Behavior of EHL Films in Cyclic Squeeze Motion*

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The behavior of elastohydrodynamic lubrication (EHL) films formed between an optical flat and a normally vibrating steel ball is examined by means of the duochromatic optical interferometry technique. The film entrapped between the ball and flat plate forms an envelope at the end of the loading process. The maximum height of the film, which depends on the non-Newtonian response of oils and the squeeze number, remains constant during the cycle. Under conditions of short strokes and high frequency, air bubbles produced in the unloading process result in the collapse of the entrapped EHL film.

Key Words: Tribology, Machine Element, Cyclic Squeeze Motion, Elastohydrodynamic Lubrication, Non-Newtonian Fluid

1. Introduction

It is very important to understand the behavior of elastohydrodynamic (EHL) films between contacting surfaces in order to improve working performance and to prevent surface failures and vibrations. In machine elements such as gears, rolling bearings and cams and followers, the film thickness and load change with time. It is therefore necessary to elucidate the effects of normal approach and cyclic squeeze motion of the opposing solids on oil film behavior. Research to elucidate the normal approach problem in the EHL range was started by Christensen's theoretical work⁽¹⁾ in 1961 and Dowson and Jones'

experimental study⁽²⁾ in 1967. They found that oil is entrapped between contacting surfaces and forms a dimple. Since then numerous investigations have been carried out by various researchers from different points of view⁽³⁾⁻⁽⁷⁾. However, basic research on the behavior of oscillatory or cyclic EHL squeeze films seems to be rather insufficient⁽⁸⁾. In particular, the film behavior of an unsteady state, where the contact load increases in the loading process and decreases in the unloading process, has been seldom discussed, although it is a very important practical problem. The purpose of this study is to elucidate the basic characteristics of EHL films in circular contacts under cyclic squeeze motion by means of the duochromatic optical interferometry technique⁽⁹⁾.

Nomenclature

a : diameter of Hertzian circle corresponding to maximum contact load during cyclic motion without oil

E' : reduced elastic modulus, $2/E' = (1 - \nu_B^2)/E_B + (1 - \nu_D^2)/E_D$

E_B, E_D : elastic moduli of steel ball and optical flat

$h_{\max}$: maximum film thickness in oil entrapment

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during cyclic squeeze motion

p_m : average contact pressure

$H_{\max}$: dimensionless maximum film thickness,

$$H_{\max} = h_{\max}/R$$

R : radius of steel ball

S : displacement of ball as rigid body

S_0 : total amplitude of cyclic motion without oil

t : time

T : period of cyclic motion

w : contact load

w_0 : maximum contact load during cyclic motion without oil

α : pressure coefficient of viscosity

η_0 : viscosity at atmospheric pressure

λ : squeeze number, $\lambda = \eta_0 \omega (a/R)^2 / E'$

ν_B, ν_D : Poisson's ratios of steel ball and optical flat

ω : angular velocity of cyclic motion

2. Experimental Procedure

Figure 1 shows a schematic diagram of the experimental apparatus used in this study. The contacting surfaces were composed of a precision 25.4 mm diameter steel ball and two kinds of optical flat coated with a semireflecting chromium layer. The cyclic squeeze motion was produced by oscillating the steel ball sinusoidally against the fixed optical flat. The steel ball was mounted on a lever arm. One end of the lever

Fig. 1 Schematic diagram of experimental apparatus

arm was supported by a pin, and the other end was attached to a cam through a connecting rod. The cam has a double eccentric mechanism so that the amplitude of the cyclic squeeze motion can be continuously changed. The distance between the centers of the ball and the pin was 45 mm, which was long enough to assume the sinusoidal motion in this study as the cyclic squeezing motion or vibration in a vertical plane.

The contact load could be measured by means of a pair of strain gages attached to a pillar supporting a holder, in which the steel ball was fixed. The amplitude of vibration was detected by a no-contact gap detector with an eddy current proximity probe set at a distance about 0.5 mm from the underside of the lever arm directly below the middle of the steel ball.

