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Discussion on the Technique of Relative Optical Interference Intensity for the Measurement of Lubricant Film Thickness

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Abstract The technique of relative optical interference intensity (ROII) has been developed for measuring lubricant film thickness. Here, we describe in detail the principle and the characteristics of the film thickness measurement system based on the existing ROII method. Some researchers have reported a large calculation error in film thickness with the use of ROII method. The description and analysis of the resolution, accuracy and important factors influencing the measurement results of this measurement technique presented here illustrate that the ROII method should be used in a specific optical system with negligible multiple beam reflections, but not in an ordinary one. The reported calculation error in film thickness using the ROII method comes from using an inappropriate optical system and inappropriate coating parameters. In fact, the ROII method, which is a very accurate method for measuring the thickness of a thin lubricant film, with a high resolution in film thickness of 0.5 nm and a horizontal resolution of 1.4 μm, can only be used in a two-beam interference system.

Keywords Film thickness · ROII method · Thin film lubrication

List of symbols

e	The extinction coefficient
h	Lubricant film thickness
Δh	Variation of the lubricant film thickness
I	Light intensity
I_1	Light intensity of beam 1
I_2	Light intensity of beam 2
I_3	Light intensity of the secondary reflection component
$I_{\max}$	Maximum interference light intensity
$I_{\min}$	Minimum interference light intensity
$I_{\max(n)}$	Maximum interference light intensity of the interference order n
$I_{\min(n)}$	Minimum interference light intensity of the interference order n
ΔI	The grey value gradation
$\bar{I}$	Relative interference light intensity
λ	Wave length of the incident light
k	Reflective index of lubricant
δ	Phase difference of two beam interference
Φ	Phase change caused by the surfaces of the chromium layer and the steel ball
$\bar{I}_0$	Relative light intensity when the lubricant film thickness is zero
n	Interference order

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1 Introduction

During the past several decades, a great deal of attention has focused on the study of film thickness measurement systems that can be used in elastohydrodynamic lubrication (EHL). One of the most important experimental techniques is based on optical interference. The application for EHL studies was first published by Cameron and Gohar in 1966 [1], who constructed the first graph of the horseshoe constriction in contact area between a highly polished steel ball and flat glass. This work was followed by several important improvements, including deposition of a semi-reflective chromium layer on the glass disc [2] and use of monochromatic and duo-chromatic interferometry [3]. Due to limitations in the wavelength of visible light, the film thickness resolution of these methods was $\geq$100 nm. Many efforts have been made to improve the accuracy and resolution of the optical interferometry approach, such as the spacer layer technique [4–10] and fringe intensity method, which was first mentioned by Roberts and Tabor in 1971 [11].

In 1996, our group presented a technique, which it called relative optical interference intensity (ROII), that could provide a high resolution—up to 0.5 nm—in film thickness measurement [12–16]. The technique is based on the subdivision of the interference image by the interference light intensity, which will be described in the following section. Guo and Wong [17, 18] recently pointed out an error in film thickness measurement using the ROII method, suggesting that the interference images should come from multiple-beam interference instead of two-beam interference. They found that the interference intensity distribution deviated from the cosine interference distribution, which resulted in a 30–40% error in calculating the film thickness and their solution was to use a multiple-beam intensity-based approach to analyze the film thickness from the interference image. In a subsequent paper, Glovnea et al. [10] quoted Guo and Wong's articles and claimed the accuracy of ROII is poor. However, in our opinion, the defects of the ROII method pointed out by Guo and Wong [17, 18] must come from using the ROII method in an ordinary optical set-up. However, the ROII technique must be used in a two-beam interference system. Multiple reflections are negligible in our ROII optical system, and the error in the film thickness measurement is no more than 5% when the system under the appropriate conditions. The aim of our study was to illuminate that ROII can only be applied in a strictly constrained optical system with negligible multiple-beam reflections.

