**UNIVERSITI PUTRA MALAYSIA**

# ISOTHERMAL AND THERMAL ANALYSES OF ELASTOHYDRODYNAMIC LUBRICATION OF HARD ROLLING CONTACT

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**By**

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Thesis Submitted in Fulfilment of the Requirements for the Master of Science in the Faculty of Engineering,
Universiti Putra Malaysia.

March 1997

# ACKNOWLEDGMENTS

In the name of **ALLAH** the most Benevolent and Merciful. All Praise be for ALLAH giving me the opportunity, patience, help and guidance in completing this thesis. My deepest gratitude and love to my mother, my wife, other family members and all friends who constantly pray for my success.

I am indebted to the chairman of my supervisory committee, Assoc. Prof. Ir. Dr. Shah Nor Basri for his dedicated efforts, invaluable advice and intellectual guidance throughout the study. I am also thankful to Assoc. Prof. Ir. Dr. Desa Ahmed and Dr. Ahmed Faris, members of the supervisory committee for their constructive comments in the preparation of the final manuscript. The author is grateful for the financial support to this project by the European Commission. Special thank to Dr. David T. Gethin, Reader at the University College of Wales, Swansea, UK. for his guidance and comments during my writing up of the first three chapters. I am also grateful to Dr. T. Nonaka, University of Koyoto, Japan for supplying a copy of basic computer program to solve numerically the two

dimensional Reynolds equation for EHL problem. I am thankful to Prof. J. J. Kalker, Delft University of Technology, Netherlands for supplying a computer program and other useful information. Special thanks to Dr. Abdul Magid Hamouda at Mechanical and Manufacturing Engineering Dept., University Putra Malaysia (UPM) for his specific reading of the thesis and clearly written comments. Also I like to appreciate and thank Dr. Mark Bohan at Welsh Centre for Printing and Coating, University of Wales, Swansea, England for his reading, direct comments and report on the thesis. With my pleasure, I must thank my friends Usman Inuwa Shehu and Abdul Majeed Mohammed (Ph.D Students at UPM) for their editing of the thesis. I would also like to thank all of my colleagues at UPM and my friends, Sallah S. El Ammari, Farag A. Jaber, Omar M. El Sanousi and Abd Naser Ali for their fine understanding and cooperation. Last but not least, I would like to extend my expression and great appreciation to all those who contributed to the success of this study directly or indirectly. May ALLAH bless them all. Amin.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

## LIST OF PLATES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| $D_{ij}$ | Influence Coefficients to Calculate Elastic Deformation of Node I due to $p_j$ |
| E | Elasticity Modulus |
| E' | Effective Elastic Modulus |
| $E_o$ | Initial Elastic Modulus of Material in Contact |
| $F_x$ | Force in x Direction |
| $F_y$ | Force in y Direction |
| G | Shear Modulus |
| g | Acceleration of Gravity |
| h | Lubricant Film Thickness |
| $h_c$ | Film Thickness at Maximum Pressure |
| $h_s$ | Inlet Film Profile |
| H | Dimesionless Film Thickness, h/R |
| $h_m$ | Film Thickness at Point of Maximum Pressure |
| $H_{min}$ | Minimum Film Thickness |
| $h_o$ | Film Thickness on Line of Centres |
| K | Lubricant Conductivity, W/(m°c) |
| $m_x, m_y$ | Mass Flow per unit Width, x and y Direction |
| p | Pressure |
| $Q_{gen}$ | Rate of Generation of Heat per unit Volume |
| $Q_{out}$ | Amount of Heat Flow out Oil Film |
| $Q_{in}$ | Amount of Heat Flow into Oil Film |
| $Q_{R1}$ | Amount of Heat loss via Roller1 |

