



UNIVERSITI PUTRA MALAYSIA

**ELASTOHYDRODYNAMIC ANALYSIS OF ROLLING LINE
CONTACT USING BOUNDARY ELEMENT METHOD**

MAHMOUD HASSAN ONSA

ITMA 2001 7

**ELASTOHYDRODYNAMIC ANALYSIS OF ROLLING LINE
CONTACT USING BOUNDARY ELEMENT METHOD**

By

MAHMOUD HASSAN ONSA

**Thesis Submitted in the Fulfilment of the Requirement for the
Degree of Doctor of Philosophy in the Institute of Advanced Technology
Universiti Putra Malaysia**

April 2001



To the soul of my Father.

To my Mother, my Wife, A'ayah and Iman.

Abstract of thesis presented to the senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy.

ELASTOHYDRODYNAMIC ANALYSIS OF ROLLING LINE CONTACT USING BOUNDARY ELEMENT METHOD

By

MAHMOUD HASSAN ONSA

April 2001

Chairman: Assoc. Prof. Dr. ShahNor Basri, P. Eng.

Faculty: Institute of Advanced Technology

This study aims at incorporating the use of the boundary element method (BEM) as an efficient and fast numerical method for the solution of the problem of the elastohydrodynamic (EHL) of hard rolling line contact. EHL of hard rolling is the dominant mode of lubrication in many critical, highly stressed machine elements such as gears, cams and followers, and bearings. The study of the stress concentration and deformation is important to predict the performance and the life expectancy against failures. These failures are manifested in wear, fatigue and scuffing. This fundamental study is based on isothermal, steady state, and smooth line contact EHL. The rolling of two cylindrical rollers was approximated by a roller and a plane.

The hard rolling EHL relates to counter-formal contact elements made of high elastic modulus materials such as metals. The problem is to seek a solution, which reconciles the hydrodynamic equation represented by the Reynolds equation, and the elasticity equation while at the same time allowing for the variation of the lubricant properties with pressure. The resultant regime is highly non-linear.



A hybrid solution is utilised to solve the elasticity problem using the BEM, and to solve the Reynolds equation for the pressure using the finite difference method (FDM) in a fully coupled solution. The BEM fundamentally consists of the transformation of the partial differential equations, which describe the behaviour of the variables inside and on the boundary of the domain into integral equation relating to the boundary values, and the numerical solution of these equations. The boundary integral equation is formulated for the elasticity and solved using the BEM. The hydrodynamic equation is solved using FDM. The coupled solution is solved using Newton-Raphson iterative technique. The converged solution gives the pressure distribution and the lubricant film thickness.

The overall result of executing the hybrid BEM-FDM program gives a full agreement when compared to the program using FDM while resulting in reduction in the CPU time. The results also agree with other published numerical works. These verify the use of the developed method. To fully utilize the advancement of the developed program, an extension of the models needs to include a non-Newtonian behaviour of lubricant and the thermal effects.



**ANALISIS HIDRODINAMIK-KENYAL BAGI SENTUHAN GARIS
PENGGELEKKAN MENGGUNAKAN KAEDAH UNSUR SEMPADAN**

Oleh

MAHMOUD HASSAN ONSA

April 2001

Pengerusi: Prof. Madya Dr. ShahNor Basri, P. Eng.

Fakulti: Institut Teknologi Maju

Objektif ini adalah untuk menggabungkan penggunaan kaedah unsur sempadan (BEM) sebagai satu kaedah berangka yang berkesan dan cepat bagi penyelesaian masalah pelinciran hidrodinamik-kenyal (EHL), bagi sentuhan garisan penggelekan keras. EHL bagi penggelekan keras adalah ragam yang paling mustahak bagi pelinciran dalam banyak unsur mesin yang kritikal serta bertegangan tinggi seperti gear, sesondol dan pengikut, dan galas. Kajian bagi tumpuan tegasan dan ubah bentuk adalah penting bagi meramalkan prestasi dan jangkaan hayat menentang kegagalan-kegagalan. Kegagalan-kegagalan ini dibuktikan dalam haus, lesu dan penghauslakuran. Kajian asas ini berasaskan EHL sesuhu, keadaan mantap, dan sentuhan garis halus. Penggelekan bagi dua buah penggelek silinder telah dianggarkan oleh sebuah penggelek dan satu satah.