2 Principle of the Relative Optical Interference Intensity Method

2.1 Detailed Description of the ROII Technique

The technique of relative optical interference intensity is based on the basic optical interference principle. The model of the technique is shown in Fig. 1, which was originally described by Luo et al. [12–14]. A super-polished steel ball is in contact with a glass disc coated with a chromium semi-reflected layer, bringing the Hertz area into being. There is a layer of oil film between these two

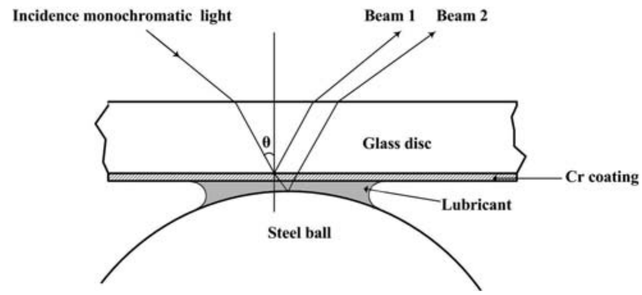

Fig. 1 Principle sketch of the two-beam optical interference

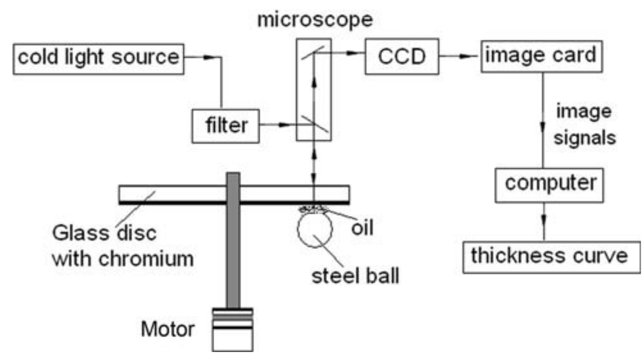

Fig. 2 The schematic image of the measurement system for the relative optical interference intensity (ROII) method

surfaces. The experimental set-up of the system is shown in Fig. 2 and includes a light source, a filter, a microscope, a camera and a computer with an image card. When a monochromatic light beam reaches the upper surface of the semi-reflective chromium layer, it will be divided into two beams that are reflected separately by the surface of the chromium layer and the steel ball surface. These two beams become interferential. Interference fringes are first formed in the CCD camera through the microscope and then digitized by the computer. The film thickness in the contact area can be determined by the light intensity/grey value between the minimum and the maximum values, which is called the relative light intensity. The basic expression of optical interference under the vertical incidence condition is [19]:

$$
\begin{aligned}
I &= I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta \\
&= I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(4\pi k h/\lambda + \Phi) \qquad (1)
\end{aligned}
$$

where I is the measured interference intensity, I_1 and I_2 are light intensity values of beam 1 and beam 2, respectively, δ is the phase difference, λ is the wave length of the monochromatic light, k is the refractive index of the lubricant and Φ is the phase change caused by the chromium layer and the steel ball surfaces. The film thickness can be calculated by the following equation:

$$h = \frac{\lambda}{4\pi k}[\arccos(\bar{I}) - \Phi] \quad (2)$$

where the $\bar{I}$ is the relative light intensity given by the following equation:

$$\bar{I} = \frac{2I - (I_{\max} + I_{\min})}{I_{\max} - I_{\min}} \quad (3)$$

In Eq. 3, $I_{\max}$ and $I_{\min}$ are the maximum intensity and minimum intensity, respectively. Details regarding the derivation of Eqs. 2 and 3 have been described in Luo [12] and Luo et al. [13]. As the film thickness is zero, the relative light intensity is denoted as $\bar{I}_0$, and Φ can be calculated from Eq. 2:

$$\Phi = \arccos(\bar{I}_0) \quad (4)$$

Substituting Φ in Eq. 2 with Eq. 4, the h should be described as:

$$h = \frac{\lambda}{4\pi k}[\arccos(\bar{I}) - \arccos(\bar{I}_0)] \quad (5)$$

It should be noted that Eq. 5 is used to calculate the lubricant film thickness in the first interference order. As the light intensity varies as a cosine curve, there should be an additional item in the equation when the film thickness is greater than the first order. Figure 3 shows the ideal variation in the intensity with increasing film thickness [20, 21]. Here, n is defined as the interference order. Each interference order is labeled in Fig. 3. Equation 5 should be modified to the following form:

$$h = \frac{\lambda}{4\pi k}\{n\pi + [\arccos(\bar{I}) - \arccos(\bar{I}_0)] \cdot \cos n\pi\} \quad (6)$$