$Q_{R2}$ Amount of Heat loss via Roller2

$q$ Reduced Pressure, $q = (1-e^{-\alpha P})/\alpha$

$R$ Equivalent Radius of Roller, $1/R = 1/R_1 + 1/R_2$

$R_1$ Radius of upper Roller

$R_2$ Radius of Lower Roller

$R'$ Radius of Curvature

$T$ Dimensionless Temperature, $t/t_o$

$t$ Time

$U$ Dimensionless Speed Parameter, $\eta_o u/E'R$

$u$ Mean Surface Velocity in x direction, $1/2(u_1+u_2)$

$u_1$, $u_2$ Surface Velocities of Solids in x-direction

V1,V2 Surface Velocities, y direction

$w_z$ Load per unit Length of Roller

$W$ Dimensionless Load Parameter, $w_z/E'R$

$x_E$ Any value at the Inlet Region

$x_1$ Unknown Value in the Inlet Line Contact

$x_o$ Unknown Value in the Outlet Line Contact

x, y, z Coordinates Axes

## Greek Symbols

$\alpha$ Pressure Exponent of Viscosity

$\tau$ Shear Stress

$\gamma$ Shear Strain Rate

| | |
|---|---|
| $\tau_{zx}$ | Lubricant Shear Stress in x direction in Plan whose Normal is z |
| $\tau_{zy}$ | Lubricant Shear Stress in y direction in plan whose Normal is z |
| $\eta$ | Dynamic Viscosity Coefficient |
| $\eta_{\circ}$ | Viscosity at Atmospheric Pressure |
| $\rho$ | Lubricant Density |
| $\nu$ | Kinematic Viscosity |
| $\varsigma$ | Combined Displacement of Two Solids |

## Subscript

| | |
|---|---|
| E | Related to Value in the Outlet Line Contact |
| EHD | Elastohydrodynamic |
| EHL | Elastohydrodynamic Lubrication |
| i | Related to Value in the Inlet Line Contact |
| inlet | Related to Lubricant Inlet Position |
| out | Related to Lubricant Outlet Position |

Abstract of thesis submitted to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science.

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MARCH 1997

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In the field of industrial tribology, elastohydrodynamic lubrication (EHL) is a comparatively recent area of research. It only became properly established in the early 1960s. EHL of rolling contact is mainly divided to two phases (soft and hard), depending on the elasticity modulus of the material in contact. Hard rolling which relates to materials of high modulus of elasticity e.g. metal, is the part of interest in the present study.

The first objective of the research is to study the elastohydrodynamic lubrication problem of hard rolling line contact. Second is to investigate the isothermal and thermal conditions for EHL in hard rolling system. The contact geometry of the rolling process was specified as a line contact. An incompressible fluid flows in to the system. Under both isothermal and thermal conditions, a Newtonian lubricant was described. Two different widely used lubricants were tested. First, is a mineral Naphthenic (TN22) and the second is a synthetic Cycloaliphatic (ST40).

It is assumed that two rollers of equal radius are moving relatively with same speed on a plane of different velocity. Two coordinate axes were considered (x and y). The parameters and conditions of controlling the system of contact are theoretically selected to match the practical field situations. Newton-Raphson and the finite difference methods were represented in the mathematical technique used for computations.

Two isothermal models and another two of thermal conditions were developed. The analysis for the isothermal and thermal models did not show any obvious difference between the mineral and synthetic oil film used. The results of pressure distribution and film thickness for the two thermal models under isoviscous and viscous conditions did not show any change in pattern. The comparison between isothermal and thermal behaviour has shown that the thermal effects have a strong influence on the pressure spike amplitude. The present results were compared and discussed with other earlier published results.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi syarat ijazah Sarjana Sains.

**ANALISIS ISOTERMA DAN TERMA PELINCIRAN ELASTOHIDRODINAMIK SENTUHAN GULINGAN KERAS**

oleh

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Didalam bidang tribologi industri, pelinciran elastohydrodynamic (EHL) adalah merupakan suatu yang agak baru kepada dunia penyelidikan. Ianya hanya menjadi satu kenyataan yang berasas pada sekitar awal tahun enampuluhan. EHL yang berhubung dengan penggulingan bersentuh (rolling contact) telah terbahagi kepada dua fasa (lembut dan keras) yang bergantung kepada modulus keanjalan sesuatu bahan yang bersentuh. Penggulingan keras merupakan sesuatu yang berkait rapat dengan bahan yang mempunyai modulus keanjalan yang tinggi bahan logam, yang mana didalam penulisan ini ianya menjadi sebahagian dari kajian.

Objektif pertama daripada kajian ini adalah untuk mendapatkan pemahaman yang mendalam terhadap permasalahan sistem pelinciran EHL keatas gulingan keras. Kedua, adalah untuk mengkaji syarat isothermal dan terma terhadap EHL didalam sistem penggulingan keras apabila dua bahan pelincir dari jenis berlainan digunakan.

