Tribology International 71 (2014) 50–61

Contents lists available at ScienceDirect

Tribology International

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

Edge contact effect on thermal elastohydrodynamic lubrication of finite contact lines

Morteza Najjari, Raynald Guilbault *

Department of Mechanical Engineering, École de technologie supérieure, 1100 Notre-Dame Street West, Montréal, Québec, Canada H3C 1K3

ARTICLE INFO

Article history:
Received 10 May 2013
Received in revised form
4 November 2013
Accepted 7 November 2013
Available online 21 November 2013

Keywords:
Thermal EHL
Non-Newtonian lubrication
Finite line contact
Edge contact

ABSTRACT

Minimum lubricant film thickness and maximum pressure every so often appear close to roller ends. This study combines the Boussinesq–Cerruti half-space equations with a free boundary correction procedure for precise modeling of edge contact conditions. The thermal EHL model developed associates this representation to a standard finite difference of the energy equation, and to a modified finite difference expansion of the Couette term of the Reynolds equation. To complete the model, the Carreau expression describes the shear-thinning response of the lubricant. The investigation includes different roller profile corrections. The results show that a large radius crowning modification combined with a rounding of the corners constitutes the most effective profile adjustment.

1. Introduction

An elastohydrodynamic lubrication regime (EHL) develops when high pressures (compared to Young modulus of the bodies) generate significant surface deformations, impacting the lubricant film shape. Usually, in real applications such as gears, cams and roller bearings, contact lines are of a finite length, a condition which leads to the edge contact problem, with the most severe case arising between contacting surfaces of different lengths. To reduce the damaging effect of finite contact lines, mechanical designers commonly round off or axially profile the surfaces close to the body ends. The well-known studies published by Gohar, Cameron, Wymer and Bahadoran [1–4] are among the very few to have investigated the finite line contact problem. Their experimental investigations analyzed the effects of roller geometry on EHL lubricant film shape and thickness. For instance, the optical fringe obtained by Wymer and Cameron [3] demonstrated that the film thickness thins down near the roller ends. Even though recent reviews [5–7] show that analyses of infinite line contact and point contact problems have been well developed over the past decades, the early finite line contact numerical simulations (Mostofi and Gohar [8], Kuroda and Arai [9], Xu et al. [10] and Park and Kim [11]) were limited to light or moderate loads. More recent publications have examined the influence of assembly precision and surface modifications. For example, Kushwaha et al. [12] investigated the influence of alignment on the film shape between rollers and raceways; Chen et al. [13] studied the effect of crowning and logarithmic roller end profiles, and Liu and Yang [14], and Sun and Chen [15] analyzed the thermal EHL of finite line contact under heavy loads with the multigrid approach developed by Lubrecht [16]. Recently, Zhu et al. [17] presented a mixed EHL investigation including realistic geometries and surface roughness effects on finite line contact modeling. Xue et al. [18] carried out experimental EHL studies of finite rollers with logarithmic end profiles under heavy loads, and found that the film at the roller ends may be thinner than the outlet film at the mid-length position.

While increasing the treatment sophistication of the Reynolds equation, the advent of the multigrid approach facilitated numerical investigations of high pressure EHL problems, and consequently, the description of the lubricant behavior in finite line contact conditions. However, in addition to the oil flow perturbations accounted for in the Reynolds equation, the free surfaces at the ends of a contact line also strongly affect the deformation of the loaded surfaces. Nevertheless, to the author's knowledge, the potential localized solid–fluid interactions have never been thoroughly described.

Under dry contact conditions, the free boundaries have a significant influence on the contact stresses and deformation [19]. For example, the finite length roller-half space contact condition is well known to generate high stress concentration at the roller limits. Conversely, the plane stress condition at the free boundaries of coincident end rollers permits small axial expansions, and consequently, local contact pressure reductions, which may be approximated by Eq. (1) [19].

---

* Corresponding author. Tel.: +1 514 396 8862; fax: +1 514 396 8530.
E-mail addresses: morteza.najjari.1@ens.etsmtl.ca (M. Najjari), raynald.guilbault@etsmtl.ca (R. Guilbault).