where $n = 0, 1, 2\ldots\ldots$

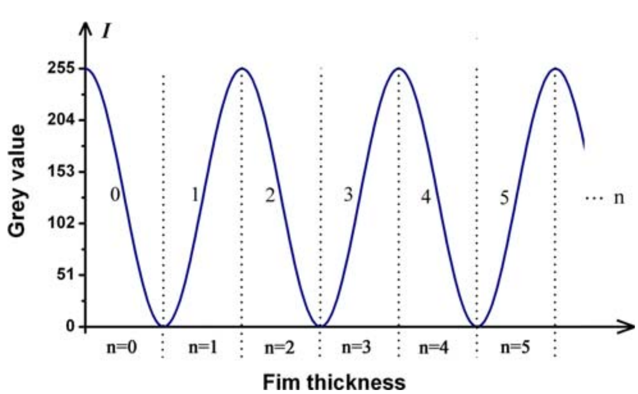

Fig. 3 Ideal variation in light intensity with increasing film thickness using the two-beam optical interference technique

2.2 Resolutions of the ROII Technique

The resolutions of the ROII technique include horizontal resolution and vertical resolution. The horizontal resolution is determined by the real distance between two adjacent pixels, which depends on the magnification of the microscope and the image resolution of the image processing system. Normally, we obtain a horizontal resolution of 1.4 μm with a 4× magnification of the microscope.

The resolution of the film thickness in the vertical direction is determined by the change in film thickness caused by the variation of per-unit grey value. According to Eq. 5, the variation in film thickness is shown as the following:

$$\Delta h = \frac{\lambda}{4\pi k}[\arccos(\bar{I} + \Delta\bar{I}) - \arccos(\bar{I})] \quad (7)$$

$$\Delta\bar{I} = \frac{2\Delta I}{\mathrm{I}_{\max} - \mathrm{I}_{\min}} \quad (8)$$

where ΔI is the grey value gradation. As shown in Eq. 7, the resolution is concerned with the difference between the maximum light intensity and the minimum light intensity, the interference light wavelength and the refractive index of the lubricant. The distance between the maximum and the minimum light intensity can reach about 150 in our present optical system. In the study reported here, monochromatic light with a wavelength of 600 nm is used. When oil with a refractive index of 1.40 is used as the lubricant, a resolution of 0.5 nm can be obtained according to Eq. 7 [12, 13].

3 Key Techniques for Avoiding Multiple-Beam Interference

Guo and Wong [17] and Wong and Guo [22] calculated the distribution of interference intensity for the optical system at different Cr-film thickness. These researchers claimed that the intensity distribution deviated from a cosine-like curve, resulting in the Cr film increasing to 20 nm. The deviation came from multiple-meam interference and resulted in a larger error in calculating film thickness using Eq. 6. In their approach, the multiple-beam interference is utilized to calculate the lubricant film thickness. However, in our ROII technique, the reflectivity and the transmissivity of the coating must be strictly controlled to avoid multiple-beam interference; in fact, the reflectivity and transmissivity of the Cr layer must be exactly set at 18 and 55%, respectively, giving a result that the Cr film thickness is about 5 nm. The thickness of the chromium layer is an important factor influencing interference, but it is not the only one. A layer of

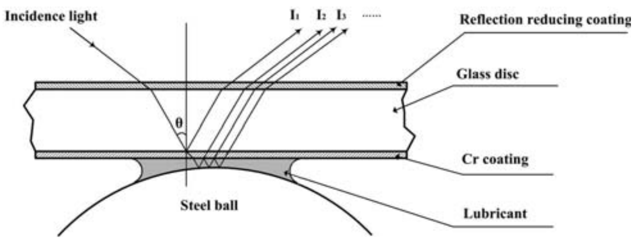

Fig. 4 The schematic image of the multiple-beam interference generated between the two surfaces. I_1, I_2, I_3 Light intensity values of beam 1, 2 and 3, respectively

reflection that reduces the MgF coating is used to reduce the reflectivity of the upper surface of the glass disc from 4 to less than 1%. The reflectivity of the steel ball surface is about 60%. As shown in Fig. 4, when an incidence beam with an intensity of I reaches the chromium layer, it is divided into two beams. One is reflected with an intensity of 18% I, denoted as I_1. The other beam passes through the chromium layer with an intensity of 55% I and then is reflected by the surface of the ball with an intensity of 33% I; part of that beam penetrates the chromium layer again to form beam 2, with an intensity of 18% I, denoted as I_2. By this method, the intensities of beam 3 (I_3) and beam 4 (I_4) are 1.9% I and 0.2% I. Thus, the I_1 and I_2 possess the same intensity, and clear interference fringes can be obtained. The influence of multiple-beam interference caused by I_3, I_4…… can be ignored due to the extremely small intensity compared with I_1 and I_2. As a result, the interference intensity can be verified to be a cosine-like curve distribution caused by I_1 and I_2.