Figure 2 shows a typical chart of the displacement S of the steel ball and the contact load w as a function of time.

The duochromatic optical interferometry technique was used to measure the shape and thickness of the lubricating film. The interferometric fringe pattern formed with wavelengths of two colors (red and green) was recorded with a 35mm camera or a high-speed color VCR (200 frames per second) attached to a microscope. A crown glass disk of 60 mm diameter and 15 mm thick and a sapphire disk of 45 mm diameter and 8 mm thick were used as the optical flat. The reduced elastic modulus E' was 110 GPa for the former and 295 GPa for the latter.

The oils used were a mineral bright stock (BS), synthetic hydrocarbons (HC) which are the co-oligomers of ethylene and α -olefin, and tar-hydrogenated oils (TN). Their properties are listed in Table 1.

The experiments were performed at room temperatures ranging from 20°C to 26°C and a maximum contact load of $w_0 = 39.2$ N, which gave a maximum

Fig. 2 Relationship between contact load and displacement of steel ball ($T = 1$ s, $S_0 = 9.2 \mu\text{m}$, $w_0 = 39.0$ N)

Hertzian pressure of 0.52 GPa and a Hertzian diameter of 0.38 mm for the crown glass disk and 1.01 GPa and 0.14 mm, respectively, for the sapphire disk. The total amplitudes S_0 of vibration used were 9, 12, 14 and 23 μm , and the frequency was changed in the range of 0.5 to 40 Hz. Under vibrations with oil, the maximum contact load during a cycle became larger as compar-

ed with conditions without oil. Its amplification factor for BS and HC oils was less than 1.08 irrespective of the kind of optical flat used. For TN oils, however, the factor increased with an increase in the squeeze number λ ; the value for TN 320 was $2.5 \times 10^{12} \lambda + 1.05$ with the sapphire disk and $9.6 \times 10^{14} \lambda + 0.93$ with the crown glass disk.

Table 1 Properties of oils

Oil		Viscosity, mm ² /s		Specific gravity 15 / 4°C	Viscosity-pressure coefficient GPa ⁻¹ , 40°C
		40°C	100°C		
Bright stock (BS)		393	30.4	0.878	17.9
Synthetic paraffinic oil	HC-20	164.5	20.27	0.8336	14.7
	HC-40	416.8	41.06	0.8389	16.1
	HC-100	1400	111.5	0.8451	17.1
	HC-600	9358	610.0	0.8485	17.7
Tar-naphtenic oil	TN22	19.8	3.7	0.974	31.2
	TN68	62.4	5.8	0.988	44.4
	TN320	291	9.9	1.005	70.2
	TN710	710	14.3	1.008	80.5

3. Results and Discussion

3.1 Time variation of film shape

Figure 3 is a series of interferograms showing the time variation of film shape in a cyclic squeeze motion. The corresponding midplane film profiles are shown in Fig. 4. t/T is the dimensionless time where t is the time measured from the end of the loading process and T is the period of vibration. The negative time in this figure corresponds to the loading process, i. e., the steel ball approaches the optical flat, and the positive time corresponds to the unloading process. When the load is applied through the steel ball against the optical flat, oil entrapment occurs and

Fig. 3 Time variation of film shape (TN 320, $\lambda = 8.89 \times 10^{-15}$, $S_0 = 9.1 \mu\text{m}$, $w_0 = 39.2 \text{ N}$, $T = 0.54 \text{ s}$)

