Front. Mech. Eng. China 2007, 2(2): 193–196
DOI 10.1007/s11465-007-0032-8

RESEARCH ARTICLE

WANG Xuefeng, GUO Feng, YANG Peiran

A measurement system for thin elastohydrodynamic lubrication films

Abstract An elastohydrodynamic lubrication (EHL) film measurement system using multi-beam interferometry is introduced in this paper. The measurement principle and the instrumentation are discussed. A simple and efficient method is suggested to obtain the fringe order of measured points. It is demonstrated that the presented measurement system can provide continuous measurement of lubricating films from nano to micro scales at a nano-level resolution, and can be used to investigate ultra-thin EHL films and tiny variations in EHL films.

Keywords multi-beam interferometry, elastohydrodynamic lubrication, fringe order

1 Introduction

Due to the advanced studies of elastohydrodynamic lubrication (EHL), different measurement methods of nano lubrication films have been developed. Digital spectrum analyses with colorful interferograms have been introduced, such as the spacer layer method by Johnston et al. [1], the hue saturation intensity (HSI) approach by Gustafsson et al. [2], and an improved spacer layer method by Glovnea et al. [3]. To obtain film thickness, monochromatic interferograms can be reconstructed by intensity analysis. For example, a relative optical interference intensity technique, which can achieve a resolution of 0.5 nm, was presented by Luo et al. [4–6]. Monochromatic interferometry provides an excellent fringe visibility and the maximum detectable film thickness can be as high as 4–5 μm. Guo et al. [7] carried out a full theoretical analysis of an optical EHL measurement system and proposed a multi-beam intensity-based (MBI) approach. Based on the MBI scheme, this paper discusses a new wide-range and higher resolution nanometer/micron lubricating film thickness measurement system.

Translated from *Tribology*, 2006, 26(2): 150–153 [译自: 摩擦学学报]

WANG Xuefeng (✉), GUO Feng, YANG Peiran
School of Mechanical Engineering, Qingdao Technological University, Qingdao 266033, China
E-mail: mewangxf@yahoo.com.cn

WANG Xuefeng
College of Electromechanical Engineering, Qingdao University of Science & Technology, Qingdao 266061, China

2 Basic principle of measurement technique

In conventional optical EHL, the film thickness between points of constructive interference (bright fringe) and destructive interference (dark fringe) cannot be evaluated accurately [8]. Two adjacent dark (or bright) fringes indicate an optical thickness variation of $\lambda/2$, where λ is the wavelength. With advanced digital image processing, the intensity value of any point between constructive interference and destructive interference can be obtained readily and used to infer a much smaller gap size. However, the relation between the interference intensity and the film thickness needs to be known before the gap size is evaluated. As schematically shown in Fig. 1, a typical optical EHL contact is a four-medium system: glass, chromium, lubricant, and steel; they are symbolized as medium 0, 1, 2, and 3, respectively. $\bar{E}_0^+$ stands for the electric vector of incident light; $\bar{E}_0^{-m}$ $(m = 1, 2, \ldots)$ denotes the electric vector generating the interference. The subscript 0 represents the medium (0: glass). With the exception of $\bar{E}_0^{-1}$, which is directly reflected from the Cr/glass interface, all the others are from layers below. The resultant interference intensity $\boldsymbol{I}$ can be expressed as

$$I = \left|\bar{E}_0^-\right|^2 = \left|\bar{E}_0^{-1} + \bar{E}_0^{-2} + \bar{E}_0^{-3} + \bar{E}_0^{-4} + \cdots\right|^2 = \left|\sum_{m=1}^{\infty} \bar{E}_0^{-m}\right|^2 \quad (1)$$

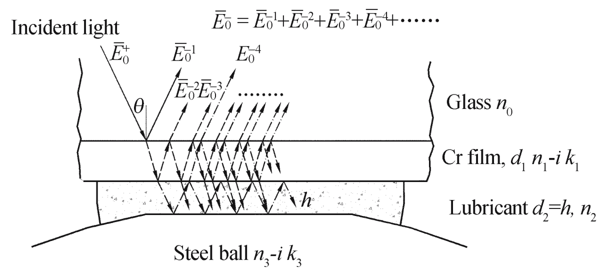

Fig. 1 Schematic illustration of EHL contact and its optics

According to Eq. (1) and the optical parameters of the system, a quantified relation between the interference intensity and the film thickness can be obtained.