EHL penggelekan keras berhubung dengan unsur sentuhan melawantentuk yang terdiri daripada bahan modulus kenyal tinggi seperti logam. Masalahnya ialah untuk mencari satu penyelesaian, yang menyesuaikan persamaan hidrodinamik

yang diwakili oleh persamaan Reynolds, dan persamaan kenyal, sementara pada waktu yang sama membenarkan perubahan sifat-sifat bahan pelincir dengan tekanan. Regim yang terhasil adalah tak-lurus.

Satu penyelesaian hibrid telah digunakan bagi menyelesaikan masalah kekenyalan menggunakan BEM; dan menyelesaikan persamaan Reynolds bagi tekanan menggunakan kaedah perbezaan terhingga (FDM) dalam penyelesaian terganggu sepenuhnya. BEM secara dasarnya mengandungi penjelmaan bagi persamaan kebezaan separa yang menerangkan kelakuan bagi pembolehubah yang tidak diketahui di dalam dan di atas sempadan domain kepada persamaan kamiran berkaitan dengan nilai-nilai sempadan, dan penyelesaian berangka bagi persamaan ini. Persamaan kamiran sempadan ini telah dirumuskan bagi kekenyalan dan diselesaikan menggunakan BEM. Persamaan hidrodinamik telah diselesaikan menggunakan FDM. Penyelesaian terganggu telah diselesaikan menggunakan teknik lalaran Newton-Raphson. Penyelesaian tertumpu memberikan tekanan dan ketebalan filem pelincir.

Keputusan-keputusan keseluruhan dalam melaksanakan aturcara hibrid BEM-FDM memberikan persetujuan sepenuhnya jika dibandingkan dengan aturcara menggunakan FDM, sementara menghasilkan pengurangan dalam masa CPU. Keputusan-keputusan ini juga menawarkan persetujuan yang baik dengan kerja-kerja berangka yang lain yang telah diterbitkan. Ini mengesahkan penggunaan kaedah yang telah dibangunkan. Untuk memanfaatkan sepenuhnya kerja penyelidikan ini, aturcara yang telah dibangunkan memerlukan tambahan dalam model dengan memasukkan kelakuan tak-Newtonian bagi pelincir dan kesan haba.

ACKNOWLEDGEMENTS

Praise be to ALLAH the ALMIGHTY in giving me the help, guidance and patience to complete this thesis.

I would like to express my sincere thanks to the chairman of the supervisory committee, Assoc. Prof. Dr. Ir. ShahNor Basri for his continuous help, support, friendship, hospitality and encouragement throughout this work. I am truly grateful to Dr. Mohd. Sapuan Salit, who is a member of the supervisory committee and served as the chairman during Dr. ShahNor's sabbatical leave. I thank him for the brotherly handling of all matters concerning my research. I am also indebted to Dr. Megat Mohamad Hamdan Megat Ahmad for his technical advice and comments. I thank them all for their patience in reading, revising and commenting my thesis, and I thank their constructive advices and guidance.

I am most grateful to the University of Khartoum (Sudan) and the European Commission for the financial support conceded to my study. Thanks to Prof. David T. Gethin of University of Wales, Swansea for the guidelines given during his short visits to Malaysia. In addition, thanks are offered to Prof. H. P. Evans of University of Wales Cardiff, and Prof. Arto Lehtovaara of Tampere University of Technology, Finland for their valuable suggestions and comments.

I would like to thank the staff of Institute of Advanced Technology and the staff of Department of Aerospace Engineering, UPM for availing their computing facilities to conduct this work, and for not hesitating to give any needed resource.



I wish to extend my sincere gratitude to Dr. Mohamed Musadaq El Awad, who was a lecturer in the Department of Mechanical and Manufacturing Engineering, UPM for his invaluable suggestions in the early stages of the work. Great appreciation is also extended to all Sudanese, Libyans, Malaysians and other nationalities colleagues and good friends and to all those who contributed directly or indirectly to the success of this study, may ALLAH bless them all.

Last, but not least, I wish to express my gratefulness to my wife who sacrificed a lot to give me a good environment to finish this work, and my thanks are to my daughters, mother, brothers and sisters for their moral support and encouragement.



