright fringe is $\Delta = 2h\cos\theta + \lambda'/2 = k_0\lambda'$, where k_0 is fringe order, $k_0 = 1,2,\cdots$, etc. If the two emergent rays cancel, there is destructive producing a dark interference fringe. This condition is $\Delta = 2h\cos\theta + \lambda'/2 = (2k_1 + 1)\lambda'/2$, where $k_1 = 0,1,2,\cdots$, etc. Usually, a beam of incident light falls vertically onto upper surface of the glass, so $\cos\theta = 1$.

Clearly, as to whether the fringe is light or dark can depend on the oil film thickness. When the roller contacts directly with the glass, that is k_1=0 and h=0, there is a dark area. The oil film thickness is λ'/4 at first light fringe around the dark area, and the oil film thickness is λ'/2 at first dark fringe which is on the periphery of first light fringe, and so forth. That means the oil film thickness difference between adjacent dark and light regions equals λ'/4. At last, the oil film thickness of every point can be calculated according to fringe number. The wavelength of light in the oil film (λ') is related to the wavelength in air (λ_0) by $\lambda' = \lambda_0/n$, where n is the refractive index of the oil film. And it varies with the density (ρ) of oil film. At high pressure, there is Lorenz formula, $[(n^2 - 1)/(n^2 + 1)]/\rho = C$, where C can be obtained by measuring n and ρ at normal pressure.

Inference of film thickness information from fringe patterns required careful calibration of the interference fringes. This was completed in a similar manner to that was described by Wymer and Cameron.[2] Calibritions established the separation of two surfaces corresponding to each fringes. Figure 6 gives the interferogram of static contact at end of a roller, and Figure 7 shown the measured profiles of tested rollers end, which compared with the ideal Lundberg's profile.

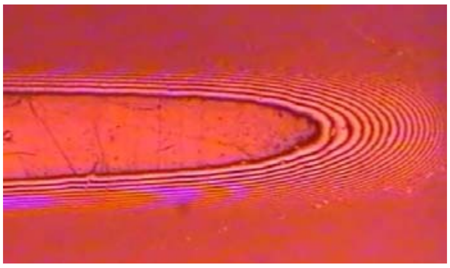


Figure 6. Interferogram of static contact.

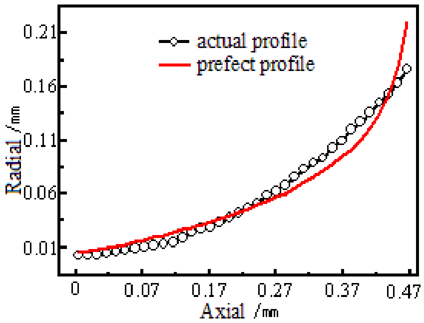


Figure 7. Measured profiles of rollers end.

TESTING CONDITIONS

The upper flat rectangular glass is made of crown glass and optically polished to 1.2×10^{-2} μm integral mean deviation of profile (Ra). Its surfaces are parallel to within 2.0 μm. And a 200 A semi-reflecting layer of chromium is vacuum deposited onto the lower surface, to allow the formation of interference fringes. This is in accordance with the usual practice when employing optical interference techniques to measure the oil film of EHL. The tested rollers used are made of chromium steel 15 from bearing roller manufacturers' factory which are made with refined lapping manu- facturing method, and the surface roughness are about 1.32×10^{-2} μm Ra. It is not easy to obtain a roller of a higher surface finish because of the difficulty in forming the required profile.

The load on the roller needed to produce 0.92 GPa contact pressure is about 2452 N. Figure 8 gives the variation of tested roller entrainment speed, 0.51 rpm for crankshaft. Lubricating oil is supplied to the gap between the tested roller and upper glass race and is retained by the fixed cage. The oil used is PB1300 or PB2400 whose properties are listed in Table 1. The temperature is accurate to ±1□. As the contact is in pure rolling, the test conditions are considered isothermal.

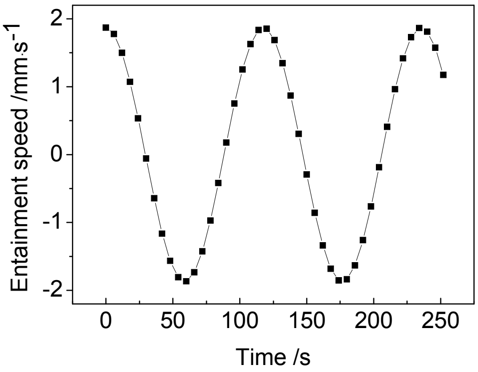


Figure 8. Entrainment speed of cylinder specimen.

