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Experimental study of elastohydrodynamic lubrication behaviour under single oil droplet supply

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ABSTRACT

In this study, an oil droplet passing through an elastohydrodynamic lubrication contact is observed via interferometry, and the effects of droplet size, entrainment speed, load, and slide/roll ratio (*SRR*) are studied. The results show that the surface area of the droplet is enlarged because of the squeeze spread and capillary force at the inlet region, which influence the film growth. With a large droplet size, the spreading diameter increases and a thick film is generated. When the entrainment speed increases, the surface area enlargement of the oil droplet at the inlet is found to be insufficient, and only a local dimple-shaped film is formed. The *SRR* has a direct effect on the lubricant distribution. In particular, the load and viscosity effects exhibit different characteristics compared with the case of typical fully flooded lubrication.

1. Introduction

The current industry has an increasing demand for minimization of the quantity of oil used to lubricate tribo-pairs for saving energy and reducing emissions. There has been significant progress in the lubrication strategies for engineering applications, including oil–jet, oil–drop, oil–-mist, and oil–air lubrication [1–6]. Among the above solutions, oil–air lubrication is preferred for its low increase in temperature rise and low-friction loss when used in high-speed and precision mechanical components where small quantities of lubricants are metered and transported by compressed air along a pipe wall in the form of streaks, and finally delivered to the lubrication points as small droplets [4–9]. Numerous studies have been conducted to demonstrate the effect of the working parameters of oil–air lubrication systems on the lubrication efficiency, in particular, for spindle bearings. Jeng and Gao established a test rig for high-speed bearings with oil–air lubrication and studied the relationship between the operating parameters and temperature increase [4]. Jiang and Mao investigated the effects of the pipe length, oil discharge interval, oil viscosity, and nozzle design on the performance of hybrid ceramic and steel ball bearings [5]. A parametric study of the oil–air lubrication of a high-speed spindle was performed by Wu and Kung, who proposed that the oil discharge, lubrication cycle, and air pressure were the three dominant factors causing the temperature increase of the spindle [6]. When applying oil–air lubrication in a continuous-casting machine, fresh oil and cooling air were supplied to the bearings for obtaining more stable films, reducing the temperature increase, and keeping the bearing free of foreign contaminants and water [7]. The oil–air lubrication method is also utilized in turning tools [8] and gear lubrication systems [9]. However, little is known regarding the mechanism of film formation in tribo-pairs when a lubricant is supplied as micro oil droplets.

Excellent work has been conducted to formulate the theory of fully flooded elastohydrodynamic lubrication (EHL), for example, the research by Gohar and Cameron [10], Hamrock and Dowson [11], Venner [12], Spikes [13], and others [14–17]. However, in engineering applications, lubricant starvation often occurs in case of EHL, and several studies have been reported in this regard, such as those by Wedeven et al. [18], Chiu [19], Pemberton et al. [20], and others [21–23]. These studies investigated the effects of the oil–air meniscus position, replenishment of the lubricant, and properties of the lubricants on the film generation. The fact that the lubrication achieved with oil droplets is also effective in the regime of lubrication starvation, as shown in Fig. 1, has been demonstrated in our lab. Owing to the discontinuous distribution of oil droplets, lubricant supply starvation occurs at the inlet, and consequently, film formation exhibits transient behaviours. However, the above studies on the starved EHL theory [18–23] cannot be used directly to explain Fig. 1 as they usually model starvation as a uniform thin layer on the bounding surfaces. It can be clearly seen that the lubricating film is the result of the synergistic action of an individual droplet and its neighbours. In addition, it is critical to understand the film generation behaviour of a single droplet before comprehending how several droplets work together to

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Nomenclature

a	diameter of a Hertz contact, m
y	coordinate along the rolling direction, m
x	coordinate perpendicular to the rolling direction, m
V	volume of oil droplet, m^3
w	load, N
θ	contact angle, degree
η	viscosity, Pa·s
u_d,u_b	surface velocity of disc and ball,m/s
u	entrainment speed, m/s
L	distance of the oil droplet to the center of the contact zone,m
L_0	the initial value of L,m
T	time instant,s
t_n	nominal lubrication time,s
D_{ini}	the initial diameter of the droplet,m
SD	spread width,m
SRR	slide/roll ratio

form a film.

Qian et al. [23] used fluorescence to examine the lubricant flow around an EHL contact when oil droplets with 20–100 μL volume were supplied. Emden et al. [24] demonstrated the cavitation bubble formation at the exit of an EHL contact. They found that the shape of the oil pool and transition process were affected by the amount of oil supplied and its motion. Most recently, Li et al. [25] measured the spreading behaviour of an oil droplet when it surrounded a static point contact and examined the film formation when it was entrained into the point contact with different working parameters. Through numerical calculations, Zhang et al. [26] and Li et al. [27] studied the film formation mechanism of an oil droplet entering the EHL contact region and revealed the effects of different parameters. However, more experimental work is required to address the topic of film formation and its lubrication behaviour when a single droplet is supplied to an EHL contact. Therefore, the present study was proposed to measure the behaviour of a single oil droplet passing through an EHL point contact via optical interferometry. The effect on the film formation is studied in terms of the diameter of the droplet, oil viscosity, entrainment velocities, loads, and *SRRs*.