I certify that an Examination Committee met on 11th April 2001 to conduct the final examination of Mahmoud Hassan Onsa on his Doctor of Philosophy thesis entitled “Elastohydrodynamic Analysis of Rolling Line Contact Using Boundary Element Method” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the examination committee are as follows:

A. Magid Hamouda, Ph.D.
Associate Professor
Institute of Advanced Technology
Universiti Putra Malaysia
(Chairman)

ShahNor Basri, Ph.D.
Associate Professor
Institute of Advanced Technology
(Member)

Mohd. Sapuan Salit, Ph.D.
Institute of Advanced Technology
Universiti Putra Malaysia
(Member)

Megat Mohd. Hamdan Megat Ahmad, Ph.D.
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Masjuki Hasan, Ph..D.
Professor
Department of Mechanical Engineering
Faculty of Engineering
University Malaya
(Independent Examiner)


MOHD. GHAZALI MOHAYIDIN, Ph.D.
Professor/ Deputy Dean of Graduate School,
Universiti Putra Malaysia

Date: 14 MAY 2001

This thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.

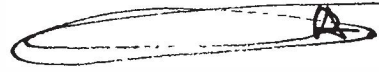


AINI IDERIS, Ph.D.
Professor/ Dean of Graduate School,
Universiti Putra Malaysia

Date: **14 JUN 2001**

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.



MAHMOUD HASSAN ONSA

Date: 17 April 2001

TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGEMENTS	vii
APPROVAL	ix
DECLARATION	xi
LIST OF TABLES	xv
LIST OF FIGURES	xvii
NOMENCLATURE	xx
 CHAPTER	
1	INTRODUCTION 1
1.1	Overview 1
1.2	Lubrication Regimes 4
1.3	The Elastohydrodynamic Lubrication (EHL) 5
1.4	Types of Rolling Contacts 7
1.5	Analysis of EHL Problem 8
1.6	Boundary Element Methods 10
1.7	Objectives 11
1.8	Significance of this Study 12
1.9	Structure of the Thesis 12
2	LITERATURE REVIEW 14
2.1	Introduction 14
2.2	Experimental EHL Film Thickness Measurements 14
2.3	Theoretical EHL 20
2.4	Numerical Solutions to EHL Lubrication 24
2.4.1	Newton-Raphson Technique 25
2.4.2	Multi-level or Multi-grid Techniques 26
2.4.3	Finite Difference Method 27
2.4.4	Finite Element Method 28
2.4.5	Boundary Element Method 29
2.5	BEM and the Contact Problem 32
2.6	Line Contact EHL 36
2.7	Isothermal and Thermal Elastohydrodynamic Lubrication 36
2.8	Closure 38
3	THEORY OF ELASTOHYDRODYNAMICS OF HARD ROLLING 39
3.1	Introduction 39
3.2	Reynolds Equation 40
3.2.1	Assumptions Made for Reynolds Equation and Their Justifications 41
3.2.2	Simplifications of Reynolds Equation 42
3.3	Hard Rolling versus Soft Rolling EHL 43
3.4	Hertzian Pressure Distribution 44



3.5	Rolling Contact Geometry	47
3.6	Rolling Contact Representation	49
3.7	Lubricant Film Geometry	53
3.8	Elastic Deformation Equation	54
3.9	Lubricant Properties	55
	3.9.1 Barus Pressure-Viscosity Relation	55
	3.9.2 Roelands Pressure-Viscosity Relation	56
	3.9.3 Mass Density Pressure Relation	59
3.10	Dimensionless Parameters	60
3.11	Closure	63
4	NUMERICAL SOLUTION	64
4.1	Introduction	64
4.2	Hybrid Solution	65
4.3	BEM Solution	66
	4.3.1 Boundary Integral Equation Formulation	67
	4.3.2 Boundary Integral Equation	68
	4.3.3 Quadratic Isoparametric Elements	69
	4.3.4 Shape Functions	69
4.4	Elasticity Equation Model I (BEM)	71
4.5	Reynolds Equation	72
	4.5.1 Dirac Delta Function and the Fundamental Solution	73
	4.5.2 Discretization of Reynolds Equation	74
	4.5.3 Calculation of the Pressure Gradient	76
4.6	Initial Film Thickness and Pressure Distribution	78
4.7	Elasticity Equation Model II (FDM)	79
4.8	Coupled Solution of the Elasticity and Reynolds Equations	84
	4.8.1 Partial Coupling	84
	4.8.2 Full Coupling	86
	4.8.3 Special Partial Coupling	86
4.9	Newton-Raphson Technique	86
4.10	Fluid Properties Functions	90
	4.10.1 Mass Density Pressure Relation	90
	4.10.2 Viscosity Pressure Relation	90
4.11	Grid Generation	91
	4.11.1 Constant Element-size Mesh	92
	4.11.2 Multi-interval Mesh	92
	4.11.3 Adaptive Element-size Mesh	93
4.12	Closure	94
5	COMPUTER PROGRAM AND RESULTS	95
5.1	Introduction	95
5.2	Working Environment	96
5.3	Working with Personal Computers	97
	5.3.1 Test I	97
	5.3.2 Test II	98
	5.3.3 Test III	99
5.4	Main Program Layout	100
	5.4.1 Input Data	101



