NUMERICAL ANALYSIS OF ELASTOHYDRODYNAMIC LUBRICATION WITH BIO-BASED FLUIDS

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To my beloved parents, my siblings & friends.

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ABSTRACT

During the last couple of decades, the level of public considerations of increasing world energy crisis and environmental issues in various industrial applications has risen, including in the application of lubricants in machine elements. In this study, a numerical approach was developed to investigate the feasibility to use vegetable oils as lubricants in application of roller element bearing, namely elastohydrodynamic lubrication (EHL), especially for the contact between the inner ring and the cylindrical roller element. This simulation solved Reynolds equation simultaneously with elastic deformation and pressure-viscosity equation to analyse EHL pressure and film thickness. In this simulation, some vegetable oils were used as lubricants and results were compared with mineral oils and synthetic oils that are available in the market. It was discovered that in the condition of $W = 2.0452 \times 10^{-05}$, $U = 1.0 \times 10^{-11}$, and $T = 40^{o}$C, camellia oil was the best vegetable oil to replace mineral oil or synthetic oil because the maximum pressure working on the contacted surfaces of roller element bearing was lower than those of other vegetable oils. However, all simulated vegetable oils can be used as lubricants based on their pressure profiles and film thicknesses. The effects of some parameters, such as applied load, speed and temperature on the pressure distributions and film thickness profiles were also studied for all vegetable oils. The results demonstrated that the pressure and film thickness increased as the speed and load increased, but the increase of the temperature caused the pressure and film thickness to decrease.

ABSTRAK

Dalam beberapa dekad yang lalu, peringkat pertimbangan awam kepada peningkatan krisis tenaga dan isu-isu pada alam sekitar dalam pelbagai aplikasi perindutrian telah meningkat, termasuk penggunaan pelincir dalam elemen mesin. Dalam kajian ini, pendekatan berangka telah dibentuk untuk menyiasat kemungkinan menggunakan minyak sayuran sebagai pelincir dalam pemakaian galas penggguling, iaitu pelinciran elastohydrodynamic (EHL), terutamanya untuk sentuhan antara cincin dalaman dan roller silinder. Simulasi ini menyelesaikan persamaan Reynolds serentak dengan persamaan elastik deformasi dan persamaan tekanan-kelikatan bagi mengira tekanan dan ketebalan filem. Dalam simulasi ini, beberapa minyak sayuran telah digunakan sebagai pelincir dan hasil kajian dibandingkan dengan minyak mineral dan minyak sintetik yang tersedia di pasaran. Dalam keadaan $W = 2.0452 \times 10^{-05}$, $U = 1.0 \times 10^{-11}$, and $T = 40^{o}$C dalam kajian ini mendapati, minyak *camellia* ialah minyak sayur yang terbaik untuk menggantikan minyak mineral atau minyak sintetik kerana puncak tekanan yang bekerja pada permukaan galas adalah lebih rendah daripada minyak sayuran lain. Walau bagaimanapun, semua minyak sayuran boleh digunakan sebagai pelincir yang berdasarkan profil tekanan dan bentuk ketebalan filem. Tambahan pula, kesan daripada beberapa parameter, seperti halaju, beban dan suhu ke atas tekanan dan ketebalan filem telah dikaji untuk semua minyak. Hasil kajian menunjukkan bahawa tekanan dan ketebalan filem meningkat kerana kelajuan dan beban meningkat, tetapi peningkatan suhu menyebabkan tekanan dan ketebalan filem menurun.