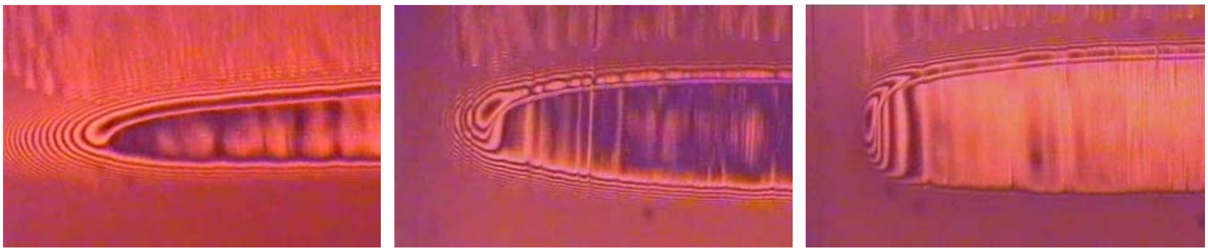
Table 1. Properties of PB oil

oil	Viscosity (Pa·s)		Density(20ºC) kg·m^{-3}	Refractive index
	20□	100□		
PB1300	117.0	0.577	896.0	1.497
PB2400	1050.0	4.70	905.0	1.504

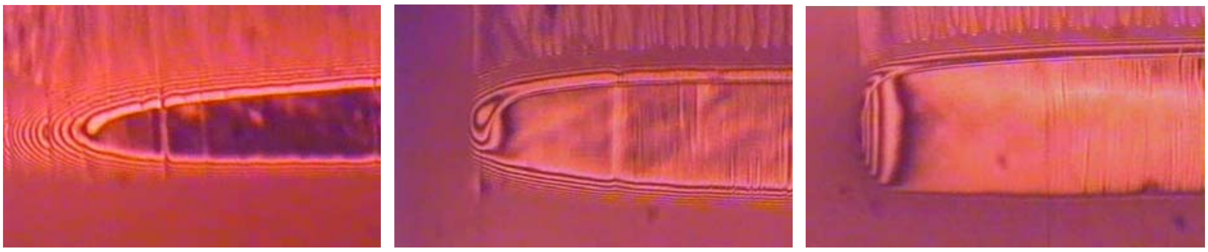
TESTING RESULTS

Figure 9 gives out the comparison of film shape varies of interference pictures of 495 N, 1668 N and 2452 N applied loads Which can make the maximum Hertz contact pressure reached to 0.42 GPa, 0.76 GPa and 0.92 GPa respectively. The variation law of oscillating velocity is shown in Fig. 8. The oil used was PB1300 for the former one, and the oil PB2400 was used in the both experiments of latter. The horizontal direction of the pictures is the axial direction of roller contacts and the vertical direction is the roller oscillatory motion direction.

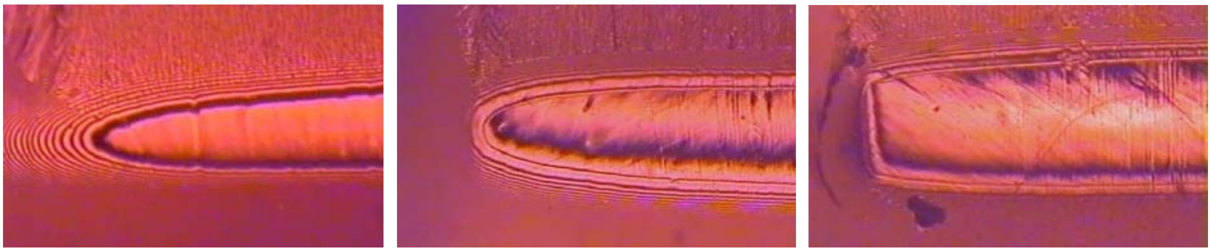
The film profiles across absolute minimum film thickness of above interference pictures are compared in Figure 10. It is obviously that the applied load and lubricant effects upon the oil film shape and film thickness.