5.4.2	Calculation of the Initial Pressure and Elastic Deformation	103
5.4.3	Calculation of the Active Coordinate Range	104
5.4.4	Relaxation Criteria	104
5.4.5	Newton-Raphson Iteration	104
5.4.6	Solution of the Elasticity Equation using BEM	104
5.5	Graphical Presentation	105
5.6	Calculation of the CPU Time	105
5.7	Effect of Number of Elements	106
5.7.1	Constant Element-size Mesh	107
5.7.2	Multi-interval Constant Element-size Mesh	111
5.8	Effect of Viscosity Model	113
5.9	Effect of Rolling Speed	114
5.10	Numerical Problems Faced in the Solution	116
5.9.1	Cavitations	116
5.9.2	Stability	117
5.11	Closure	119
6	COMPARISONS AND DISCUSSIONS	120
6.1	Introduction	120
6.2	Experimental Work	120
6.3	Comparisons between BEM-FDM Hybrid Model and FDM Solutions	121
6.4	Comparison with Houpert and Hamrock Results	125
6.5	Comparison with Hughes et al. Results	127
6.6	Comparison with Lehtovaara Results	129
6.7	Closure	132
7	CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK	133
7.1	Conclusions	133
7.2	Recommendations for Further Work	134
	REFERENCES	136
	APPENDICES	146
A	Elastic Deformation Equation	147
B	Example of a Matlab Program for Plotting	152
	VITA	154



LIST OF TABLES

Table		Page
2.1	Dimensionless parameters definitions and typical ranges	23
2.2	Typical range for the EHL hard rolling parameters (Gohar, 1988)	24
2.3	Calculation parameters and results for line contact (Gohar and Kuhn,1994)	34
3.1	Example of typical values for Hertzian half width	46
3.2	Typical range for the EHL hard rolling parameters (Gohar, 1988)	58
4.1	Elasticity equation dimensionless parameters	80
5.1	Squaring 1.0000001 by itself twenty-seven times	97
5.2	Machine precisions for some microcomputers	99
5.3	Accuracy and speed of various working environments	100
5.4	Parameters of hard rolling used for the variation of the mesh configuration	106
5.5	The effect of mesh size in the calculation of the magnitude of the pressure spike and the maximum central pressure	108
5.6	Example of four interval constant–element-size mesh	111
5.7	Parameters of hard rolling used for the variation of the viscosity model	113
5.8	Parameters used for calculation of pressure and film thickness	115
6.1	Dimensional and dimensionless parameters for comparison between the BEM and FDM	122
6.2	Dimensional and dimensionless parameters for comparison between the BEM and FDM	123
6.3	Dimensionless variables for comparison with Houpert and Hamrock (1986)	126
6.4	Geometric and material parameters for comparison with Hughes et al. (1999)	128
6.5	Characteristic variables used by Lehtovaara (1998)	130