Fig. 4 Behavior of entrapped oil ((1) to (9) correspond to (1) to (9) in Fig. 3, $\lambda = 8.89 \times 10^{-15}$, $S_0 = 9.1 \mu\text{m}$, $w_0 = 39.2 \text{ N}$, $T = 0.54 \text{ s}$)

the entrapped region increases in size as the loading process proceeds. During the loading process the film thickness at the middle of the oil entrapment (central film thickness) remains constant, and the shape of the film entrapped between the steel ball and flat disk forms an envelope, which approximately corresponds to the film profile obtained at the end of the loading process. The time variation of the entrapped film shape in the unloading process is roughly the reverse of that in the loading process although the entrapped region is narrower in the unloading process than in the loading process and consequently the minimum film thicknesses exist inside the envelope formed in the loading process. However, the central film thicknesses of the oil entrapment stay at a constant value, which is the same as that in the loading process. That is, it can be concluded that time variation of film shape in the cyclic squeeze motion can be roughly estimated from the film shape at the end of the loading process.

Figure 5 shows film profiles obtained with BS oil during the loading and unloading processes. Although the central film thickness obtained with BS is thinner than that with TN 320, the variation of film shape during one cycle is almost the same as in the case of TN 320.

For both TN 320 and BS oils, the central film

(a) Loading process

(b) Unloading process

Fig. 5 Behavior of entrapped oil (BS, $\lambda = 8.67 \times 10^{-15}$, $S_0 = 9.1 \mu\text{m}$, $w_0 = 38.8 \text{ N}$, $T = 0.29 \text{ s}$)

thicknesses in the loading and unloading processes remain constant. It is difficult to expect such a phenomenon for viscous fluids. According to the phase diagrams constructed under quasistatic condition by Ohno et al.⁽¹¹⁾, BS is likely to be in a visco-elastic state at pressures above about 0.30 GPa and in a elastic-plastic state at pressures above about 1 GPa. With TN 320, the corresponding pressures are about 0.14 GPa and 0.30 GPa, respectively.

Figure 6 shows pressure distributions in the loading process, which are calculated from film profiles in Figs. 4(a) and 5(a). The pressures in the greater part of the oil entrapment exceed the value corresponding to the visco-elastic state; the greater part of the entrapped oil is unlikely to behave as a viscous fluid. That is, it can be concluded that the frozen oil entrapments shown in Figs. 3 to 5 are caused by the solidification of oil.

3.2 Collapse of oil entrapment

The effects of the squeeze number λ and the amplitude of vibration on oil film profiles are shown in Figs. 7 and 8, respectively. Increases in the squeeze number and amplitude give rise to increase in the approaching velocity of the steel ball against the flat disk, i. e., increase in the film squeezing action. As a result, the central film thickness and the amount of oil

(a) TN 320 (Fig. 4(a))

(b) BS (Fig. 5(a))

Fig. 6 Time variation of pressure distribution in loading process

- (1) $\lambda = 2.47 \times 10^{-15}$, $S_0 = 9.1 \mu\text{m}$, $w_0 = 38.6\text{N}$
 (2) $\lambda = 8.90 \times 10^{-15}$, $S_0 = 9.1 \mu\text{m}$, $w_0 = 39.8\text{N}$
 (3) $\lambda = 1.76 \times 10^{-14}$, $S_0 = 9.2 \mu\text{m}$, $w_0 = 40.2\text{N}$

Fig. 7 Effect of squeeze number

- (1) $S_0 = 9.1 \mu\text{m}$, $\lambda = 8.90 \times 10^{-15}$, $w_0 = 39.8\text{N}$
 (2) $S_0 = 12.3 \mu\text{m}$, $\lambda = 8.91 \times 10^{-15}$, $w_0 = 39.9\text{N}$
 (3) $S_0 = 23.1 \mu\text{m}$, $\lambda = 8.91 \times 10^{-15}$, $w_0 = 39.4\text{N}$