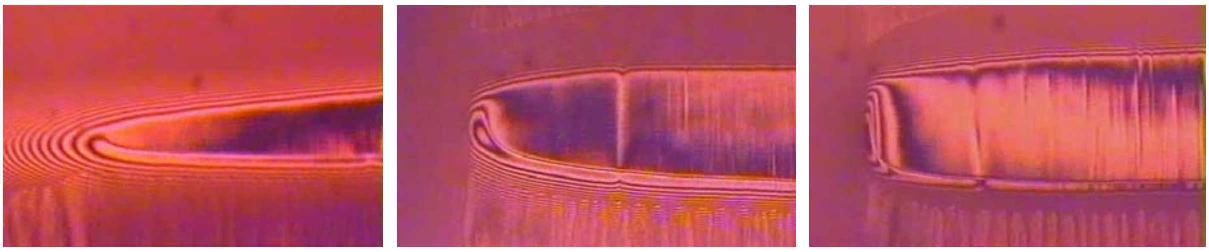
t =T/12



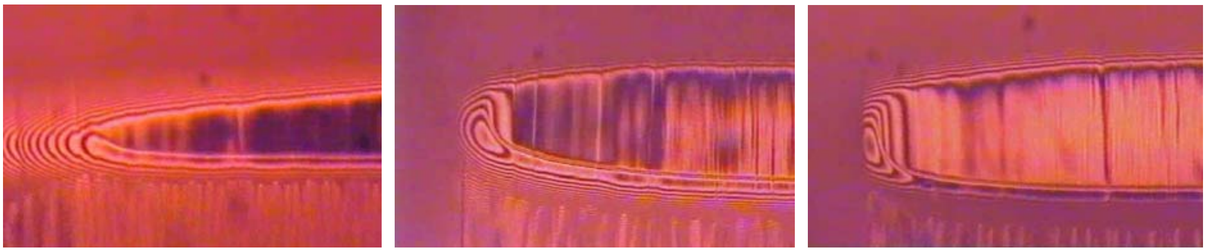
t =2T/12



t =3T/12



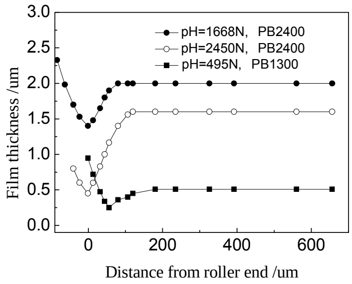
t =4T/12



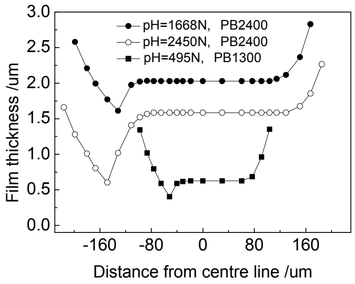
t=5T/12

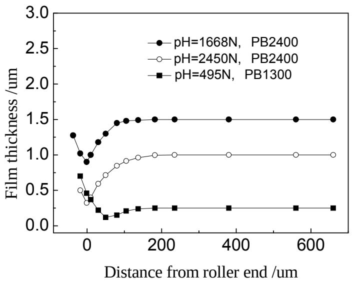
(a) 0.42 Gpa, PB 1300 (b) 0.76 GPa, PB 2400 (c) 0.92 GPa, PB 2400

Figure 9. Comparison of film shape varies of interference pictures at different applied loads