The conventional optical EHL theory only considered the two-beam interference formed by $\overline{E}_0^{-1}$ and $\overline{E}_0^{-4}$, and the interference intensity is a cosine function of the lubricating film thickness [8]. In fact, the high reflectivity of the lubricant/steel interface and the light absorption property of steel and chromium can make the variation of the interference intensity deviate from the cosine distribution with different film thicknesses [9], as shown in Fig. 2(a). It can be seen from Fig. 2(b) that the reconstructed local shape with the two-beam interference theory is an erroneous wavy surface and 34 nm is overestimated when measuring the gap size between points A and B. It should be pointed out that the errors from the two-beam interference theory can be ignored when the EHL film thickness is at a micron level. However, the MBI scheme should be used when the film thickness is at a submicron/nano level or local tiny variations of film thickness.

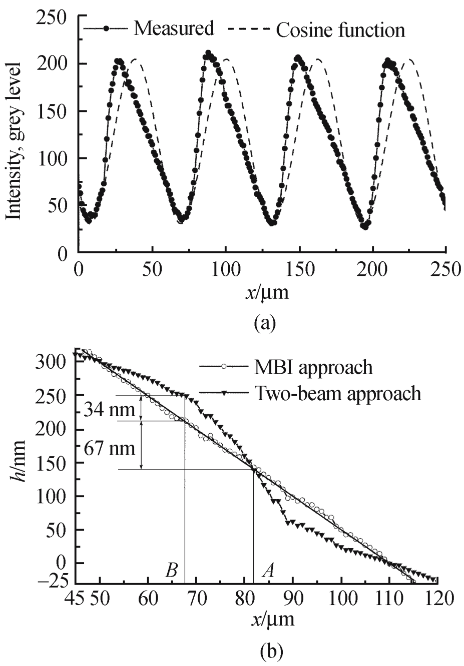

Fig. 2 Measurement of an air film between a wedged Cr-coated glass plate and a high precision steel surface
(a) Measured intensity; (b) Reconstructed gap profile

3 The lubricant film measurement system based on the MBI scheme

3.1 Apparatus configuration

Elastohydrodynamic lubrication contact can be achieved by using a ball/disc structure. A beam quasi-monochromatic light is obtained by a beam of white light through a narrow band interference filter (central wavelength: 600 nm; FWHM: 10 nm), and reflected from the beam splitter inside the microscope, then normally projected on the EHL contact region. The resultant interference pattern is magnified by the microscope, and captured and transmitted into a computer by a CCD (charge-coupled device) camera. The video microscope system has a focal depth of 3.5 μm, a view field of 627 μm × 470 μm, and a spatial optical resolution of 0.98 μm/pixel. The disc is made of K9 glass. The thickness of the chromium layer whose acquired approach is expatiated in Ref. [7] is 22 nm and its surface roughness is $R_a = 4$ nm. The steel ball with a diameter of 25.4 mm has a surface roughness of $R_a = 11$ nm.

3.2 Fringe order counting strategy

In this system, measured points include not only the points of constructive interference (brightest fringe) and destructive interference (darkest fringe), but also all the points between them. Therefore, the concepts of bright fringe-order range and dark fringe-order range are defined and symbolized by β and δ, respectively. Then, every single point's fringe-order range of an EHL interferogram can be specified by (δ, β). Any point with a film thickness of between gap sizes of the n-th and ($n+1$)-th dark fringes is classified as being the n "dark fringe-order range"; similarly, those with film thickness of between gap sizes of the n-th and ($n+1$)-th bright fringes belong to the n "bright fringe-order range". In a typical optical EHL system, for any point, the difference of its dark and bright fringe-order ranges must follow

$$\delta - \beta = 0 \text{ or } 1 \tag{2}$$

Consider such a point with a change in thickness (either increase or decrease) and a destructive interference has occurred. Its fringe-order ranges before and after the change in thickness are specified by (δ_1, β_1) and (δ_2, β_2), respectively. Then, β_2 must be equal to β_1 because there was no constructive interference during the change. Thus,

$$\begin{aligned} \delta_2 &= \delta_1 + 1 \quad \text{for } \delta_1 = \beta_1 \\ \delta_2 &= \delta_1 - 1 \quad \text{for } \delta_1 > \beta_1 \end{aligned} \tag{3}$$