A validation test was carried out using an air wedge formed by a Cr-coated glass plate and a highly polished steel plate. The inset in Fig. 5a shows the parallel interference fringe, and it is clear that the intensity variation with gap thickness strictly follows the cosine function in two-beam interferometry. Figure 5b shows that the reconstruction of the profile matches the original one very well.

4 The Influence of Metal Media in a Two-Beam Interference System

As visible light passes through a metal medium, the intensity will attenuate and the phase velocity will change. The optical characteristics of the metal impact on the two-beam interference system in two ways: attenuation of the intensity and phase change in the metal media and at the interfacial surface, both of which will be discussed separately.

When the light wave is transmitted in the metal media, the scalar expression of the wave is [23]:

$$E_x = E_0 e^{-\sqrt{\frac{\omega\mu\sigma}{2}}z} e^{i\sqrt{\frac{\omega\mu\sigma}{2}}z} \tag{9}$$

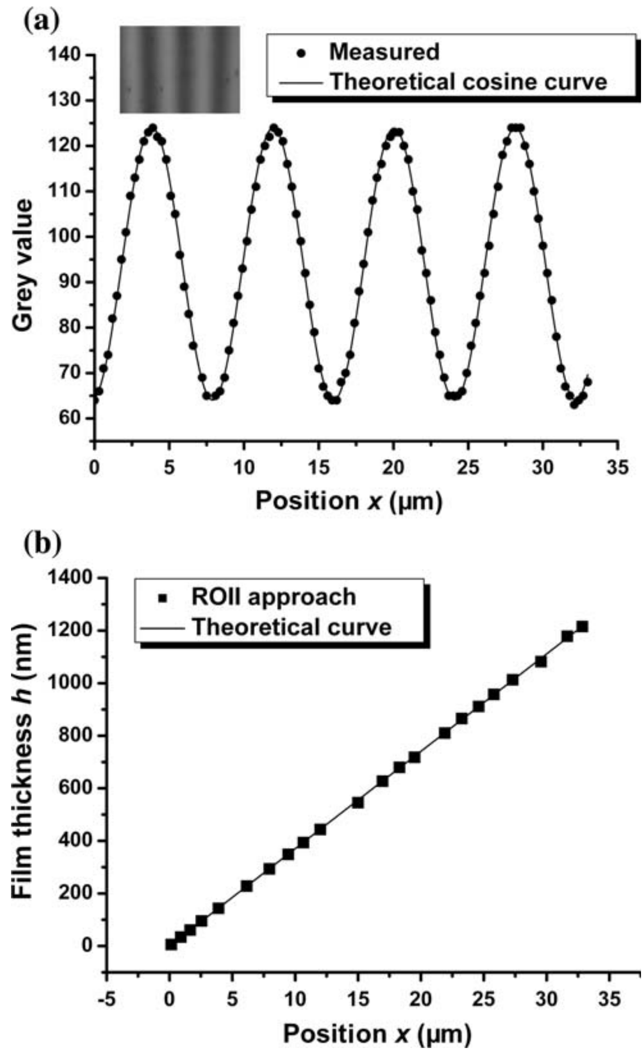

Fig. 5 Measurement of an air wedge between a Cr-coated glass plate and a high precision steel surface. **a** Measured intensity, **b** reconstructed gap profile

where E is the scalar field intensity, ω, μ, σ are the material parameters of the media and z is the transmission distance. For the metal layer with thickness z_m, the intensity is attenuated as the exponential decay of $e^{-\sqrt{\frac{\omega\mu\sigma}{2}}z_m}$, and the phase change is $\sqrt{\frac{\omega\mu\sigma}{2}}z_m$.

For the reflection at the metal interface, according to the basic optical theory, the refractive index (R.I) of metal can be expressed as [23]

$$\vec{k} = k(1 + ie) \tag{10}$$

where $\vec{k}$ is complex number, k and e are real numbers and e is the extinction coefficient.

