A Study on the Measurement for the Nano Scale Film Formation of Ultra Low Aspect Ratio

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Keywords: elastohydronynamic lubrication(ehl), nano scale film thickness, aspect ratio, trichromatic incident light filtering system, coaxial alignment, nano resolution, image processing method,

Abstract. The measurement of ultra low aspect ratio fluid film thickness is very crucial technique both for the verification of lubrication media characteristics and for the clearance design in many precision components such as MEMS, precision bearings and other slideways. Many technologies are applied to the measurement of ultra low aspect ratio fluid film thickness (i.e. elastohydrodynamic lubrication film thickness). In particular, in-situ optical interferometric method has many advantages in making the actual contact behaviors realized with the experimental apparatus. This measurement method also does the monitoring of the surface defects and fractures happening during the contact behavior, which are delicately influenced by the surface conditions such as load, velocity, lubricant media as well as surface roughness. Careful selection of incident lights greatly enhances the fringe resolutions up to ~1.0 nanometer scale with digital image processing technology.

In this work, it is found that coaxial aligning trichromatic incident light filtering system developed by the author can provide much finer resolution of ultra low aspect ratio fluid film thickness than monochromatic or dichromatic incident lights, because it has much more spectrums of color components to be discriminated according the variations of film thickness. For the measured interferometric images of ultra low aspect ratio fluid film thickness it is shown how the film thickness is finely digitalized and measured in nanometer scale with digital image processing technology and space layer method. The developed measurement system can make it possible to visualize the contact deformations and possible fractures of contacting surface under the repeated loading condition.

Introduction

Many precision mechanical elements have multi-physics behaviors because their contact sizes and gaps are very small compared to the sizes of contacting bodies. The contact behaviors in such elements are generally dealt with molecular dynamics in physics field as well as continuum mechanics in engineering field. The terminology for contact behaviors with thin media between contact bodies in the tribology field is boundary and elastohydrodynamic lubrications (ehl), which are not easily distinguishable in real engineering contacts, although the principle of contact theory makes any difference between them. If the film thickness between the contact bodies comes to the ~nm scale, making any differences between the two terminologies such as boundary and ehl is meaningless. In particular, if the contact area is very large compared to contact gap of ~nm scale shown in Fig. 1, the lubricating media's behaviors is very different from its bulk behaviors due to the molecular restructuring or relaxation behaviors. Under the circumstances of this contact condition, it is necessary to investigate the lubricant behaviors of shear resistance over the contact area in order to control the frictional performance in as well as the wear protection in the precision devices.

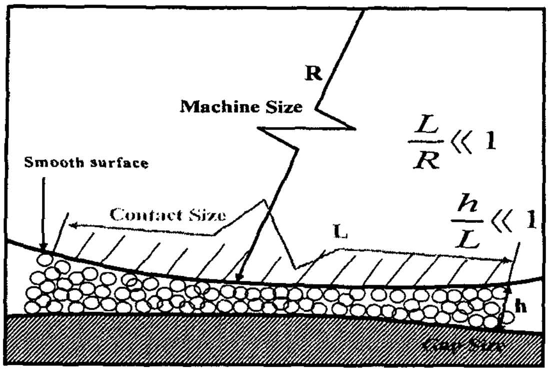
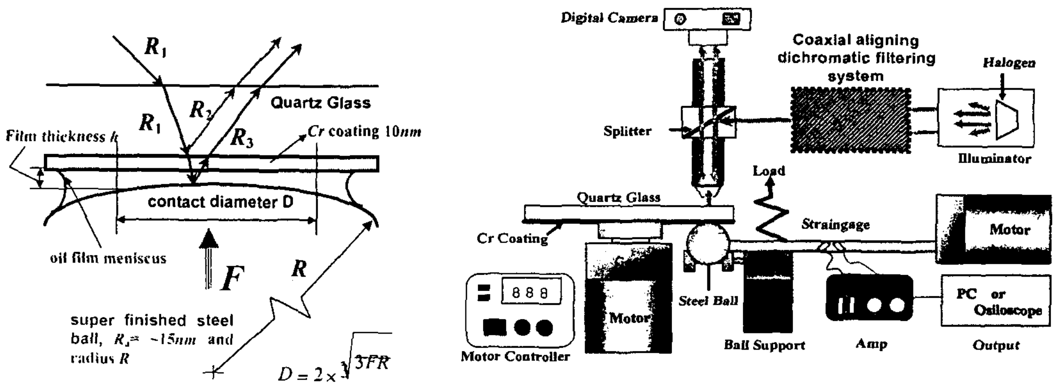


Fig. 1 Contact geometry with ultra low aspect ratio (h/L<10^{-5}) with ~nm scale gap of lubricating media.