The conclusion is similar when a constructive interference occurs with variations of the film thickness. In optical EHL experiments, the fringe-order range (δ, β) of an optional reference point, such as the contact center, can be obtained by enlarging the film thickness by gradually accelerating the entraining speed. Then, according to the above relationship, the fringe-order range of all other points can be obtained.

3.3 Film thickness evaluation

In optical EHL interferometry, the variational periods of the interference intensity with the film thickness is $\lambda/(2n)$, where λ is the wavelength and n is the refractivity of the lubricant used. Every film thickness h has only a corresponding film thickness h_0 with the fringe-order range ($\delta = 0,\ \beta = 0$) or ($\delta = 1,\ \beta = 0$) and both h and h_0 have the same interference intensity, where h_0 is the zero-order film thickness. The film thickness h can be calculated as

$$h = h_0 + \beta \frac{\lambda}{2n} \tag{4}$$

The relationship between h_0 and the interference intensity can be calculated using the MBI theory [7]. Figure 3, whose abscissa is the film thickness of $\beta = 0$, shows the relationship between the zero-order film thickness and the normalized intensity (ZTNI) for the current optical system. The negative film thickness is used for an easy processing. The curve in Fig. 3 is divided into two parts, I and II, by the minimum intensity, which refer to these points having ($\delta = 0,\ \beta = 0$) and ($\delta = 1,\ \beta = 0$), respectively. The difference of the film thickness between points A and B is 59 nm, and points B and C 125 nm. The film thickness can be calculated according to Eq. (4): region I is used if the fringe-order range agrees with $\delta - \beta = 0$, while region II is used if the fringe-order range agrees with $\delta - \beta = 1$.

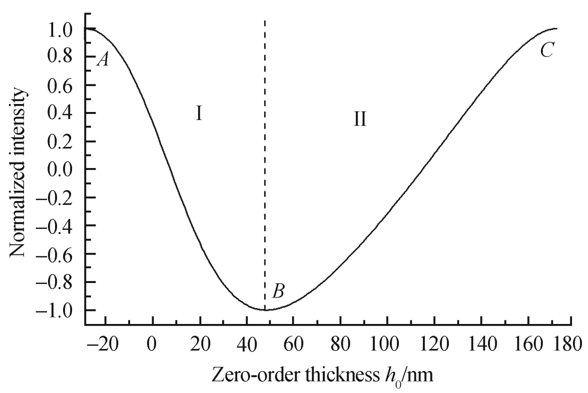

Fig. 3 Zero-order thickness vs. normalized intensity (ZTNI) for a lubricant of R.I. = 1.485

An optical analysis using the MBI theory is shown in Fig. 1. The relationship between the zero-order film thickness h_0 and the relative interference intensity $\Re$ can be directly obtained as follows [6]

$$\Re = \frac{I}{I_{\text{in}}} \tag{5}$$

where I is the measured energy intensity of the reflected beam and I_{in} is the energy intensity of the incident light. The normalized $\Re$ is as follows

$$\bar{\Re} = \frac{2\Re - \Re_{\max} - \Re_{\min}}{\Re_{\max} - \Re_{\min}} = \frac{2I - I_{\max} - I_{\min}}{I_{\max} - I_{\min}} = \bar{I} \tag{6}$$

where $\Re_{\max}$, $\Re_{\min}$, $I_{\max}$ and $I_{\min}$ are the maximum and the minimum of $\Re$ and I when the film thickness changes, respectively. In the linear working range of the CCD system, the measurement readout I_{m} (in grey levels) and the light energy intensity I are as follows