Fig. 8 Effect of amplitude of vibration

entrapped increase as shown in Figs. 7 and 8. However, a further increase in the squeeze number results in asymmetric fringe pattern and in particular with BS, HC and TN 22 oils the entrapped film collapses completely so that direct contact between contacting surfaces occurs as shown in Fig. 9. Figure 10 shows the relationship between $H_{\max} = h_{\max}/R$ and λ . Solid symbols correspond to the occurrence of asymmetric fringe pattern. Within the limits of these experiments, the oils were roughly classified into two groups according to their characteristics. As seen from Fig. 10, one group is composed of BS, HC and TN 22 oils, and the other TN 68, TN 320 and TN 710 oils. Values of $H_{\max}$ corresponding to the same squeeze number are greater for the former group than for the latter, and furthermore for the former group the transition from the fringe pattern with coaxial circles or symmetric fringe pattern to asymmetric fringe pattern occurs at rather low squeeze numbers as compared with the latter group. These differences are considered to be caused by the difference of viscosity characteristics of oil at high pressures. Under the conditions of the present experiments, the values of αp_m , which can be

Fig. 9 Collapse of entrapped film (BS, $\lambda = 4.39 \times 10^{-14}$, $S_0 = 9.1 \mu\text{m}$, $w_0 = 39.3\text{N}$)

Fig. 10 Relationship between maximum film thickness and squeeze number (solid symbols correspond to collapse of stable fringe pattern)

considered as a measure of the packing of oil molecules⁽¹²⁾, are 14.6 for BS oil, 12 to 13.5 for HC oils and 24.4 for TN 22 oil, corresponding to the former group and 36 to 71 for oils of the latter group. That is, according to the results obtained by Ohno et al.⁽¹¹⁾, the oils of the former group behave as viscoelastic solids and those of the latter group behave as elastic-

plastic solids.

3.3 Effects of reduced elastic modulus

The oil film profiles at the end of the loading process with TN 320 for almost the same squeeze number using the glass disk and sapphire disk are shown in Fig. 11. The reduced elastic modulus E' is larger for the case of the sapphire disk than for the case of the glass disk. Thus, the Hertzian contact diameter for the former case is smaller than that for the latter case and the maximum Hertzian pressure is larger for the former than for the latter. As a result, although the maximum contact area occupied by the oil entrapment during a cycle for the sapphire disk is narrower than that for the glass disk, the maximum film thickness during the cycle and the corresponding minimum film thickness are thicker for the sapphire disk than for the glass disk. Consequently, the maximum volume of the entrapped oil is larger for the sapphire disk than for the glass disk. This means that for the case of the sapphire disk a large amount of oil is needed in order to sustain a stable oil entrapment characterized by coaxial fringe patterns as compared with the case of the glass disk. That is, it can be suggested that if the comparison is made under the same load conditions, the critical squeeze number λ_c corresponding to the threshold of the collapse of coaxial fringe pattern is lower for sapphire disk than for the glass disk regardless of oils. Figure 12 supports the above supposition.

Figure 13 shows shapes of the contacting surfaces calculated using the finite-elements method from the film profiles shown in Fig. 11. There is a large difference between the sapphire disk and the glass disk. With the glass disk, the steel ball sinks deeply in

Fig. 11 Effect of reduced elastic modulus (sapphire: $\lambda = 7.00 \times 10^{-15}$, $w_0 = 40.0$ N, $T = 0.58$ s, $S_0 = 9.1$ μ m, glass: $\lambda = 6.86 \times 10^{-15}$, $w_0 = 39.0$ N, $T = 0.10$ s, $S_0 = 9.4$ μ m)

(a) BS

(b) TN 320

Fig. 12 Effect of squeeze number on maximum film thickness ($S_0 = 9$ μ m, solid symbols correspond to collapse of stable fringe pattern)

Fig. 13 Elastic deformations of contact surfaces (sapphire: $\lambda = 7.00 \times 10^{-15}$, $w_0 = 40.0$ N, $T = 0.58$ s, $S_0 = 9.1$ μ m, glass: $\lambda = 6.86 \times 10^{-15}$, $w_0 = 39.0$ N, $T = 0.10$ s, $S_0 = 9.4$ μ m)

Fig. 14 Effect of amplitude of vibration on film profile

the deformed glass disk and the amount of deformation of the surface of the steel ball is rather small. However, the time variations of fringe pattern and film profile obtained using the sapphire disk are the same as those obtained using the glass disk.