2. Experimental apparatus and conditions

2.1. Apparatus

The experiments were performed using an optical EHL test rig, as schematically shown in Fig. 2, consisting of a steel ball loaded against a glass disc. The loaded side of the glass disc is coated with a bilayer (bottom Cr and top SiO_2), and the reflectance is approximately 20% [28]. A high-precision polished steel ball with a diameter of 25.4 mm and roughness of $Ra = 8$ nm is used. Two servo motors drive the glass disc and steel ball separately to achieve different *SRRs*. The interferograms were recorded by a high-speed video camera.

In this study, the entrainment speeds were varied from 0 to 0.1 m/s.

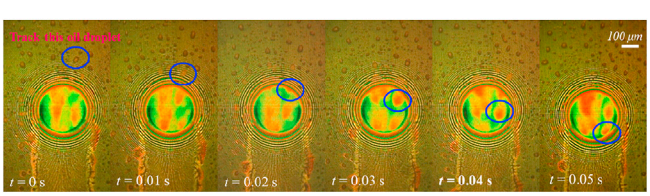

Fig. 1. Oil droplets on the disc surface and interferograms at different time instants in an EHL contact.

Before the experiments, the oil droplet was arranged on the glass disc with a micropipette. The dichromatic interference intensity modulation (DIIM) approach was used to reconstruct the film profiles, and detailed descriptions can be found in Refs. [29,30].

2.2. Test lubricants and others

The experiments were performed at a temperature of 20 ± 1 °C and humidity of 50 ± 5% RH. Different types of lubricants were used and their physical properties are listed in Table 1. Before each test, both the ball and disc were cleaned with ethanol and acetone and then dried with dry nitrogen.

In the tests, the exact volume of the droplet was calculated by equation (1). As shown in Fig. 3, the oil droplet resting on the disc surface is assumed to have the shape of a spherical segment. D_{ini}, defined as the initial base diameter of the spherical segment, was used to represent the droplet size. The center of the contact area is set as the origin of the coordinate system. The x and y coordinates are adopted perpendicular to and parallel with the entrainment direction, respectively.

$$V = \frac{\pi D_{\text{ini}}^3}{24} \frac{(1-\cos\theta)^2(2+\cos\theta)}{\sin^3\theta} \tag{1}$$

The *SRR* is set by

$$SRR = \frac{2(u_d - u_b)}{u_d + u_b} \tag{2}$$

3. Results and discussion

3.1. Film shape at different speeds

In the experiments depicted in Fig. 4, two identical droplets of 5P4E travel through the contact region at two speeds of 100 mm/s and 2 mm/s. It can be seen that different film shapes are generated. The transient interferograms were captured by the high-speed video camera with 1000 fps.

From the captured interferograms of the oil droplet moving at 100 mm/s as shown in Fig. 4 (a), it can be seen that a dimple-shaped film is generated; this has been previously numerically demonstrated by Li et al. [27]. The dimple-shaped film can be attributed to the poor spread of the droplet at the inlet and resistance to its squeeze spread within the

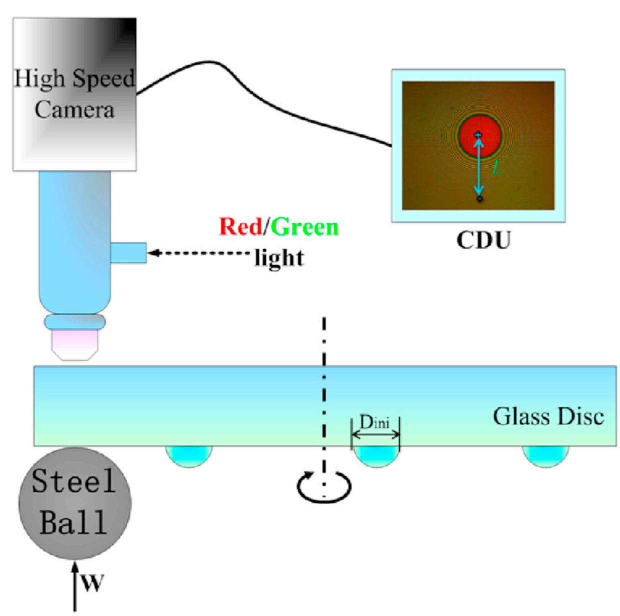

Fig. 2. Schematic diagram of the test apparatus.