Tribology International 106 (2017) 1–9

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Effects of lubricant rheology and impact speed on EHL film thickness at pure squeeze action

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ARTICLE INFO

Keywords:
Elastohydrodynamic lubrication
Non-steady state film thickness
Squeeze action
Lubricants

ABSTRACT

A squeeze film action is an essential phenomenon in elastohydrodynamically lubricated conjunctions subjected to impact loading or sudden halting of motion and affects both film thickness and friction. This study presents experimental results of film thickness behaviour of lubricant entrapment under diverse conditions including initial impact gaps, initial approaching speeds, loading speeds and variety of lubricants during introductory part of impact loading. The results are compared with recent theoretical solution. It is shown that the entrapped film shape directly depends on loading speed and the central film thickness is mainly determined by the approaching speed and lubricant viscosity and can be approximated by power law where the influence of impact times/speeds can be estimated from basic rheological properties of lubricants.

1. Introduction

Majority of studies concerning elastohydrodynamic lubrication (EHL) have been focused in the past on phenomena occurring under steady state conditions. The steady state EHL is nowadays well understood via both experimental and theoretical investigations and it is possible to reliably predict film thickness and friction of such EHL contacts. However, in many machine elements, such as traction continuously variable transmissions (CVT), gears, cam and followers and even steadily loaded rolling element bearings, neither the speeds nor the loads are time-independent. Also, every machine has to stop sometimes due to an accident or due to the nature of machine operating conditions, as in case of CVTs or rolling bearings of stepper motors. The resulting mutual normal approach of contact surfaces given by impact loading or sudden halting of motion causes a squeeze film action to have a crucial influence on EHL conjunction.

Since the beginning of investigations of non-steady state EHL contacts in 1960s, there has been a particular interest in impact loading issues. Christensen, in his pioneer work [1] dealing with a ball impacting a lubricated layer, found that very high contact pressures arose and deep dents were produced for lubricated contacts in comparison with dry contacts. Subsequently, the occurrence of a dimple with maximum film thickness in central area of contact and an entrapment of very high-pressured lubricant in this area were confirmed experimentally by direct observation [2]. Also, the effects of piezoviscosity of lubricants were considered in the theoretical studies [3,4] and the effects of molecular weight of mineral oils were investigated experimentally [5]. An interesting attribute of squeezed films – the second sharp pressure peak – was revealed using a thin pressure transducer in the centre of contact; the peak occurs at the end of impact time when the steel ball rebounds from the lubricated surface [6]. Theoretical evidence of this phenomenon was given in papers [7–9] together with broad description of EHL contacts subjected to impact loadings where a time lag between the occurrence of maximum force and minimum film thickness was analysed as a result of damping and elasticity of lubricant film. The study [7] further pointed out that minimum film thickness of entrapped lubricant increases with increase in impact velocity of falling ball on a flat lubricated surface. The related theoretical works [10–12] investigated pressure and film thickness distributions under squeeze motions.

The biggest boom of experimental studies in this research field took place at the end of 1990s, mainly due to the affordability of high speed cameras. Larsson and Lundberg [13] demonstrated via optical interferometry that a depth and a diameter of central dimple are affected by lubricant viscosity, maximum applied load and impact speed of the ball mounted on the pendulum falling onto a lubricated glass disc. Other experimental works [14,15] focused on pure squeeze action shown, as well as previous contributions, that a central dimple film shape with minimum thickness at the periphery region of contact is formed and a pressured lubricant is entrapped between the approaching surfaces for a long time after the impact.

For lubricant entrapment under conditions of sudden halting of rolling/sliding motion, acceleration together with rheological properties of lubricants have been proved both experimentally [16–20] and

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http://dx.doi.org/10.1016/j.triboint.2016.10.023
Received 21 July 2016; Received in revised form 10 October 2016; Accepted 14 October 2016
Available online 15 October 2016
0301-679X/

Nomenclature

a	deceleration	n	power-law index
a_h	slope of dimple side curve	t	time
C	dimensional constants	t_O	impact time
h	film thickness	t_{ini}	approach time
h_c	central film thickness	v_{ini}	initial approaching speed
h_{gap}	air gap between surfaces	v_F	loading impact speed
h_{ini}	initial central impact gap	v_{hc}	initial speed of central film thickness reduction
h_{max}	maximum film thickness	w	load
L, M	dimensionless Moes parameters	α	pressure-viscosity coefficient
		η	dynamic viscosity
		η_O	dynamic viscosity at ambient pressure

theoretically [21–23] as important parameters for squeezed films phenomena. Furthermore, if the rolling/sliding conjunction was subjected to sudden changes in load, the squeezed film of lubricant was generated at the inlet of contact and was entrained through it without a change in thickness and shape [24,25]. Sakamoto, Nishikawa, Kaneta, Guo and other authors [25–30] revealed formation of non-central dimple occurring under pure squeeze motions. This kind of dimple of entrapped lubricant was produced at the periphery of EHL contact where the maximum film thickness was also located. The periphery dimple was obtained especially for small initial gaps between the approaching surfaces or pre-loaded oiled contacts and also for high loading speeds and lubricants close to glass transition due to their dynamic properties associated with increase in pressure.