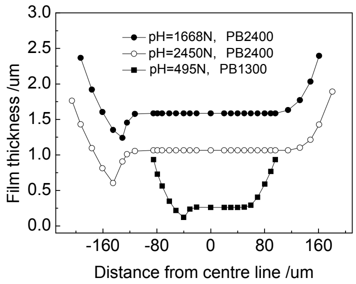


t=T/12





t=2T/12



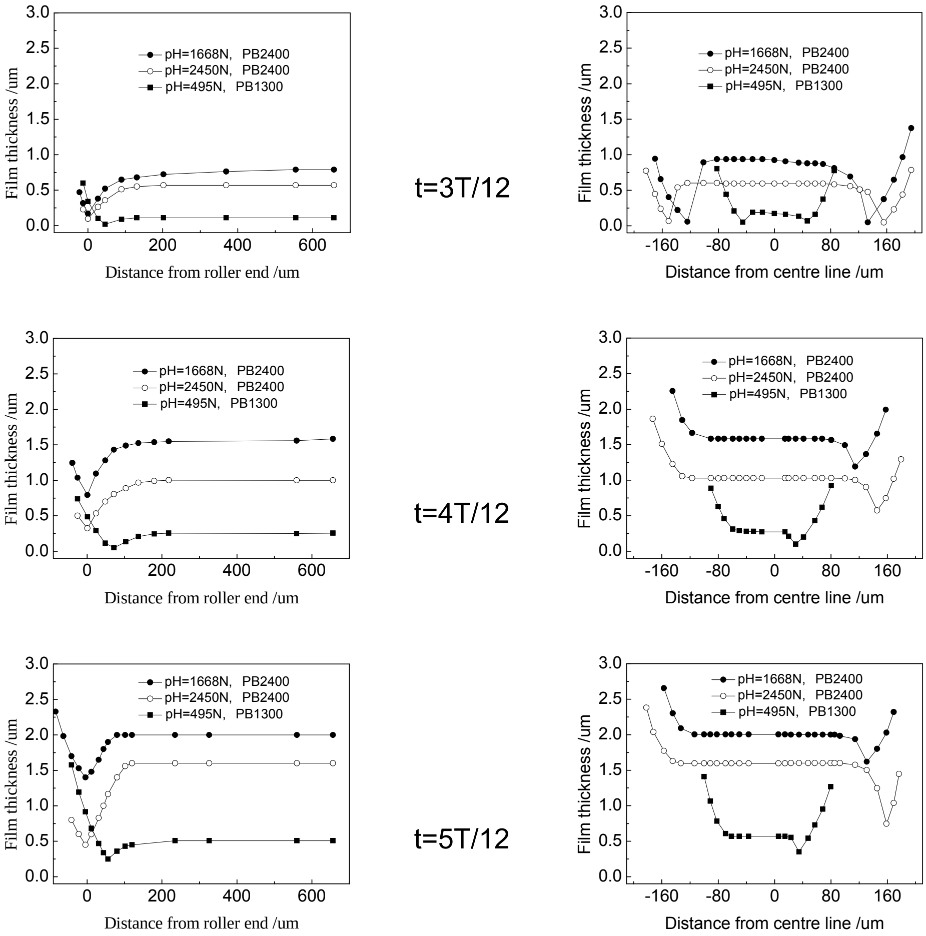


Figure 10. Film profiles across side closure along axial direction and in the direction of motion with different applied loads.

From Figure 9 and Figure 10, it could be seen that at T=3/12, where the cylinder specimen surface velocities decreased to zero and then start in opposite directions, this stopping suddenly under load can often form larger lubricant entrapments in the contact area, which is weakly viscosity-dependent or load-dependent. These phenomena could be important in reducing wear during the oscillating direction changes for roller contacts. The side constrictions are always the most severe, representing, with a heavy loaded profiled roller, a thinning of up to 95%. They are strongly viscosity and load dependent.

CONCLUSIONS

For studying the EHL properties of oscillating roller contacts with modified profile, the interferometric technique has enabled accurate film thickness to be measured within a dynamic roller contacts. The principle and structure analysis of an optical interferometry test rig is introduced, which could be used to measure the oil film shape and thickness between a profiled roller and a glass plate under pure oscillating rolling. The apparatus allows the pure rolling roller contacts, both dry and lubricated, to be mapped. And a number of EHL features for different viscosity or load have been enabled to be found by the device.

Measurement of the film profile has given details of the constrictions occurring in the film. The side constrictions are always the most severe. They are strongly viscosity and load dependent.

At the instant of motion direction change, where the cylinder specimen surface velocities are zero, the stopping suddenly under load can often form large lubricant entrapments, which is weakly viscosity-dependent or load-dependent. These could reduce wear for oscillating roller contacts.

Acknowledgements

This work was carried out with financial support from the Technical Development Foundations of Shanghai Automobile Industry (No.0320) and Innovative Team Program of Universities in Shanghai of Shanghai Municipality Education Commission (B.48-0109-09-002) and Key Innovational Program of Shanghai Municipal Education Commission (No.11ZZ89). The authors wish to thank Prof. Jingning Ding of Center of Low-Dimension Material Micro/Nano Device and System of Changzhou University, P.R.China, for his help in making the apparatus and experiments.