6.6 Example of calculation of the dimensionless parameters L and M used by Lehtovaara (1998)

131



LIST OF FIGURES

Figure	Page
1.1 Divisions of tribology from tribology to elastohydrodynamic lubrication	3
1.2 Generation of pressure by hydrodynamic wedge action (Summer-Smith, 1994)	5
1.3 Lubricated non-conformal surfaces of high-elastic-modulus material	7
1.4 Pure rolling contact of roller bearing	8
1.5 Rolling and sliding contact in two meshing spur gears (Wallach and Chowenhill, 1989)	8
2.1 Asperity contact in EHL	16
2.2 a. EHL line contact pressure distribution. b. EHL line contact film thickness for calculation parameter in Table 2.3 (Gohar and Kuhn, 1994)	35
3.1 Parameters of hydrodynamic lubrication	42
3.2 Hertzian contact and pressure distribution of two cylinders	45
3.3 Roller bearing as a representation of direct internal and external rolling	47
3.4 Profile of two involute gears teeth close to their contact	48
3.5 Rolling contact and the equivalent cylinder of reduced radius R and plane	49
3.6 External rolling cylinders representation	50
3.7 Internal rolling cylinders representation	53
3.8 Distortion terms of a distorted roller	54
3.9 Barus viscosity-pressure relation	56
3.10 Roelands viscosity-pressure relations for a typical lubricant	58
3.11 Ratio of η_B to η_R variation with pressure	59
3.12 Variation of density with pressure using equation [3.22] and Hirano et al. (1985) results	60
4.1 Quadratic isoparametric element	70



4.2	Co-ordinates system	72
4.3	Dirac delta function $\delta(x-a)$	74
4.4	Calculation of the elastic deformation	81
4.5	Geometric interpretation of Newton Raphson technique	87
4.6	Non-converging situation of Newton Raphson technique	87
4.7	Program flow chart	89
4.8	Nodes of the grid for a roller and plane presentation	91
5.1	Program squaring	98
5.2	Program accuracy	98
5.3	Program accspeed	99
5.4	Detailed program structure	102
5.5	Elements and nodes for solution of the elasticity equation using hybrid model	105
5.6	Results of pressure and film thickness of not converged solution, (50 elements)	108
5.7	Pressure distribution and film thickness using 80 and 420 constant element-size meshes	109
5.8	Pressure distribution and film thickness using four constant element-size meshes	110
5.9	Pressure distribution and film thickness using four multi-interval constant element-size meshes	112
5.10	Pressure and film thickness using Barus and Roelands viscosity models	114
5.11	Dimensionless pressure distribution for rolling speeds equal to 0.0, 4, 14 and 24 m/s	115
5.12	Dimensionless film thickness for rolling speeds 0.0, 4, 14 and 24 m/s	116
5.13	Unstable behaviour happening near the pressure spike position	118
6.1	Comparison between BEM-FDM hybrid and FDM solutions for test data of Table 6.1	122

6.2	Comparison between hybrid BEM-FDM and FDM models (Onsa et al., 2000a)	123
6.3	Comparison between BEM-FDM hybrid and FDM solutions for test data of Table 6.2	124
6.4a	Comparison of pressure distribution with Houpert and Hamrock (1986) results using dimensionless variables in Table 6.3	126
6.4b	Comparison of film thickness with Houpert and Hamrock (1986) results using dimensionless variable in Table 6.3	127
6.5	Comparison between the BEM-FDM solution and Hughes et al. (1999) results for 0.5 GPa maximum pressure	129
6.6	Comparison between the BEM-FDM solution and Hughes et al. (1999) results for 1.6 GPa maximum pressure	129
6.7	Lehtovaara (1998) pressure distribution for dimensionless material parameter ($L = 10$) and dimensionless load parameter ($M = 2$ (a), $M = 5$ (b), $M = 20$ (c) and $M = 100$ (d))	131
6.8	Lehtovaara (1998) fluid film thickness for dimensionless material parameter ($L = 10$) and dimensionless load parameter ($M = 2$ (a), $M = 5$ (b), $M = 20$ (c) and $M = 100$ (d))	132
A.1	Plane cylindrical and Cartesian co-ordinates used for line-load, w acting on the boundary surface of elastic half-space, Tripp (1985)	149
A.2	Line strip load in Cartesian co-ordinates	151



NOMENCLATURE

a_i	Weighting factor used in dP/dX formula at node i
b	Hertzian half width
BEM	Boundary element method
C_j	Weighting factor used to integrate P
CPU	Central processing unit
E	Modulus of elasticity
E'	Reduced modulus of elasticity
EHL	Elastohydrodynamic lubrication
FDM	Finite difference method
FEM	Finite element method
G	Dimensionless material property
$G(X, \zeta)$	Weighting factor
G_y	G matrix
h	Film thickness
h'	Reynolds equation term = $\rho h^3 / 12 \eta$
h_{min}	Minimum film thickness
H	Dimensionless film thickness
H_{min}	Dimensionless minimum film thickness
H_c	Dimensionless central film thickness
H_y	H matrix
i, j, k	Indexes
L	Dimensionless material parameter, $L = G (2U)^{1/4}$
M	Dimensionless load parameter, $M = W (2U)^{-1/2}$
N	Number of nodes