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LIST OF SYMBOLS

a	-	weighting factor used to define dP/dX at node i
b	-	Semiwidth of Hertzian contact, $2R\sqrt{2W/\pi}$, m
C_j	-	Weighting factor
D_{ij}	-	Influence coefficient
E	-	Modulus of elasticity
E'	-	Effective elastic modulus
G	-	Material parameter, $\alpha E'$
H	-	Dimensionless film thickness, Rh/b^2
H_0	-	Dimensionless central film thickness at $X = 0$
H_{end}	-	Dimensionless film thickness at outlet boundary
h	-	Film thickness, m
h_e	-	Film thickness where $\partial p/\partial x = 0$, m
h_0	-	Film thickness at $x = 0$, m
i, j	-	nodes
K	-	Dimensionless sliding constant, $3\pi^2 U/4W^2$
N_{max}	-	Maximum number of nodes used in mesh
P	-	Dimensionless pressure, p/p_h
P_s	-	Dimensionless pressure spike

p	-	Pressure, Pa
p_{H}	-	Maximum Hertzian pressure, $E'b/4R = E'\sqrt{W/2\pi}$, Pa
R	-	Equivalent radius of contact, m
r	-	Radius of surface, m
U	-	Dimensionless speed parameter, $\eta_0 u/E'R$
u	-	Average entrainment rolling speed, $(u_a + u_b)/2$, m/s
W	-	Dimensionless load parameter, $w/E'R$
w	-	Applied load per unit length, N/m
X	-	Dimensionless distance, x/b
X_{end}	-	Dimensionless location of the outlet boundary
x	-	Distance along rolling direction, m
Z	-	Roelands parameter
α	-	Pressure-viscosity coefficient, m^2/N
ρ	-	Lubricant density, kg/m^3
ρ_0	-	Density at atmospheric pressure, kg/m^3
$\overline{\rho}$	-	Dimensionless density, ρ/ρ_0
$\overline{\rho}_e$	-	Dimensionless density where $H = H_{\mathrm{e}}$
η	-	Lubricant viscosity, Ns/m^2
η_0	-	Lubricant viscosity at atmospheric pressure, Ns/m^2
$\overline{\eta}$	-	Dimensionless viscosity, η/η_0
υ	-	Poisson's ratio
δ	-	Elastic deformation, m
$\overline{\delta}$	-	Dimensionless elastic deformation, $\delta R/b^2$

Subscripts

a	-	Surface a
b	-	Surface b
H	-	Hertz
i	-	at node number i
j	-	at node number j
out	-	Outlet position
in	-	Inlet position

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CHAPTER 1

INTRODUCTION

1.1 Background

The purpose of this study is to prepare a numerical modeling of elastohydrodynamic lubrication, hereinafter referred to EHL, in order to calculate pressure profiles and film thicknesses in line contact, using bio-based oils as lubricants. Furthermore, this simulation was also developed to investigate the influence of variation in load, speed or curvature radius that engenders the squeeze effect on the parameters of EHL line contact problem. Temperature effect on the characteristics of EHL is moreover investigated by running simulation at various temperatures.

1.1.1 Fluid Film Lubrication

Tribology is a field science and technology of friction, wear and lubrication due to relative motion of surface contacts with liquids, known as lubricants. It derived from the Greek word tribos for ‘rubbing’. The word “tribology” was formally introduced since the publication of the “Department of Education and Science Report” which issued by Peter Josh in 1966 (Khonsari and Booser, 2008) as a chairman of the British Ministry of State for Education and Science committee. The report also concluded that saving money could be reached by fully improving in design lubrication, friction and wear. This discipline science is not only about mechanical field, but also involving chemical and material technology. One of the purposes of tribology is to optimize bearing designs, lubricants and materials for bearings by studying the reduction of friction and wear characteristics to conserve energy, increase productivity and reduce maintenance process (Hamrock *et al.*, 2004; Khonsari and Booser, 2008).

The fundamental aspects of hydrodynamic lubrication were discovered and formulated by N. P. Petrov (1836-1920), B. Tower (1845-1904), and O. Reynolds (1842-1912), as mentioned by Pinkus (1987). They realized that the lubrication process was not caused by mechanical interaction between two solid surfaces, but it was engendered by the dynamic of fluid film between those surfaces. Nicolai Petrov was interested in the friction area, who published two postulates: first, viscosity is the most important property of fluid, instead of its density; and second, friction in a bearing is produced by viscous hearing involving its fluid film.