$$I_{\text{m}} = aI + b \tag{7}$$

where a and b are constants, and determined by the specifications of the CCD and ADC (analog-digital converter) used. Hence, the normalized I_{m} can be written as

$$\begin{aligned} \bar{I}_{\text{m}} &= \frac{2I_{\text{m}} - I_{\text{m,max}} - I_{\text{m,min}}}{I_{\text{m,max}} - I_{\text{m,min}}} \\ &= \frac{2(aI+b) - (aI_{\max}+b) - (aI_{\min}+b)}{(aI_{\max}+b) - (aI_{\min}+b)} = \bar{I} \end{aligned} \tag{8}$$

where $I_{\text{m,max}}$ and $I_{\text{m,min}}$ are the maximum and minimum of I_{m} when the film thickness changes, respectively. It can be seen from Eqs. (6) and (8) that both $\bar{\Re}$ and $\bar{I}$ are equal to $\bar{I}_{\text{m}}$, that is, h_0 can be worked out directly by using I_{m} measured, and there is no necessity of knowing I_{in}. In general, a CCD camera is equipped with AGC (auto gain control) and gamma correction to get better images. However, this will modify the real grey-level readout. Therefore, the AGC and gamma correction of the CCD camera should be shut off to obtain a linear response of the measurement system.

3.4 Resolution of the measurement technique

Figure 3 shows that the resolution of the measurement system, which can be roughly represented by the gradient of the curve, depends on the film thickness. The resolution is the lowest near the points of constructive interference and destructive interference. The resolution in region I is higher than that in region II in Fig. 3. In the present system, the maximum interference intensity is discretized into 200 grey levels (30–230), and the difference of the film thickness between points B and C is 125 nm, which gives a theoretical average resolution of 0.63 nm/grey level in region II; similarly, the theoretical average resolution is 0.38 nm/grey level in region I. Taking into account the effects of other factors, such as the noise signal of the CCD camera, the thickness resolution is estimated to be about 1 nm.

In addition, the effects of the medium's surface roughness on the interference intensity are not considered. The gradient of the roughness peak of the chromium film surface is 0.004 rad and that of the ball surface is 0.01 rad. Both are much smaller than π; therefore their effects on the interference intensity can be ignored. On the other hand, the roughness peak can lead to variations of chromium film thickness. Same film thickness does not have the same corresponding interference intensity, which can affect the measurement results. Strictly, the film thickness measured is a mean because the mean of chromium film thickness is used in the present experiments.

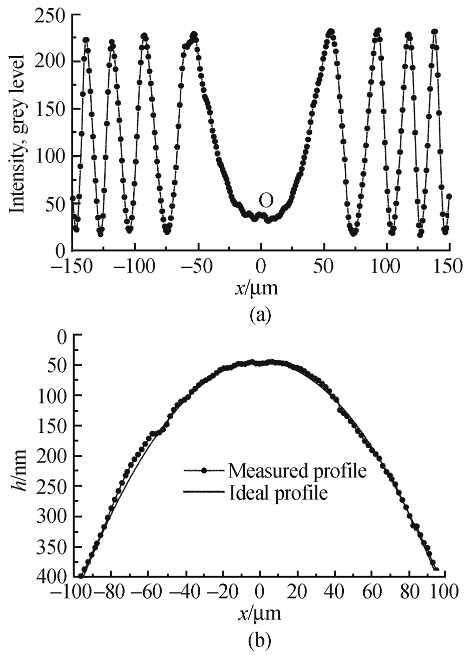

Fig. 4 Measurement of gap between a glass disc and a steel ball of 25.4 mm diameter during separation
(a) Intensity distribution; (b) Film gap reconstruction

4 Application in film lubrication measurement

Figure 4 shows the measurement results obtained from a gap between a steel ball with a diameter of 25.4 mm and a Cr-coated glass disc separated by a very viscous polybutene. In experiments, the steel ball was separated from the disc surface at an extremely low speed. The fringe-order range of the central point *O*, which is taken as the reference, is ($\delta = 1$, $\beta = 0$). The fringe-order range of any other points can be inferred according to the measured intensity variation. Figure 4(b) shows the profile of the steel ball measured. The profile of the steel ball measured between coordinates x of -85 and -55 μm in Fig 4(b) deviates from the theoretical curve much more, which could result from the disfigurement and uncleanness of the ball.