In a fixed interference system, the phase change caused by the chromium layer and the steel ball surface will be invariable, which has been discussed in Luo [24]. The effect of the metal refraction on the beam intensity has been discussed by Wong and Guo [22]. In a pure two-beam interference system, the cosine function between the interference intensity I and the gap distance will not be affected by a constant phase change and the changes in the beam intensity. The large deviation in the intensity from a cosine curve reported by Wong and Guo [22] was likely caused by the existence of multiple beam components.

In conclusion, the key to the ROII method is eliminating the existence of the multiple-beam interference as much as possible to ensure that the light intensity distribution follow the cosine law in Eq. 1.

5 Discussion

It should be noted that the optical set-up used by Guo and Wong [17, 18] is different from ours, including the light incidence mode, the coating parameters and the process. In the measurement procedure using the ROII technique, I_{max} and I_{min} are very important. A large error in film thickness will be the result if these two values are not correct. An interference image acquired between the flast glass and the steel ball is shown in Fig. 6a, and the measured light intensity distribution is as shown in Fig. 6b. I_{max} and I_{min} are not uniform in the different interference orders outside of the point contact area, and the maximum light intensity value I_{max} becomes smaller and smaller and the minimum light intensity value I_{min} becomes larger and larger with increasing interference order n. As mentioned above, the film thickness is significantly determined by the optical intensity parameters I_{max} and I_{min}.

Guo and Wong [17] presented a light intensity curve deviating from a cosine-like curve (Fig. 7a). As mentioned above, the deviation is attributed to the significant effect of the metal media in their optical system. Figure 7b shows the light intensity distribution measured along the radius in the lateral direction on the interferogram in Fig. 6a. The intensity distribution obtained in our measurement system shows a cosine-like curve with the amplitude of the curve decreasing with the increase of the interference order, as shown in Fig. 7b. The measured grey value can be fitted using Hertz contact theory well.

The measurement under stationary contact is carried out in our study using the ROII method discussed above, with the consideration of non-uniform I_{max} and I_{min}. The calculation result is plotted in Fig. 8a with a dot-curve. The solid line in Fig. 8a is the ball shape calculated by the gap formula out of the contact area using Hertz contact theory.

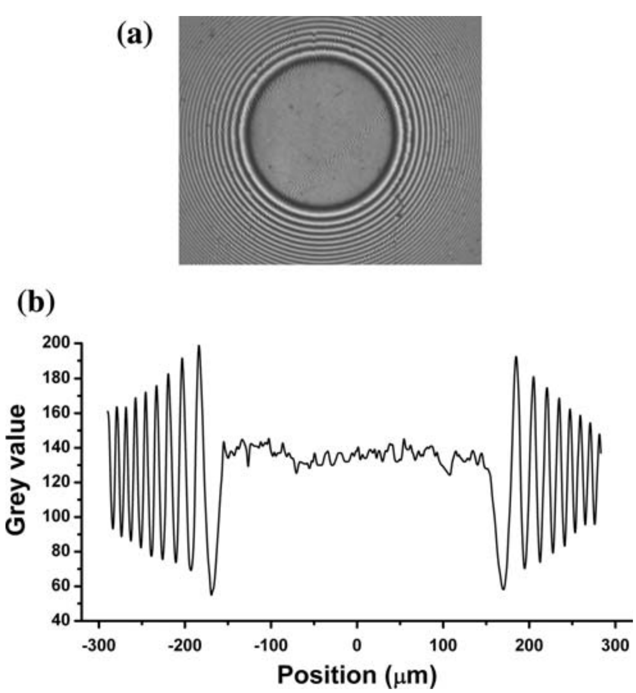

Fig. 6 **a** The interference image under a maximum Hertz pressure of 0.54 GPa and stationary contact, **b** the light intensity distribution along the centerline of the contact region