Many experimental studies have been performed regarding the measurement of gap distance for ultra low aspect ratio contact behaviors. In-situ interferometric measuring system for the lubricant film thickness is developed with simulating the contact conditions for ehl and boundary lubrication.[2] The advantages of interferometric measuring system is that the resolution for the film thickness is 1~2 nm scale over the contact area ~150μm diameter. If the incident light has well-filtered wavelength, the resolution for the film gap is enhanced down to 1nm scale.

In this work, we have developed the in-situ interferometric measuring apparatus for film gap of ~nm scale with trichromatic coaxial incident light system and digital image processing system. Under the various contact conditions, the film gaps over the contact area are investigated by visualizing the contact behaviors in real time, which will provide useful information how the contact in the precision system is protected for well performance and long endurance life.

Experimental Apparatus



(a) (b)

Fig. 2 (a) Optical path difference for the film thickness between two solid materials (b) In-situ interferometry system for ultra low aspect ratio contact mechanism.

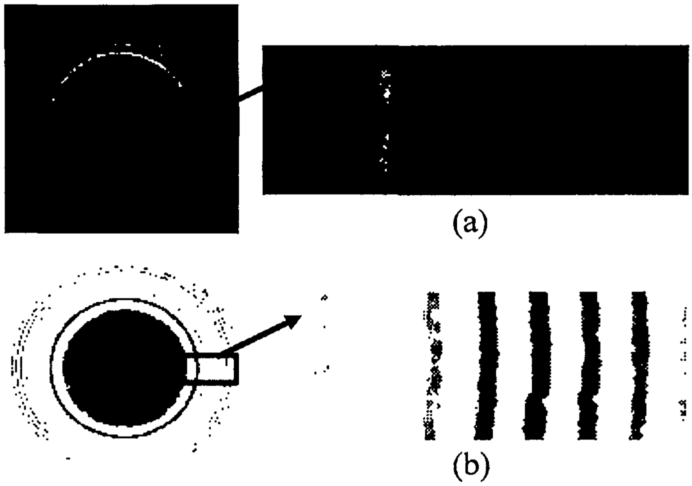


Fig. 3 Fringe spectrums for (a) monochromatic and (b) trichromatic incident lights.

The performance of the optical interference method is very strongly dependent on the coating layer on the transparent glass whose thickness are coated with around 10*nm* thickness of *Cr* layer on the highly transparent glass of 150*mm* diameter as shown in Fig. 2. White light from halogen lamp is filtered with day red, green and blue filters after which the wavelengths of three kinds of incidents lights are combined into trichromatic light source. The super finished steel ball of 25 *mm* diameter with the roughness of R_a= ~15*nm* scale are placed contacting with glass disk so that the trichromatic incident light can be reflected in order to get the most distinct interferometric resolution without any noise.

The fringe spectrums for monochromatic (Fig. 3 (a)) and trichromatic (Fig. 3(b)) incident lights, namely Newton rings under the static loading condition are vividly different by the fringe thickness and color variation. This is the reason that the gap between the two solid materials can be measured by ~1nm resolution with digital image processing technology. In this experimental apparatus, the elastic modulus and Poisson's ratios of glass disk and steel ball are E_b= 207 × 10^9 N/m^2, E_d= 763$10^9$ N/m^2, ν_b= 0.30, ν_d =0.25, respectively.

Digital Image Processing for Nanometer Scale Resolution

One of the powerful methods in color decomposition is CIE 1976 $L^*a^*b^*$ decomposition technique that uses three independent components L^*, $a^*$and b^* in order to reproduce digitally formatted colors in the computer. CIE $L^*a^*b^*$ decomposition of interferogram colors in in-situ interferometric image can provides perceptual uniformity, device. The tristimulus values of $X_{n,}$,Y_n and Z_n for reference trrichromatic incident light is computed after the red, green and blue components (*RGB*) of the incident light are decomposed. Every pixel in the color interferogram outside of Hertzian contact circle as shown in Fig. 4 is decomposed into RGB values, which are subsequently converted into L^*, $a^*$and b^* values for the calibration of film thickness. The film thickness outside of Hertzian contact area is obtainable by numerical computation of Hertzian contact theory. The film gap-color chart is then obtained by matching the L^*, $a^*$and b^* values with the gap between steel ball and glass plate from Hertzian contact theory. [17] (Fig. 4)

