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Behavior of hydrodynamic lubrication films under non-steady state speeds

H.C. Liu [a,b], F. Guo [a,*], B.B. Zhang [a], P.L. Wong [b]

[a] School of Mechanical Engineering, Qingdao Technological University, 11 Fushun Road, Qingdao 266033, China
[b] Department of Mechanical and Biomedical Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong, China

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ABSTRACT

The transient characteristics of hydrodynamic lubricating film thickness and its change rate (or squeeze effect) under start-up/shut-down and acceleration/deceleration motions were analyzed using a newly developed optical slider-on-disc test system. For a start-up/shut-down process, the change rate of film thickness attains its maximum when the final steady speed is achieved. In accelerating/decelerating motions, it was shown that the film thickness varies with some time lag to the speed, but its change rate is in phase with the speed. Influences of loads, frequencies and the maximum speed on the time lag were investigated. The film thickness hysteresis during acceleration–deceleration was explained by the measured squeeze effect. Numerical calculation was also carried out and the results quantitatively agree with the experiments.

1. Introduction

Hydrodynamic lubrication (HL) exists widely in industrial machine elements with conformal contacts, such as sliding/journal bearings, squeeze film dampers and hydro-viscous drive speed-regulating start [1]. Lubricating film thickness is one of the key operating parameters, which directly indicates the effectiveness of fluid film lubrication. Breakdown of lubrication film eventually gives rise to wear or failure of the lubricated surfaces, and is easy to occur under non-steady state conditions. For example, lubricating films undergo intermittent motions in a mechanical system driven by a step-motor, and failure may occur if the lubrication film is not well understood and designed. Therefore, it is an essential issue to obtain the true oil film thickness under dynamic conditions in HL studies. Up to now, transient behaviors of hydrodynamic lubrication are mainly studied through theoretical/numerical analyses based on the Reynolds equation or the well-known Navier–Stokes equation. For plane slider or journal bearings, models and advanced algorithms have been presented to examine the film thickness, pressure variation, load-carrying capacity, temperature field and rheological effect under transient conditions, and large amounts of reports have been presented and Ref. [2–6] only list some of the work. Venkateswarlu and Rodkiewicz [3] showed that when the sliding speed is closing to its final value in a start-up process, the transient load capacity and drag force asymptotically approach their steady state values. Kennedy et al. [4] displayed that for a step change of the slider speed, the transient temperature and pressure are dependent of the initial conditions and the final speed of the slider. Yang and Rodkiewicz [5] numerically studied time-dependent behaviors of a centrally supported tilting pad bearings subjected to harmonic vibration and obtained the pressure and temperature change. A dynamic parameter was introduced to describe the effects of the tangential and normal motions. However, it is not easy to experimentally study transient HL film thickness in details, for example, those generated by a fixed-inclination slider bearing which is a basic model in lubrication theory [1]. Therefore some theoretical work has not been validated yet. A number of test methods have already been developed [7–14] and efforts are being made to study the transient behaviors. However, most of those experimental approaches enable the measurement of average film thickness only or the profile of the film shape with a relatively low resolution [9–14] and they are more suitable for industrial applications for identifying the effectiveness of lubrication.

On the other hand, optical interferometry proves to be very successful in the laboratory measurement of non-conformal EHL film thickness, and has been used in transient EHL under variable speed conditions including start-up, shut-down, reciprocating motion, unidirectional speed variation and other cyclic acceleration–deceleration motion [15–21]. Nishikawa et al. [15] presented EHL film data under reciprocating motion in ball-on-disc rolling/sliding contact and some intrinsic features of film building were revealed. The EHL film breathes cyclically as the wedging and squeezing action are not in phase, and film formation changes with oil types indicating the non-Newtonian and thermal effects. Their experimental results were subsequently correlated to the numerical analyses by Vahid et al. [22]. More

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[*] Corresponding author.
E-mail address: mefguo@163.com (F. Guo).

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Nomenclature

b	length of the slider in x (sliding) direction, m
h	film thickness, m
h_1, h_0	film thickness at inlet and outlet, m
H	dimensionless film thickness, $h/(h_1-h_0)$
H_0	dimensionless outlet film thickness, $h_0/(h_1-h_0)$
l	width of the slider in y direction, m
p	hydrodynamic pressure, Pa
P	dimensionless pressure, $p(h_1-h_0)^2/6\eta b u_0$
Q	dynamic parameter, $(\lvert\partial h_0/\partial t\rvert/h_0)/(u/b)$
t	time, s
T	dimensionless time, $t/(b/u_0)$
u	x-component of sliding velocity, m/s
u_0	reference velocity, m/s
U	dimensionless x-component of sliding velocity, u/u_0
w	applied load, N
W	dimensionless applied load, $w(h_1-h_0)^2/(6\eta u_0 l b^2)$
W^*	dimensionless load-carrying capacity, $(w/l){h_0}^2/(6\eta u b^2)$
x	cartesian coordinate in sliding direction, m
X	dimensionless coordinate in sliding direction, x/b
y	cartesian coordinate perpendicular to sliding direction, m
Y	dimensionless coordinate perpendicular to sliding direction, y/l
α	inclination angle of the slider, rad
η	viscosity of lubricant, Pa s