Elastohydrodynamic lubrication is one of the hydrodynamic lubrication, which involving physical interaction between the contacting bodies and the liquid of lubricant causes these contacting surfaces will be deformed elastically and the changes of viscosity with pressure play fundamental roles. The contacting surfaces in many engineering applications, for example, roller element bearings, gears, cams, seals, etc., are non-conformal; therefore, the consequent contact areas are very small and the resultant pressures are greatly high (Houpert and Hamrock, 1986).

Based on their solid contacted bodies, EHL generally consists of two types of problems, line contact problems and point contact problems. Contact between two spherical balls and contact between ball and flat surface are represented as point contact problems. Cylindrical roller bearing is represented as line contact problems. In the line contact type, the rolling and load zones are angularly centered and rolling zone is smaller than the load zone (Laniado-Jacome *et al.*, 2010).

Significant differences between Hydrodynamic lubrication (HL) and Elastohydrodynamic lubrication (EHL) involve the added importance of material hardness, increase of viscosity under high pressure, and degree of geometric conformation of the contacting surfaces. According to the operating conditions, EHL problems can be classified as a steady state where all variables involved are the time-independent cases and unsteady state (transient) problems where all variables (such as loading, entrainment speed and the contact curvature radius) change constantly in time (Cioc, 2004).

1.1.2 Bio-based Lubrication

According to a 2007 Freedonia report (Bremmer and Plonsker, 2008), total lubricant demand in the whole world is expected to be about 41.8 million metric tons, or about 13 billion gallons, where Asia/Pacific region will be the fastest growth. The world market is segmented by application area is: Engine oils – 48%, Process oils – 15.3%, Hydraulic oils – 10.2%, and all other – 26.5%. The considerations of increasing world energy crisis and environmental issues, in some countries, several laws and regulations have been enacted to control the production, application, and disposal of lubricants. These regulations have been released to minimize health hazards and water hazards (Bartz, 1998). Because of these two reasons, there is a need to source out biodegradable lubricants with technical characteristics superior to those based on mineral oils. It already in use as lubricants for applications of chainsaw bar lubricants, drilling mud and oils, straight metalworking fluids, food-industry lubricants, open gear oils, biodegradable grease, hydraulic fluids, marine oils, and outboard engine lubricants, oils for water and underground pumps, rail flange lubricants, shock absorber lubricants, tractor oils, agricultural equipment lubricants, elevator oils, mould release oils, two-stroke engine lubricants, cold forward extrusion and so on (Erhan and Asadauskas, 2000, Simon *et al.*, 2011).

The purpose of lubrication is to control friction and wear and also to provide smooth running and a satisfactory life for machine elements. It separates surfaces in relative motion by interposing a third body that has a low resistance to shear. These lubricants are usually made by blending base oil and a special chemical additive. The base oil can be a variety of different materials; most of them are liquids (such as mineral oils, water, synthetic oils), but they may be solids (such as polytetrafluoroethylene, or PTFE) for use in dry bearings, grease used in rolling-element bearings, or gases (such as air) for use in gas bearings.

The lubricant is selected based on a number of important factors; physical properties, chemical properties, lubrication properties, environmental friendliness and cost. Physical properties of fluid lubricant are characterized by temperature and chemical properties are characterized by oxidation and radiation influences, both affected by temperature. Mineral oils have been more used than synthetic oils because of their properties and performance features, such as thermal stability, oxidation stability, and viscosity temperature behaviour, temperature range of application and radiation stability. Synthetic oils will be selected for lubricants because the required chemical or physical property cannot be obtained by mineral oils or required quality of mineral oils does not meet the standard of synthetic oils (Rudnick, 2002).