3.4 Mechanism of collapse of oil entrapment

Figure 14 shows film profiles obtained by changing the amplitude of vibration under almost the same squeeze number. An increase in the amplitude of vibration brings about an increase in the critical squeeze number λ_c .

Figure 15 is a series of photographs showing the occurrence and disappearance of air bubbles under a cyclic squeeze motion. In order to facilitate observation of the air bubbles, the photographs obtained using the glass disk without the sputtered semireflecting chromium layer are also shown. It can be seen that the air bubbles are produced and grow in the unloading process. Air bubbles never occur and never grow in the loading process. However, it should be noted that the air bubbles produced in the unloading process remain in the contact region for a while even when the succeeding loading process begins. Figure 16 shows interferograms obtained in the loading process with BS oil, which shows the effects of the squeeze number on residual air bubbles. These photographs are taken with a 35 mm camera. Two pictures adjacent to each other were taken at the same position of the stroke. As the squeeze number increases, air bubbles are likely to remain in the loading process and these residual air bubbles result in asymmetric fringe pattern or the collapse of oil entrapment. This is because air bubbles prevent the generation of hydrodynamic pressure.

Figure 17 illustrates the relationship between the lifetime of air bubbles remaining in the loading process and the shape of the oil entrapment. The ordinate is the ratio of the time duration from the disappear-

Fig. 15 Occurrence and disappearance of air bubbles (BS, $\lambda = 8.97 \times 10^{-15}$, $w_0 = 40.0$ N, $T = 0.27$ s, $S_0 = 9.2$ μ m)

ance of air bubbles in the loading process to the end of the loading process, t_B , to the time duration of the loading process, t_L (see Fig. 2); the smaller the value of t_B/t_L , the longer the lifetime of air bubbles. The solid symbols in Fig. 17 denote the occurrence of the asymmetric fringe pattern or unstable oil entrapment.

Fig. 16 Effect of squeeze number on residual air bubbles

When the squeeze number λ increases under conditions of smaller amplitude of vibration, the value of t_B/t_L decreases markedly. That is, it can be concluded that the collapse of the stable oil entrapment or the coaxial fringe patterns under the cyclic squeeze motion is likely to occur under conditions of smaller amplitude and larger squeeze number.

It can be seen in Fig. 12 that air bubbles are unlikely to occur with TN 320 oil as compared with BS oil. This is because TN 320 oil maintains the elastic-plastic and viscoelastic solid states for a longer period of time compared with BS oil even if the contact load is removed⁽¹³⁾.

Fig. 17 Relationship between lifetime of air bubbles and oil entrapment (solid symbols correspond to collapse of stable fringe pattern)

4. Conclusion

The basic characteristics of EHL films in cyclic EHL squeeze motion have been clarified by direct observations by means of the optical interferometry technique. The main results obtained are summarized as follows.

(1) The shape of EHL film entrapped between contacting surfaces during cyclic squeeze motion forms an envelope at the end of the loading process. In particular, the film thickness at the middle of the entrapment remains constant during the cycle.

(2) The above phenomena occur because the oil in the dimple behaves as a viscoelastic or an elastic-plastic solid in the present experiments.

(3) When the amplitude of the cyclic squeeze motion is small and the squeeze number is large, air bubbles, which occur in the unloading process, remain in the succeeding loading process so that pressure generation due to the film squeezing action is prevented. As a result, the reduction of film thickness or the collapse of a stable oil entrapment is induced.

(4) The behavior of EHL film during cyclic squeeze motion is almost independent of the reduced elastic modulus.

(5) However, the deformation of each contacting surface depends strongly on the difference of elastic moduli of both materials. Furthermore, the critical squeeze number corresponding to the threshold of the stable oil entrapment is influenced by the reduced elastic modulus.

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