The film thickness variation curves measured with entrainment speeds are shown in Fig. 5. For PB450, at a thickness level of less than about 2 nm, the log-log curve of thickness vs. speed deviates from the EHL linear relation, which indicates a change of the lubricant state into the thin film lubricant. In addition, Johnston et al. [1,4] also observed this change and provided different deviation trends. We conclude that different deviation trends result from the lubricant properties and the interaction of the lubricant and the solid interface. However, for H1500, in the entrainment speed range considered, both the central film thickness and the minimum film thickness with the entrainment speed are linear relations in a log-log scale. Three speed exponents, shown in Fig. 5, of the film thickness agree well with the classical EHL value. The film thickness measured ranges from 1 up to 2 542 nm. In the ultra thin film lubricant region as shown in Fig. 5, for values of the central film thickness less than 10 nm, the results have a mean standard deviation of 0.89 nm.

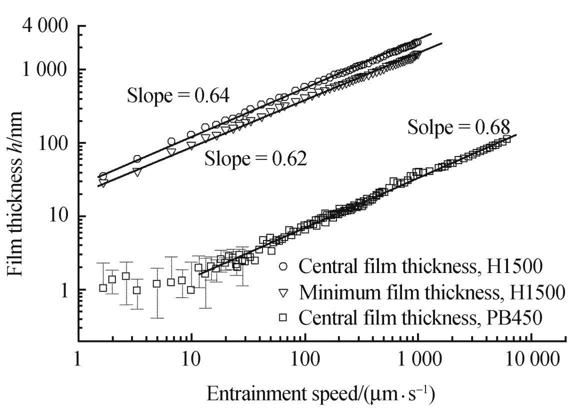

Fig. 5 Variation of film thickness with entrainment speeds under pure rolling (PB450 with a load of 3 N and H1500 with a load of 22 N)

5 Conclusions

1) The MBI thin lubricating film measurement scheme has been integrated with an optical EHL system successfully.

2) For the optical EHL contact, a simple fringe-order counting strategy has been suggested.

3) The availability of the present optical EHL system was demonstrated by a film thickness measurement ranging from 1 to 2 542 nm. Results agree with the existing theories and research conclusions.

References

1. Johnston G J, Wayte R, Spikes H A. The measurement and study of very thin lubricant films in concentrated contacts. STLE Tribology Transactions, 1991, 34(2): 187–194
2. Gustafsson L, Hoglund E, Marklund O. Measuring lubricant film thickness with image analysis. Proc Instn Mech Engrs, Part J, Journal of Engineering Tribology, 1994, 208(J3): 199–205
3. Glovnea R P, Forrest A K, Olver A V, et al. Measurement of subnanometer lubricant films using ultra-thin film interferometry. Tribology Letters, 2003, 15(3): 217–230
4. Luo Jianbin, Wen Shizhu, Huang Ping. Thin film lubrication, Part I: Study on transition between EHL and thin film lubrication using a relative intensity optical interference method. Wear, 1996, 194(1–2): 107–115
5. Huang Ping, Luo Jianbin, Zou Qian, et al. NGY-2 measurer for nano-thin lubrication film. Tribology, 1994, 14(2): 175–179
6. Luo Jianbin. Theoretical and Experimental Studies for Thin Film Lubrication. Beijing: Tsinghua University, 1994
7. Guo Feng, Wong Po Lin. A multi-beam intensity-based approach for lubricant film measuremenrts in non-conformal contacts. Proc Instn Mech Engrs, Part J: Journal of Engineering Tribology, 2002, 216(5): 281–291
8. Wen Shizhu, Yang Peiran. Elastohydrodynamic Lubrication. Beijing: Tsinghua University Press, 1992
9. Foord C A, Wedeven L D, Westlake F J, et al. Optical elastohydrodynamics. Proc Instn Mech Engrs, 1969–1970, 184(1): 487–505