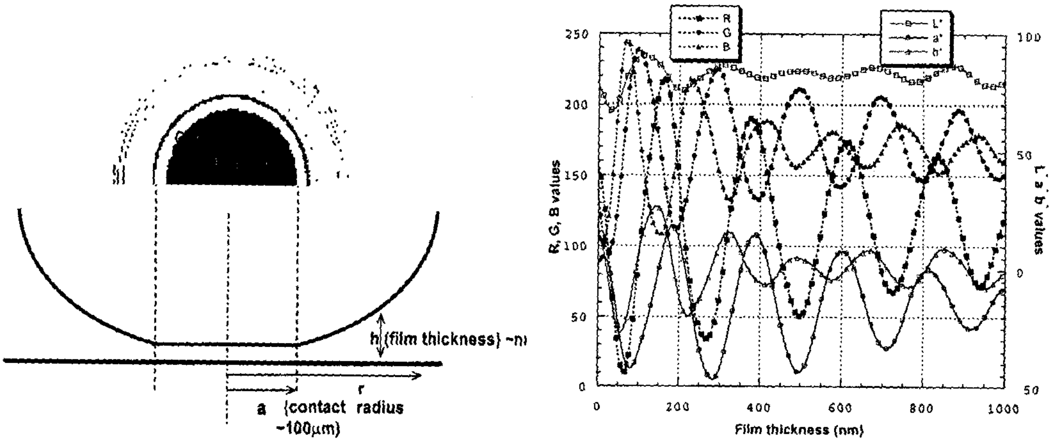


Fig. 4 Film thickness-color chart for the corresponding interferometric fringe spectrum from Hertzian contact.

With the film thickness-color chart, the gap between two solid materials can be fully investigated over the contact area in the range from *0nm* to 1000*nm*, which cannot be accessible by other measuring systems such as capacitance gap sensor, infrared light and any other spectrometers measuring only averaging value over the single large spot (~*mm* diameter size) of contact area.

Once the ehl film thickness-color chart is made as shown in Fig. 4, every $L^*a^*b^*$ formatted pixel in the captured color interferogram of ehl film thickness is compared with the values in the chart. In order for the selected pixel to get the nearest value to the computed $L^*a^*b^*$ chart, sweeping all over the captured pixels is performed for the minimization of color difference ΔE^*_{ab} with the following color difference equation.

$$\Delta E^*_{ab} = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}. \quad (1)$$

Measurement of Nanometer Scale Gap with Space Layer

Fine resolution down to ~1nm scale is obtained by using the trichromatic incident light system. However, this method can not guarantee measuring the film thickness itself of ~nm scale, because the film thickness less than λ/4 of incident light (i.e., λ=420nm for blue light) is not measurable with optical metrology system. Therefore, the transparent space layer of controllable thickness is placed on the glass disk. The film thickness is measured with the inclusion of the space layer thickness and the added value of both film and space layer thickness in Eq. 2 is computed by the image processing method explained above.[6]

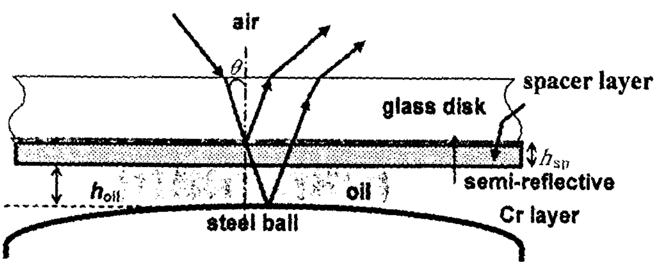


Fig. 5 Optical path difference for ~*nm* film measurement using space layer.

$$n_{oil}h_{oil} + n_{sp}h_{sp} = \frac{(N-\varphi)\lambda}{2Cos\theta}, \qquad N = 1, 2, 3, 4\ldots \qquad (2)$$

, where, n_{oil} and n_{sp} mean the refractive index for oil and space layer, respectively, and N is fringe order. λ is the wavelength of incident light and θ is the angle of incident light path onto the glass disk.

Results

The experimental contact conditions are selected into two modes. The first mode is that glass disk has linear velocity of 0.408m/s and steel ball does -0.412m/s, which causes rolling-slipping ratio Σ=410. Due to the reverse directions between the two contacting solid materials, the lubricant stays in the contact area longer than when the contact is pure rolling case so that it makes large lubricant reservoir in the gap. Therefore, the film gap is thicker in this spot than in the other area of the contact area. This behavior is presented in the left of Fig. 6 in the form of the interferogram, which is converted into the film thickness by the digital image processing technology with surface graph over the contact area as shown in the right of Fig. 6.