0301-679X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.triboint.2013.11.005

Nomenclature

α	pressure-viscosity coef. (Gpa^{-1})
β	density-temperature coef. (K^{-1})
γ	viscosity-temperature coef. (K^{-1})
ψ	Guilbault's correction factor
ρ	density (kg/m^3)
ν	coefficient Poisson's ratio
η	viscosity at given P, T and shear rate (Pa s)
$\eta_{0,1}$	shear-independent viscosity (Pa s)
$\rho_{a,b}$	density of solids a and b (kg/m^3)
τ_L	limiting shear stress (Pa)
Λ	limiting shear-pressure coefficient
a	half width of Hertzian contact area (m)
c_p	specific heat of the fluid (J/(kg K))
c_{pa}	specific heat of body a (J/(kg K))
c_{pb}	specific heat of body b (J/(kg K))
$f_{i,j,k,l}$	flexibility matrix
h_0	minimum film thickness (m)
k	thermal cond. of fluid (W/(m K))
$k_{a,b}$	thermal cond. of bodies a and b (W/(m K))
n	slope in the lubricant shear-thinning zone
p	fluid pressure (Pa)
p_0	maximum dry pressure (Pa)
p'_0	maximum plain stress dry pressure (Pa)
$u_{a,b}$	velocities of surfaces a and b (m/s)
u_e	rolling speed (m/s)
w	total load (N)
y_d	distance from the roller end (m)
z_0	dimensionless viscosity-pressure index
E'	equivalent modulus (GPa)
G	dimensionless material parameter
G_f	lubricant modulus (Pa)
L	roller length (m)
R_x	Equivalent radius in rolling direction (m)
R_y	crown radius (in y direction) (m)
S_0	dimensionless slope of viscosity–temperature relationship
T_{bulk}	bulk temperature (K)
T_0	ambient temperature (K)
U	dimensionless speed parameter
W	dimensionless load parameter

General contact solutions are often based on the classical elastic half-space theory (Boussinesq–Cerruti), which establishes the relation between the surface tractions and displacements. However, because of the underlying half-space assumption, when employed without any correction, the relation produces incorrect pressure increases near free edges. Over four decades ago, Hetényi [20,21] proposed a correction process involving a shear stress elimination from mirrored pressure distributions, in combination with an iterative treatment for normal stress correction. Recently, Guilbault [22] introduced a correction factor (Eq. (2)) which multiplies the mirrored pressures to simultaneously correct the shear and normal stress influence on displacements, thereby guaranteeing significantly lower calculation times as compared to a complete Hetényi process.

$$p'_0 \approx (1-\nu^2)p_0 \tag{1}$$

$$\psi = 1.29 - \frac{1}{1-\nu}(0.08-0.5\nu) \tag{2}$$

This paper presents a detailed numerical investigation of the potential influence of solid-fluid interactions on the pressure, film thickness and temperature distributions at the ends of finite contact lines. The study develops a model combining accuracy and high solution speed for low- to extreme-pressure EHL problems. In this model, the general non-Hertzian contact solution presented by Hartnett [23] to calculate surface deformations and pressure distributions is completed with the Hetényi shear stress elimination process and the Guilbault correction factor for the relief of the normal stress effect on the free boundaries. While a standard finite difference formulation ensures an energy equation solution, a simple algorithm based on a modified forward finite difference iterative method, presented by Cioc [24], resolves the Reynolds equation for the thermal EHL part of the global solution. The section following the model preparation compares the numerical results to experimental measurements published by Wymer and Cameron [3]. In the third section, the free boundary correction contribution is analyzed in two steps: first using only the mirrored pressures for shear correction, and thereafter integrating Guilbault correction factor for a complete correction. The last section investigates the influence of common roller profile axial modifications.

2. Model preparation and governing equations

2.1. Contact problem

The general dry contact problem resolution procedure is well described and validated in Ref. [22]. The EHL model developed in the present paper uses the same algorithm: the solution domain is divided into constant pressure cells, and the flexibility matrix written for the resulting mesh. The pressure cells are mirrored with respect to the free boundaries, and their influence is integrated into the flexibility matrix to eliminate the free boundary artificial shear stress. To remove the remaining normal stress influence, each mirror cell contribution is multiplied by Guilbault's factor prior to its integration into the flexibility matrix. This last operation completely releases the boundaries.

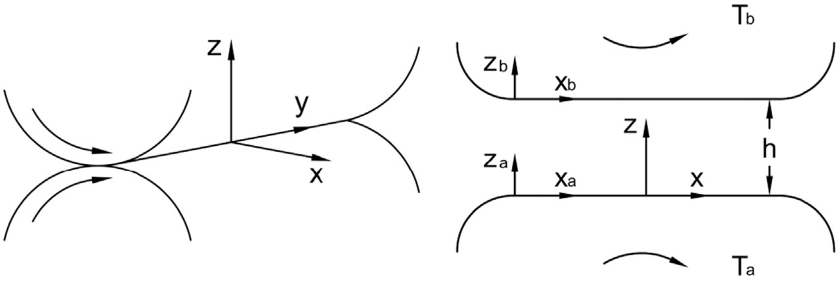

Fig. 1. Coordinate system.