In recent years, an EHL squeezed films behaviour has been investigated mainly theoretically. For very thin films under 5 nm, it was shown in theoretical analyses [31,32] that both pressure and film thickness oscillate during squeeze action due to an action of surface forces. Moreover, Kumar and Kalita [33] employed a shear-thinning model pointing out that assuming a Newtonian model may be inappropriate for linear piezoviscous oils which exhibited rapid film entrapment. A substantial effect of lubricant viscosity on entrapped film thickness was studied by another numerical simulation [34] involving a mixture of a Newtonian base oil and couple stress fluid at various volume ratios. Further, a response of the EHD contacts under load variations (normal vibrations) was examined using dynamic models [35,36] with respect to lubricant film stiffness and damping.

Previous studies usually considered squeezed films problems of EHL conjunctions as an action of a free falling body onto flat lubricated surface. Analytical predictions of central entrapped film thicknesses in line [37] and point [38] contacts for this case of squeeze motion were recently published. Unfortunately, unrealistically large initial gaps exceeding 1 µm were often applied/analysed compared to EHL contacts in actual machines, and also a limited number of lubricants or only very specific lubricant(s) were frequently employed in previous studies. There are still many particular parameters of impact loading, such as initial approaching speed of contact surfaces exhibiting a remarkable effect on the film thickness and pressure [29]. The effects of these parameters on lubricant film entrapment have not been fully clarified or experimentally confirmed yet. Hence, in this paper, the entrapment of EHL films is investigated experimentally under diverse conditions including initial impact gaps, initial approaching speeds, loading speeds and a variety of lubricants. The experimental results are compared with the recent theoretical solution [38]. The current study is mainly focused on the introductory part of impact action and thus it does not include rebounding or long-term monitoring of lubricant leaking out of EHL contact.

2. Materials and methods

A schematic view of the experimental apparatus used in this study is shown in Fig. 1. A smooth bearing steel ball of 25.4 mm diameter was pushed against a lubricated glass plate of 13 mm thickness with semi-reflective layer of chromium by precise piezoelectric linear drive. The moving body mass was 0.2675 kg including the ball and associated movable part of apparatus. The behaviour of EHL film was recorded through a microscope by high-speed colour camera with image sampling frequency of 10 000 frames per second. As a light source, a xenon lamp of 1 kW performance was used. This adjustment allows capturing of very short term transient phenomena in EHL contacts. The method of thin film colorimetric interferometry (TFCI) was employed to determine film thickness up to 900 nm and film shape of lubricant. For more details about this method see Refs. [39,40].

The impact load of 125 N was applied after the initial central gap h_{ini} of 0.5 or 0.8 µm was set. The initial gap was measured by TFCI before each test. However, it should be noted that the actual initial gap was slightly changed for lubricated contacts before starting the test due to poor stability of these contacts. The error of initial gap setup at 0.5 and 0.8 µm was ± 4% and +2 up to +11%, respectively. Nevertheless, the differences in initial gaps do not influence the conclusions of the current study.

Fig. 2 shows the progress of loading process for dry contact where the dashed line encloses linear segments of load curves (LC) at load w of 110 N corresponding to the maximum Hertzian pressure of 0.8 GPa. Since the current paper investigates the effects of lineal loading on film thickness distribution, the final interferograms were captured for lubricated contact at this instantaneous load. The instantaneous load of 110 N was chosen with respect to better stability of overall dimple film shape than that in the case of final impact load of 125 N at which the film shape is more affected by oil leakage, especially in the peripheral area of the contact. For these reasons, the film thicknesses distributions caused by nonlinear sections of load curves above the

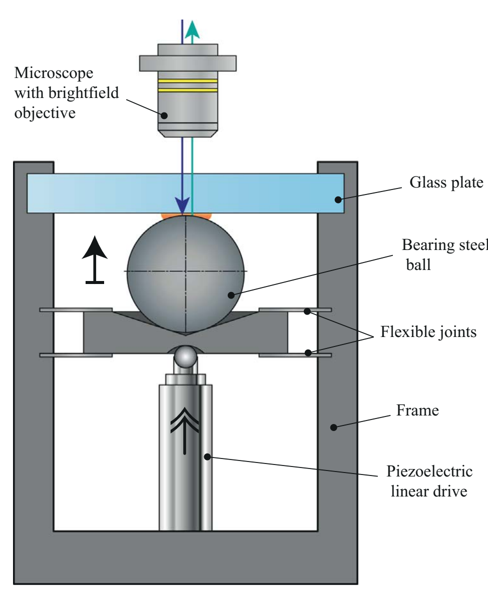

Fig. 1. Schematic representation of experimental apparatus.