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ScienceDirect

Tribology International 41 (2008) 482–492

TRIBOLOGY INTERNATIONAL

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Influence of polymeric fluid additives in EHL rolling/sliding line contacts

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Received 3 July 2005; received in revised form 5 May 2007; accepted 17 October 2007
Available online 11 December 2007

Abstract

The effect of polymeric fluid additives on EHL behavior of rolling/sliding line contacts is investigated numerically at low as well as high loads. The polymer-modified oil is represented by a homogeneous mixture of Newtonian base oil and power law fluid with varying concentration, viscosity ratio and power law index. The Reynolds equation incorporating the mixed rheological fluid model is derived using perturbation method. The EHL characteristics computed for polymer-modified oils are found to depend upon the effective viscosity of the lubricant mixture which is governed by the superposition of shear thinning behavior and piezo-thickening effect of the polymeric fluid additive. Since the reference viscosity of polymeric fluid additives is much higher than that of base oil, therefore, polymer-modified oils are shown to yield thicker fluid films in most of the cases. The results show a significant variation in maximum fluid pressure and minimum fluid film thickness with the volume fraction, reference viscosity ratio and power law index of the polymeric fluid additive.

Keywords: EHL; Polymeric fluid additives; Power law fluid; Line contacts; Viscosity ratio

1. Introduction

Elastohydrodynamic lubrication of rolling/sliding line contacts is of great relevance in the successful operation of the mechanical components such as gears, roller element bearings, cams, etc., which form a vital part of most of the machines. In order to meet the growing demand of industry for highly advanced technologies, the operating loads are increasing, the fluid films are becoming thinner and special purpose lubricants are being employed. Therefore, it is necessary to develop a better understanding of elastohydrodynamic lubrication taking account of the rheological behavior of practically used lubricants under a wide range of operating conditions.

Although several workers [1–7] have incorporated the non-Newtonian fluid behavior in EHL analysis, a major aspect remains largely unexplored. This is regarding the influence of additives in EHL conjunctions. When polymeric fluid additives are added to the base oil as film thickeners and VI improvers, the classical Newtonian as well as non-Newtonian theories fail to predict the flow behavior of the lubricants correctly. In these cases, mixture theory is applied to the lubrication problem to take account of the correct flow behavior of the lubricant. Dai and Khonsari [8] derived the governing equations for hydrodynamic lubrication involving a mixture of two incompressible fluids. The base oil was taken as Newtonian and the additive oil was assumed to be simple non-Newtonian fluid. The resulting mixture was classified as a non-homogeneous and non-Newtonian fluid. Due to non-homogeneity of the mixture, interaction terms appear in the conservation laws corresponding to each constituent [8]. The interaction terms may be dropped, under the assumption of homogeneous mixture, to obtain a simplified lubrication equation [9]. Based on this, Li [9] presented the analysis of hydrodynamic lubrication in journal bearing

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0301-679X/$ - see front matter
doi:10.1016/j.triboint.2007.10.008

Nomenclature

Dimensional parameters

b	half width of Hertzian contact zone, $b = 4R\sqrt{W/2\pi}$, (m)
E'	effective elastic modulus of rollers 1 and 2 (Pa)
H	film thickness (m)
h_{min}	minimum film thickness (m)
h_o	offset film thickness (m)
p	pressure (Pa)
p_h	maximum Hertzian pressure, $p_h = E'b/4R$, (Pa)
R	equivalent radius of contact (m)
u_o	average rolling speed, $u_o = (u_a + u_b)/2$, (m/s)
u_a, u_b	velocities of lower and upper surfaces, respectively (m/s)
v	surface displacement (m)
w	applied load per unit length (N/m)
x	abscissa along rolling direction (m)

Greek symbols

α	piezo-viscous coefficient (Pa^{-1})
γ	shear strain rate across the fluid film, $\gamma = du/dy$, (s^{-1})
ρ_o	inlet density of the lubricant (kg/m^3)
ρ	lubricant density at the local pressure and temperature (kg/m^3)
τ	shear stress in fluid (Pa)
η	fluid viscosity (Pa s)
η_a	viscosity of the additive fluid (Pa s)

Non-dimensional parameters

G	non-dimensional material parameter, $G = \alpha E'$
H	non-dimensional film thickness, $H = hR/b^2$
H_{min}	non-dimensional minimum film thickness, $H_{min} = h_{min}R/b^2$
H_o	non-dimensional offset film thickness, $H_o = h_oR/b^2$
n	power law index
N	total number of nodes
P	non-dimensional pressure, $P = p/p_h$
P_{max}	maximum fluid pressure
S	slide to roll ratio, $S = (u_b - u_a)/u_o$
U	non-dimensional speed parameter, $U = \eta_o u_o/E'R$
$\bar{v}$	non-dimensional displacement, $\bar{v} = vR/b^2$
W	non-dimensional load parameter, $W = w/E'R$
X	non-dimensional abscissa, $X = x/b$
X_{in}	inlet boundary co-ordinate
X_o	outlet boundary co-ordinate
ΔX	grid size of mesh
z_o	Roelands parameter

Greek symbols

μ	coefficient of friction
$\bar{\rho}$	non-dimensional fluid density, $\bar{\rho} = \rho/\rho_o$
$\bar{\eta}$	non-dimensional viscosity of Newtonian fluid, $\bar{\eta} = \eta/\eta_o$
η_{21}	ratio of additive and base oil viscosities, $\eta_{21} = \eta_a/\eta$
ξ	viscosity modification factor
$(\eta^*_{av.})_{inlet}$	average inlet zone effective viscosity

using a homogeneous mixture of Newtonian base oil and power law fluid additive. Similarly, Kumar et al. [10] derived the Reynolds equation and mean lubricant temperature equation for a mixture of Newtonian and Ree-Eyring fluids to demonstrate the use of mixed rheological fluid model in thermal EHL of rough rolling/sliding line contacts.

It was shown by Wu et al. [11] that the flow behavior of polymer-modified oils can be approximated by a double truncated power law fluid model. Therefore, the rheology of polymeric fluid additives is represented more closely by power law type of non-Newtonian fluid as compared to Ree-Eyring fluid model. Hence, in the present work, the effect of polymeric fluid additives on isothermal EHL behavior of rolling/sliding line contacts is investigated using a mixture of Newtonian fluid as base oil and power law fluid as additive. The effect of temperature rise on lubricant viscosity and density is neglected in order to study the superposition of shear thinning and piezo-thickening effects of the polymeric fluid additive in the absence of thermal effect. The Reynolds equation incorporating the mixed rheological fluid model is derived using perturbation method under the assumptions used by Li [9] and Kumar et al. [10].

2. Mathematical model

2.1. Rheological model of lubricant

A mixture of Newtonian and power law fluids has been considered in the present work. The mixture is homogeneous as it has been assumed that no chemical reaction takes place and the constituent fluids retain their original mechanical properties after being mixed. Hence, the total shear stress is shared by the two fluids in the proportion of their volume fractions [9,10] as follows:

$$\tau = (1 - c)\tau_n + c\tau_a \tag{2.1}$$

where c, τ_a and $(1-c)\tau_n$ are the volume fraction and shear stress of the power law fluid additive and the Newtonian base oil, respectively. The respective constitutive relationships are:

$$\tau_n = \eta\gamma \quad \text{and} \quad \tau_a = \eta_a|\gamma|^{n-1}\gamma \tag{2.2}$$