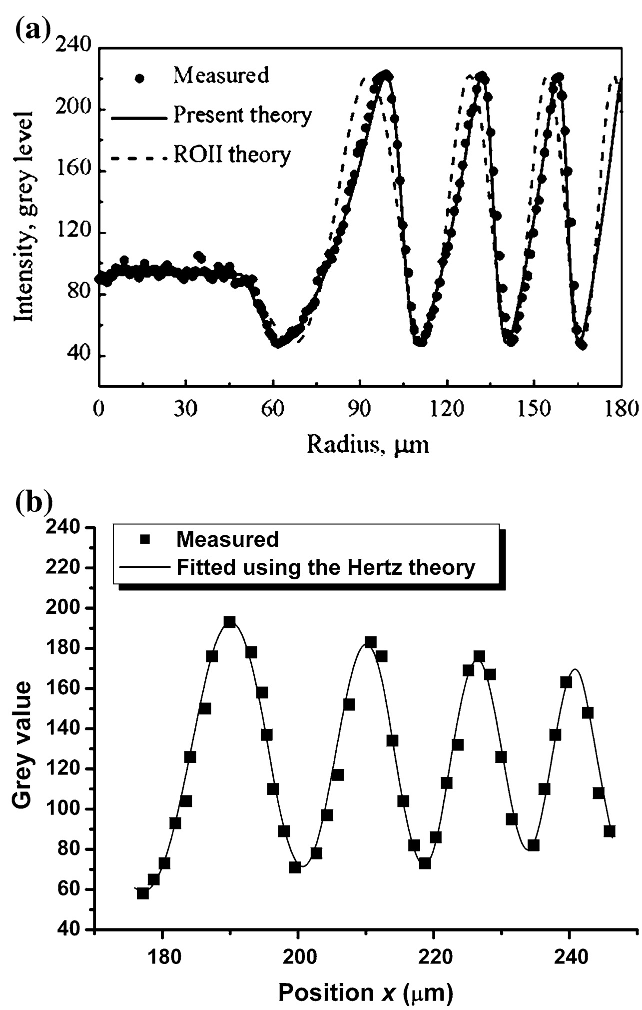

Fig. 7 The light intensity distribution along the centerline of the contact region in Guo and Wong [17] (**a**) and as measured by our ROII instrument (**b**)

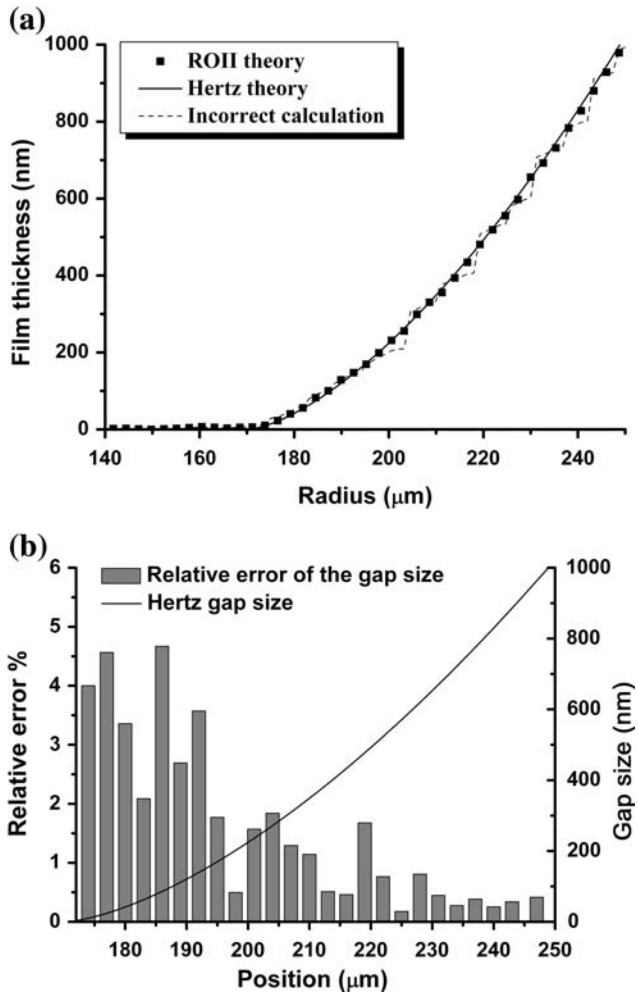

Fig. 8 **a** The film thickness under stationary contact by the ROII method. The maximum Hertz pressure is 0.56 GPa. The diameter of the steel ball is 22.225 mm. The test is carried out at the temperature of 25°C. **b** The relative error of the experiment result compared that obtained using Hertz theory