P	Dimensionless pressure = p/p_H
p	Pressure
p_H	Hertzian pressure
R, R'	Reduced radius
R_1	Radius of roller 1
R_2	Radius of roller 2
R_x, R_y	Effective radius in x and y direction
t	Traction
T_{ij}	Traction matrix
U	Average rolling velocity
U	Dimensionless speed parameter
u	Displacement, velocity
U_1	Roller 1 velocity
U_2	Roller 2 velocity
U_{ij}	Displacement matrix
W	Dimensionless load
w	Load per unit length
X	Dimensionless coordinate
x	x-coordinate along rolling direction
x, y, z	x, y, z coordinates
X_{end}	Coordinate X at end of calculation zone (exit)
X_N	Coordinate X at node N

Greek Symbols

α	Roelands pressure-viscosity
ε	Infinitesimal distance from a point
δ	Elastic deformation
$\delta(x-a)$	Dirac delta function
δ_{ij}	Dirac delta function
Γ	Boundary
η	Viscosity
η_0	Viscosity at standard temperature and pressure
η_1, η_2	Transformation coordinate system
ρ	Density
ζ_0	Point of under consideration
ζ	Any point of calculation
φ	Reynolds equation term = $\frac{d}{dx}[\rho hU]$

Subscripts

$1, 2$	Rolling body 1 and 2
H, h	Hertzian
i, j, k	Indices
min	Minimum value
N	Node number N

Note: other symbols are defined in the text.

CHAPTER 1

INTRODUCTION

1.1 Overview

The main aim of this research is to use an efficient and fast numerical method for the solution of the challenging problem of the elastohydrodynamic of hard rolling line contact. The boundary element method (BEM) is utilised to achieve this goal. The investigations lead to two numerical models; one uses BEM and the other uses the finite difference method (FDM). The novel contribution of this study to the field of hard rolling elastohydrodynamic lubrication (EHL) is to incorporate the BEM to the numerical solution of the problem.

EHL is a form of fluid film lubrication where the elastic deformation of the lubricated bodies becomes significant. The elastic deformation together with the hydrodynamic behaviour of the lubricant film determine the regime. The EHL study describes the separation using a lubricant film between two elastic machine elements loaded against each other in a relative motion. The lubricant film is capable of reducing friction and wear between surfaces by the mechanism of separating the contact surfaces. Nevertheless, the elastic deformation is the prominent characteristic of EHL, as the materials under contact can have high modulus of elasticity that denote the hard EHL, as well as a low modulus value which in turn designates the soft EHL. Since the EHL of hard rolling is the dominant mode of lubrication in many critical, highly stressed machine elements, the study of the stress concentration and deformation is important to predict the performance and the life expectancy of the machine element. In these machine

elements such as gears, cams and followers and bearings, most of the failures are manifested in wear, fatigue and scuffing.

EHL is a sort of fluid film lubrication, which is related to the hydrodynamic lubrication by the common hydrodynamic action. The Hydrodynamic lubrication is generally characterized geometrically by the conformal contact, and its applications in journal and thrust bearings are well developed. The confirmation of theoretical prediction through experiments has led to satisfactory design procedures. The conformity between the bearing components enables a substantial load to be carried at a relatively small lubricant film pressure. EHL however, is characterized by a non-conformal contact, in which the load is carried out by a small lubricant foot print area at relatively high pressure.

The concepts of lubrication come to exist in the prehistoric period. When human invented the wheel and drove it in an axle, they found that it ran easier and faster when lubricated. It is likely that even in prehistory, men were interested in two aspects of friction. Firstly, man is interested in its effect in generating heat and then producing fire, and secondly, its effect in reducing the motion of his first cart. It is known that in the Pheronic Egypt, lubrication was used to facilitate the movement of sledges carrying large statues and building blocks of stone. Cows Encyclopaedia of Science and Technology mentions that the chariots found in the Egyptian tombs have traces of lubricant, which upon analysis proved to be a mutton or beef tallow. Although lubrication is an old subject, it is still advancing with the advances in the machinery and industrial technologies, and even advances rapidly with the need to conserve energy and reduce wear.