Bio-based oils are found in the seed or fruit of various plants or animals. These materials are usually nontoxic and environmental friendly. Vegetable oil is one of the bio-based oils that manufactured using seed or fruit of plants. Comparing to mineral oil-based lubricating oils, vegetable-based lubricants are many readily biodegradable and renewable resources. Vegetable oils have to be extracted or expressed from the plant tissue in the "crude" form, which contains several minor components like steroids, pigments, waxes, etc. Generally vegetable oils contain a combination of saturated and unsaturated fatty acids, where these acid compositions have large influence to the physical and performance properties of these oils.

Lubricants based on vegetable oils are renewable and possess high biodegradability, high viscosity index, and excellent coefficient of friction and higher wear rate, possess good boundary lubricant (Adhvaryu and Erhan, 2002, Erhan and Asadauskas, 2000, Jayadas *et al.*, 2007, Mia *et al.*, 2007, Musa, 2009, Mia and Ohno, 2010, Syahrullail *et al.*, 2011).

Some researchers have studied the possibility of usage the vegetable oils for the industrial application. Adhvaryu and Erhan (2002) had improved performance of epoxidized soybean oil and modified high oleic soybean oil genetically to overcome the poor thermal and oxidative of soybean oil so it could be used as high-temperature lubricants. Wan Nik *et al*. (2005) suggested using some food grade oils, such as palm oil, sunflower oil, coconut oil, canola oil and corn oil for hydraulic fluid. Jayadas and Nair (2006) reported that coconut oil is able to be used as base oil for industrial lubricants by modifying its thermal, oxidative and low-temperature properties.

Research in considering real measuring or testing the physical properties and tribological behaviour for vegetable oils as lubricants have been done (Ohno *et al.,* 1997, Mia *et al.,* 1997, Adhvaryu and Erhan, 2002, Wan Nik *et al*., 2005). These experimental concepts take a long time and need to destruct materials. However, at this moment, researchers need the accurate results quickly, and therefore study about bio-based lubricants used in line contact of elastohydrodynamic lubrication must be conducted and then a new numerical concept should be developed for this problem.

1.2 Objective and Scope of Study

Recently, the numerical solutions for EHL problems have been developed by many researchers, including for transient EHL of line contact. However, there are only a few of them used bio-based oils for their simulations, and therefore, the numerical method should be developed using bio-based oils in order to investigate a possibility to replace mineral oils as lubricants with the bio-based oils. Beside that, the effects of temperature on the parameters of EHL line contact are also investigated in this study by running the simulation in various temperatures.

The scopes for this project include:

i. Numerical analysis is conducted to the cylindrical roller element bearing only; it means that solution is limited to the two-dimensional line contact problem.
ii. Dimensionless load (W) and dimensionless speed (U) are set fixed as the paper of Houpert and Hamrock (1986) where $W = 2.0452 \times 10^{-5}$ and $U = 1.0 \times 10^{-11}$. However, in order to investigate the effect of speed on the pressure distribution and film thickness profile, the average rolling speed (u) of roller element is set varied between 10 mm/s and 750 mm/s. Then, the load effect on the EHL parameters is investigated by varying the applied load between 10 and 40 kN/m.

iii. Temperatures are set at 0^{o}C, 20^{o}C, 40^{o}C, 60^{o}C, 80^{o}C, and 100^{o}C to show the thermal effect on the pressure and film thickness of EHL.

iv. Some vegetable oils are chosen as the lubricants based on their viscosity index (*VI*) ranging from 75 to 200. According to Khonsari and Booser (2008), this range of *VI* is acceptable for industrial application. It should be noted that the viscosity index (and other properties) of these vegetable oils are obtained from other researchers' testing (Ohno *et al.,* 1997, Mia *et al.,* 1997, Adhvaryu and Erhan, 2002).

v. The effect of surface's roughness is neglected.

vi. The chemical content of vegetable oils is not discussed in more detail.

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