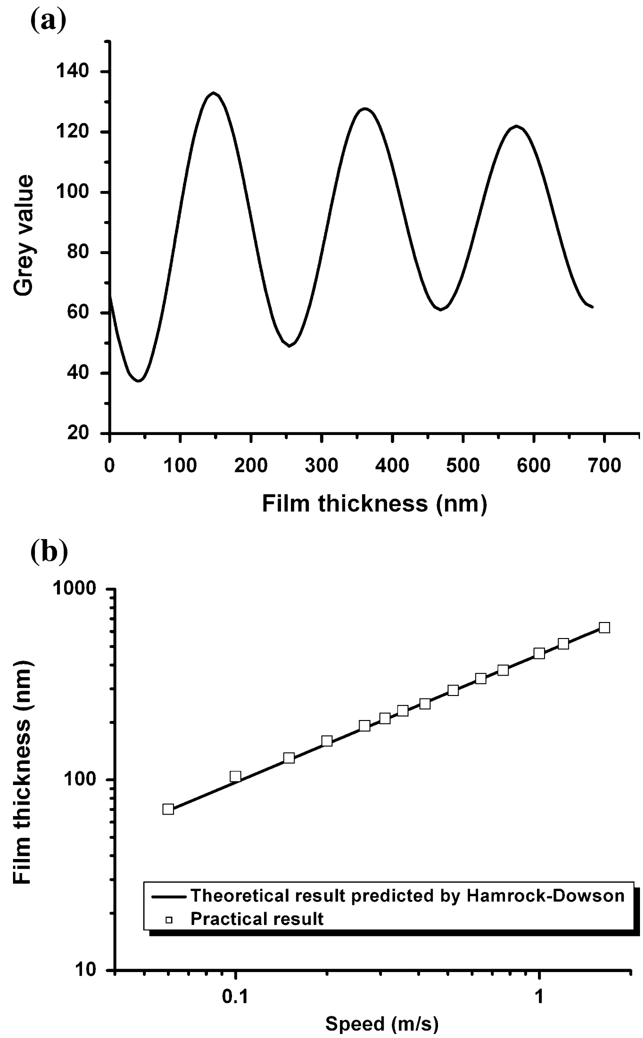

Fig. 9 Practical result. **a** The intensity curve with increasing film thickness in the central contact area, **b** film thickness as a function of speed. Dimethylsilicone oil with a viscosity of 80 cSt and a refractive index of 1.40 at room temperature is used as the lubricant. The maximum Hertz pressure is 0.56 GPa under pure rolling contact. The test is carried out at 25°C

The measured film thickness fits the ball shape very well. The film thickness acquired by using an incorrect method with uniform I_{max} and I_{min} is also plotted for comparison as a broken line (Fig. 8a). The relative error of the measured gap size using the ROII approach compared to the Hertz theory is plotted against the radius in Fig. 8b. The relative error trends to decrease with increasing film thickness. The maximum relative error is found to be 4.6% when the gap size is about 24 nm.

It should be noted that the discussion above is based upon static contact. The calculated film thickness is that around the Hertz contact zone. In the case of elastic hydrodynamic lubrication, the film thickness in the Hertz contact zone will increase with increasing speed. The interference order in the contact area will also increase with this increase in film thickness, and the I_{max} and I_{min} in the contact area also will vary as the interference order increases due to the light absorption of the lubricant. Before film thickness can be measured, a calibration process should be carried out to determine the I_{max} and I_{min} in the contact area for each interference order. Figure 9a shows the practical variation of the I_{max} and I_{min} in the contact area with increasing film thickness. After the calibration, the film thickness measurement can be performed. Figure 9b shows the measured film thickness, which matches the theoretical result predicted by Hamrock–Dowson equation very well.

5.1 Conclusions

A detailed analysis of the characteristics of the film thickness measurement system by the ROII method is presented. A large calculating error in the ROII method is confirmed as originating from the use of an inappropriate optical system and inappropriate coating parameters. The ROII method should not be used in an ordinary optical system but, rather, in a specific optical system with negligible multi-beam reflections. The existence of the multiple-beam components in the optical system will result in the distribution of the light intensity deviating from a cosine-like curve and, therefore, in a large impact of the metal media on the ROII method. In our ROII method, the thickness of the Cr film was kept to about several nanometers in order to eliminate the influence of multiple-beam interference. The I_{max} and I_{min} are not uniform at different interference orders. With proper I_{max} and I_{min}, the lubricant film thickness can be measured accurately by the ROII method. The calculation method is specifically developed for the two-beam interference system. The film thickness resolutions in the horizontal and vertical directions are 1.4 μm and 0.5 nm, respectively.