REFERENCES

1 Gohar, R., Cameron, A. The mapping of elastohydrodynamic contacts. **ASLE Trans.**, v.10, p. 215-225, 1967.
2 Wymer, D. G., Cameron, A. Elastohydrodynamic lubrication of a line contact. **Proc. Instn. Mech. Engrs.**, v. 188, p. 221-238, 1974.
3 Pemberton, J. C., Cameron, A. An optical study of the lubrication of a 65 mm cylindrical roller bearing. **ASME Trans, J. Lubr. Technol.**, v. 101, p. 327-337, 1979.
4 Ford, R. A. J., Foord, C. A. Studies on the separating oil film (EHD oil film thickness) between the inner race and rollers of a roller bearing. **Mech. Engng. Trans., The Institution of Engineers**, *Australia*, p. 140-144, 1981.
5 Dmytrychenko, N., Aksyonov, A., Gohar, R., Wan, G. Elastohydrodynamic lubrication of line contacts. **Wear**, v. 151, p. 303-313, 1991.
6 Zhu, D., Biresaw, G., Clark, S. J., Kasun, T. J. Elastohydrodynamic lubrication with O/W emulsion. **Trib. Trans. of ASME**, v. 116, p. 310-320, 1994.
7 Chen, X. -Y., Zhou, S. -Q., Ma, J. -J. Oil film thickness and shape in Lundberg's profile roller contacts. **Proc. 23rd Leeds-Lyon Sym. on Trib.**, p. 415-422, 1996.
8 Parkins, D. W., Rudd, L. Thrust cone lubrication, part 3: a test facility and preliminary measured data. **Proc. Instn. Mech. Engrs., Part J**, v. 210, p. 107-112, 1996.
9 Glovnea, R. P., Spikes, H. A. Oscillations induced in EHD film thickness by a step in entrainment speed, **Lubrication Science**, v. 15, n. 4, p. 311-320, 2003.
10 Wang, J., Hashimoto, T., Nishikawa, H., Kaneta, M. Pure rolling elastohydrodynamic lubrication of short stroke reciprocating motion, **Tribology International**, v. 38, p. 1013-1021, 2005.
11 Mostofi, A., Gohar, R. Elastohydrodynamic lubrication of a finite line contact. **J. Lubric. Technol.**, v. 105, p. 598-604, 1983.

12 Park, T. -J., Kim K. -W. Elastohydrodynamic lubrication of a finite line contact. **Wear**, v. 223, p. 102-109, 1998.

13 Barragan de Ling, F. D. M., Evans, H. P., Snidle, R. W. Thrust cones lubrication. **Proc. Inst. Mech. Eng., Part J.**, v. 210, p. 85-105, 1996.

14 Chen, X. -Y., Shen, X. -J, Xu, W., Ma, J. -J. Elastohydrodynamic lubrication of logarithmic profile roller contacts. **Chinese Journal of Mechanical Engineering**, v. 14, p. 347-352, 2001.

15 Kushwaha, M., Rahnejat, H., Gohar, R. Aligned and misaligned contacts of rollers to races in Elastohydrodynamic finite line conjunctions. **Proc. Inst. Mech. Eng., Part C**, v. 216, p. 1051-1069, 2002.

16 Kushwaha, M., Rahnejat, H. Transient elastohydrodynamic lubrication of finite line conjunction of cam to follower concentrated contact, **J. Phys. D: Appl. Phys.**, v. 35, p. 2872-2890, 2002.

17 Liu, Xiaoling, Yang, Peiran. Analysis of the thermal elastohydrodynamic lubrication of a finite line contact. **Tribol. Int.**, v. 35, p. 137-144, 2002.

18 Sun, H. -Y., Chen, X. -Y., Wang, W., Yang, P. -R. Study on finite line contact elastohydrodynamic lubrication under oscillating conditions. **Mocaxue Xuebao**, v. 26, p. 247-251, 2006. (in Chinese)

19 Bahadoran, H., Gohar, R. The Oil Film in Elastohydrodynamic Elliptical Contacts, **Wear**, v. 29, p. 264-270, 1974.

20 Foord, C. A., Wedeven, L. D., Westlake, F. J., Cameron, A. Optical Elastohydrodynamics. **Proc. Instn. Mech. Engrs.**, v. 184, p. 487-505, 1969-70.