measurements have been found in the literature to deliberately explore the EHL film thickness variation with variable entrainment speeds [16–21]. The time lag of the central film thickness to the speed was measured under reciprocating entrainment conditions [16,17] and attributed to the movement to the contact center of the thinner film at the contact rim, which is originally generated by a squeeze effect. The results were correlated to the numerical analyses by Venner and Hagmeijer [23]. The intermolecular force was also presented by Al-Samieh and Rahnejat [24] to account for the film thickness hysteresis when ultrathin film thickness is reached. However, the minimum film thickness does not show obvious phase shift with the speed in Ref. [17]. With unidirectional cyclic motion, it has been shown that there is film thickness hysteresis between the acceleration and the deceleration for both the central film thickness and the minimum film thickness. The film thickness in deceleration is larger, at shown in the work by Sugimura et al. [16], Glovnea and Spikes [18] and Ciulli et al. [19,20]. Furthermore this film thickness hysteresis is tentatively attributed to the different lubricant entrainment at different times [19].

Generally, it can be argued that the above inherent behaviors under transient conditions mostly come from the squeeze effect which is absent in steady state fluid film lubrication. Thus the understanding of the individual squeeze effect is certainly beneficial to the area of lubrication. However, EHL is a complicated process. The squeeze behavior and other effects are interrelated and cannot be readily separated. An alternative approach is to measure the squeeze behavior under hydrodynamic conditions where the flow behavior is only dominated by Reynolds equation. Unfortunately, the optical EHL test system cannot be directly in practice extended to the film thickness measurement of conformal HL due to difficulties in the flat-to-flat contact alignment and the limited measurement range. Recently, an optical slider-on-disc test rig [25] has been developed by the authors for detecting hydrodynamic lubrication film thickness. With a parallel mechanism for accurate slider inclination setting and a dichromatic interference intensity modulation (DIIM) approach for a rapid and a large range of measurement [26,27], the slider-on-disc test rig is capable for the measurement of transient HL film thickness. The objective of the present paper is to revisit the hydrodynamic lubrication theory with this newly developed optical test rig. The main focus is on the film formation and the individual squeeze effect under non-steady state conditions.

2. Experimental method

A custom-made optical slider-on-disc test rig [25] was used in the present study. As schematically illustrated in Fig. 1, the lubricated contact pair consists of a fixed-incline steel slider and a transparent rotating BK7 glass disk, in which a thin lubrication film can be generated once the disk rotates. The glass disk surface in contact with the slider was coated with a semi-reflective Cr coating which was protected by an additional transparent layer of SiO_2. The sliding surface of the steel slider was highly polished to the roughness R_a around 9 nm. The slider inclination angle α can be known precisely through the number of fringes formed in the contact. The prescribed inclination angle can be adjusted and locked by the adjusting bolts located on the load arm. The term “film thickness” used in this study is referred to as the minimum film thickness h_0 at the outlet of the slider bearing, as depicted in Fig. 1.

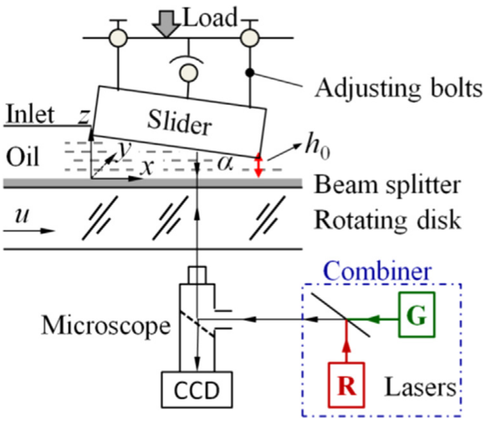

Fig. 1. Schematic diagram of the slider-on-disc setup using dichromatic interferometry.

To enable measurement of the rather thick and rapidly changing transient film, dichromatic laser lights were adopted instead of the conventional white light/monochromatic light. Two sets of interference fringes were formed using two independent laser beams (with wavelengths of 653 nm and 532 nm) and recorded by a 3CCD camera at the rate of 25 fps. The film thickness h_0 was obtained with the newly established dichromatic interference intensity modulation (DIIM) approach [26,27]. In this approach, a modulated intensity signal is obtained by the intensity subtraction between the two sets of fringes (red and green). The modulating signal or beat wave of this modulated intensity signal presents an equivalent wavelength, which is much larger than the wavelengths of the red and green components. With a proposed criterion to distinguish the first 3 half-cycles of the beat wave the measuring range can be significantly enlarged without wavelength ambiguity. With the red and green lights of 653 nm and 532 nm wavelengths respectively, the measurement range can be up to 4 μm.