Persentuhan jometri didalam proses gulingan ini telah dispesifikasikan sebagai garis sentuh. Bendalir yang tidak mampat dialirkan didalam sistem ini. Didalam dua keadaan, iaitu isoterma dan terma, pelincir Newtonian dapat diandaikan. Dua bahan pelincir yang luas penggunaannya dari jenis yang berlainan telah diuji. Bahan itu adalah Mineral Naphthenic (TN22) dan Synthetic Cycloaliphatics (ST40).

Diandaikan dua pengguling yang berjejari sama berpusing pada halaju yang sama diatas satah kelajuan berbeza pada dua paksi koordinat X dan Y. Parameter dan syarat pengawalan sistem sentuhan secara teorinya dipilih untuk menyamai keadaan sebenar. Pada peringkat awal Kaedah Newton-Raphson dan kaedah perbezaan terhingga telah digunakan didalam teknik matematik untuk tujuan pengiraan.

Analisis untuk model isoterma dan terma tidak menunjukkan sebarang perbezaan yang ketara diantara bahan lapisan mineral dan sintatik yang digunakan. Dua model isoterma dan dua model terma telah terbentuk. Keputusan pengagihan tekanan dan ketebalan lapisan untuk kedua-dua model tidak menunjukkan sebarang perubahan dari segi corak. Perbandingan diantara perlakuan isoterma dan terma telah menunjukkan bahawa kesan terma mempunyai pengaruh yang kuat terhadap amplitud pepaku tekanan.

Keputusan yang telah didapati mempunyai persamaan amat memuaskan dengan keputusan ujikaji yang sebelumnya.

# Chapter I

# Introduction

## Background Overview

Lubrication is an essential feature of most modern machinery and has wide applications in the operation of many industrial processes such as forming, forging, drawing, extrusion, and rolling. There is a great body of technological experience in the production and application of lubricants, but the scientific study of lubrication and associated problems of friction and wear is comparatively a recent development.

Nowadays the area of contact mechanics has become a very important topic for so many researchers in the field of industrial tribology. In many modern industrial applications, the contact action is unavoidable and without it the manufacturing of so many parts will be relatively impossible, because usually deformation of product takes place due to the force of contact action exerted by another part. Friction is usually present at these contacts by which heat is generated and wear occurs, leading to a highly significant loss of energy. It is estimated that one third of the world's energy resources in present use is needed to overcome friction in one form or another. Analysis of machine break-downs also shows that majority of cases of failures and stoppages are associated with interacting moving parts such as gears, bearings, couplings, sealings, cams, clutches and other machine elements (Stachowiak and Batchelor, 1993).

Recently the elastohydrodynamic lubrication (EHL) has become an effective means of controlling wear and reducing friction. In this system, lubricant is introduced at the local contact and is designed to prevent direct contact between the surfaces in relative motion. The first notable breakthrough occurred by Grubin (1949) when he managed to incorporate both the elastic deformation of the solid and the viscosity-pressure characteristics of the lubricant in analyzing the inlet region of lubricated non-conformal machine elements.

EHL of hard rolling or sliding systems can be briefly described as a form of hydrodynamic lubrication where elastic deformation of the lubricated surfaces becomes significant (Hamrock, 1994). It relates to materials of high modulus of elasticity and is usually associated with highly stressed machine elements, such as rolling element bearings and gears. The contact conditions and the controlling parameters of EHL systems for hard contact are now being investigated leading to the development of power transmission techniques which are expected to take the advantage of the system concept in a rolling configuration.

In a fully developed EHL, the elastic deformation of the solids is often significant relative to the thickness of the fluid film separating them and the contact pressure is high enough to significantly increase the lubricant viscosity within the junction. In this research the pressure distribution and film thickness in EHL for hard rolling contact will be expressed in terms of isothermal and thermal analysis under various conditions. Since pressure and film thickness both are the most significant factors in EHL system.

## Aims of Current Research

The main aims of this study are:

1) to study the elastohydrodynamic lubrication problem of hard rolling line contact,
2) to investigate the isothermal and thermal conditions for EHL in hard rolling system.

## Thesis Layout

In this thesis, Chapter II includes a literature review in the field of elastohydrodynamic lubrication, theoretical and experimental investigations and explanations for the EHL system process covering the principles of line and point contact. Also given is a general description of dry and lubricant contact. Isothermal and thermal EHL are also included.