The second mode is that the glass disk accelerates from zero to 0.286m/s during Δt=0.1s and the steel ball remains without rotating for lubricant A and B. The interferograms for film thicknesses are captured as shown in Fig. 7. From these interferograms, the film thicknesses in the horizontal contact direction are computed in Fig. 8 and 9. At the moment of sliding stating, the film thickness varies from zero to ~50nm in the sliding direction, which can not be obtained in other previous measurement technology.[3]

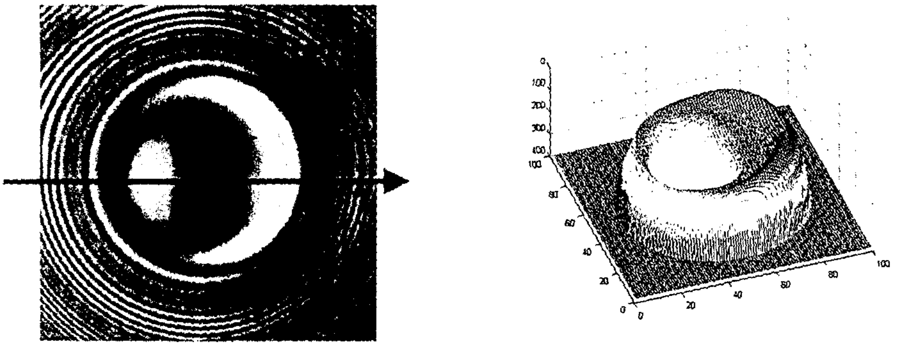


Fig. 6 Film thickness computing from the measured interferomgram by digital image processing technology (The line in the left figure presents the horizontal contact direction.) with Σ =410 (u_d=0.408m/s, u_b=-0.412m/s), where Σ is defined as $2\times(u_d - u_b)/(u_d + u_b)$ for lubricant B.

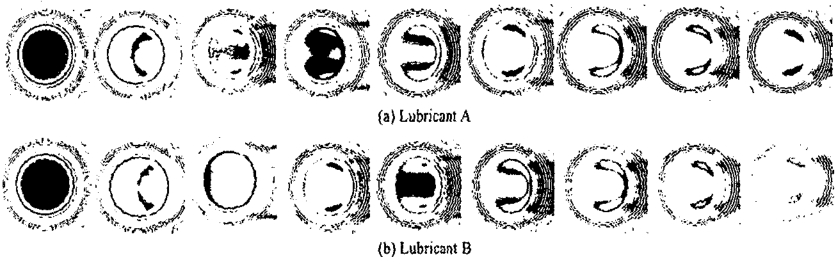


Fig. 7 Interferometric images during acceleration from 0.000m/s to 0.286m/s during Δt=0.1s for lubricant A and B.

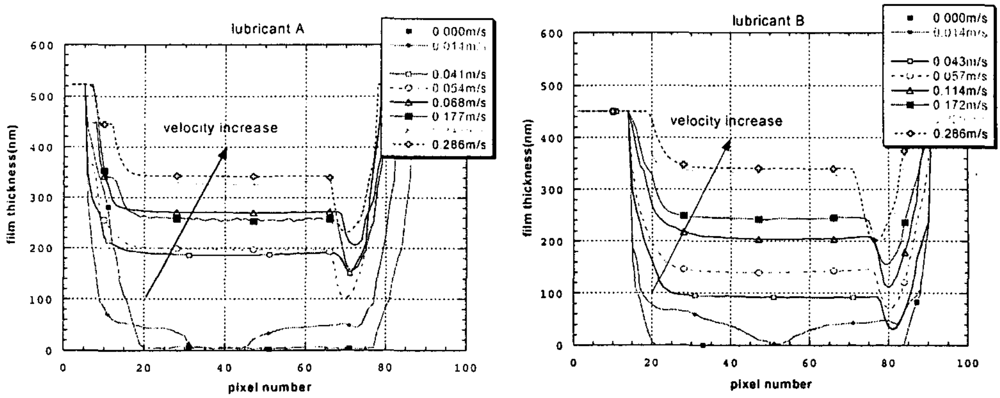


Fig. 8 Horizontal film thickness variations for Fig. 7 (a) and (b) images.

Conclusion

In this study, we have developed the measurement technology of ultra low aspect ratio contact feature and both the measurement resolution and film thickness are obtained down to ~1nm scale. With the developed technologies, two kinds of contact modes are investigated, which are very difficult with any other conventional measurement technologies. In order to verify the developed technology, two kinds of contact modes that most contact damages happen during sudden start-stop and reversal contact sliding are selected and very successful monitoring and visualization method for ultra low aspect ratio contact feature are obtained.

Acknowledgement

This work was supported by the Korea Research Foundation Grant (KRF-2003-041-D00097).

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