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References

1. Cameron, A., Gohar, R.: Theoretical and experimental studies of the oil film in lubricated point contact. Proc. R. Soc. A **291**, 520 (1966)
2. Foord, C.A., Hammann, W.C., Cameron, A.: Evaluation of lubricants using optical elastohydrodynamics. ASLE Trans. **11**, 31–43 (1968)
3. Wedeven, L.D., Foord, C.A., Westlake, F.J., Cameron, A.: Optical elastohydrodynamics. Proc. Inst. Mech. Eng. **184**(1), 487–505 (1969–1970)
4. Westlake, F., Cameron, A.: A study of ultra-thin lubricant films using an optical technique. In: Proceedings of the Symposium on Experimental Methods in Tribology, March 1968; also Proc. Inst. Mech. Eng., vol. 182, pp. 75–78 (1967–1968)
5. Westlake, F.J.: An interferometric study of ultra-thin fluid films. PhD thesis. University of London, London (1970)
6. Spikes, H.A., Guangteng, G.: Properties of ultra-thin lubricating film using wedged spacer layer optical interferometry. In: Dowson, D. (ed.) Proceedings of the 14th Leeds-Lyon Symposium on Tribology, pp. 275–279 (1988)
7. Johnston, G.J., Wayte, R., Spikes, H.A.: The measurement and study of very thin lubricant films in concentrated contact. STLE Tribol. Trans. **34**(2), 187–194 (1991)
8. Cann, P.M., Spikes, H.A., Hutchinson, J.: The development of a spacer layer imaging method (SLIM) for mapping elastohydrodynamic contacts. STLE Tribol. Trans. **39**, 915–921 (1996)
9. Spikes, H.A., Cann, P.M.: The development and application of the spacer layer imaging method for measuring lubricant film thickness. Proc. Inst. Mech. Eng. J: J. Eng. Tribol. **215**(J3), 261–277 (2001)
10. Glovnea, R.P., Forrest, A.K., Olver, A.V., Spikes, H.A.: Measurement of sub-nanometer lubricant films using ultra-thin film interferometry. Tribol. Lett. **15**, 217–230 (2003)
11. Roberts, A.D., Tabor, D.: The extrusion of liquids between highly elastic solids. Proc. R. Soc. Lond. A **325**, 323–345 (1971)
12. Luo, J.B.: Study on the experimental technique and properties of thin film lubrication. PhD thesis. Tsinghua University, Beijing (1994)
13. Luo, J.B., Wen, S.Z., Huang, P.: Thin film lubrication, part I: the transition between EHL and thin film lubrication. Wear **194**, 107–115 (1996)
14. Luo, J.B., Wen, S.Z.: Mechanism and characteristics of thin film lubrication at nanometer scale. Sci. China Ser. A **39**(12), 1312–1322 (1996)
15. Luo, J.B., Huang, P., Wen, S.Z., Lawrence, L.: Characteristics of liquid lubricant films at the nano-scale. ASME Trans. J. Tribol. **121**(4), 872–878 (1999)
16. Luo, J.B., Shen, M.W., Wen, S.Z.: Tribological properties of nanoliquid film under an external electric field. J. Appl. Phys. **96**(11), 6733–6738 (2004)
17. Guo, F., Wong, P.L.: A multi-beam intensity-based approach for lubricant film measurements in non-conformal contacts. Proc. Inst. Mech. Eng. J.: J. Eng. Tribol. **216**, 281–291 (2002)
18. Guo, F., Wong, P.L.: A wide range measuring system for thin lubricating film: from nano to micro thickness. Tribol. Lett. **17**, 521–531 (2004)
19. Yan, Y.B.: Applied Physical Optics. China Machine Press, Beijing (1990)
20. Born, M., Wolf, E.: Principles of Optics, 5th edn, pp. 257–270. Pergamon Press, New York (1975)
21. Zhuang, S.L., Qian, Z.B.: Optical Transfer Function. China Machine Press, Beijing (1981)
22. Wong, P.L., Guo, F.: Effects of absorbing media on relative optical interference intensity ROII technique. Sci. China Ser. A **44**, 431 (2001)
23. Bonn, M., Wolf, E.: Optical Principle. Science Press, Beijing (1978)
24. Luo, J.B.: On Experimental Technique and Characteristic of Thin Film Lubrication, pp. 21–23. Tsinghua University, Beijing (1994)