

ISBN: 0-8247-0703-6

This book is printed on acid-free paper.

Headquarters

Marcel Dekker, Inc.

270 Madison Avenue, New York, NY 10016

tel: 212-696-9000; fax: 212-685-4540

Eastern Hemisphere Distribution

Hutgasse 4, Postfach 812, CH-4001 Basel, Switzerland

tel: 41-61-260-6300; fax: 41-61-260-6333

World Wide Web

<http://www.dekker.com>

The publisher offers discounts on this book when ordered in bulk quantities. For more information, write to Special Sales/Professional Marketing at the headquarters address above.

Copyright © 2003 by Marcel Dekker, Inc. All Rights Reserved.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage and retrieval system, without permission in writing from the publisher.

Current printing (last digit):

10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

To Renana, Amir, and Alon

Preface

Most engineering schools offer senior courses in bearing design in machinery. These courses are offered under various titles, such as Tribology, Bearings and Bearing Lubrication, and Advanced Machine Design. This book is intended for use as a textbook for these and similar courses for undergraduate students and for self-study by engineers involved in design, maintenance, and development of machinery. The text includes many examples of problems directly related to important design cases, which are often encountered by engineers. In addition, students will find this book useful as a reference for design projects and machine design courses.

Engineers have already realized that there is a need for a basic course and a textbook for undergraduate students that does not focus on only one bearing type, such as a hydrodynamic bearing or a rolling-element bearing, but presents the big picture—an overview of all bearing types. This course should cover the fundamental aspects of bearing selection, design, and tribology. Design engineers require much more knowledge for bearing design than is usually taught in machine design courses.

This book was developed to fill this need. The unique approach of this text is that it is not intended only for scientists and graduate students, but it is specifically tailored as a basic practical course for engineers. For this purpose, the traditional complex material of bearing design was simplified and presented in a methodical way that is easily understood, and illustrated by many examples.

However, this text also includes chapters for advanced studies, to upgrade the text for graduate-level courses.

Engineering schools continually strive to strengthen the design component of engineering education, in order to meet the need of the industry, and this text is intended to satisfy this requirement. Whenever an engineer faces the task of designing a machine, his first questions are often which bearings to select and how to arrange them, and how to house, lubricate and seal the bearings. Appropriate bearing design is essential for a reliable machine operation, because bearings wear out and fail by fatigue, causing a breakdown in machine operation.

I have used the material in this book for many years to teach a tribology course for senior undergraduate students and for an advanced course, Bearings and Bearing Lubrication, for graduate students. The book has benefited from the teaching experience and constructive comments of the students over the years.

The first objective of this text is to present the high-level theory in bearing design in a simplified form, with an emphasis on the basic physical concepts. For example, the hydrodynamic fluid film theory is presented in basic terms, without resorting to complex fluid dynamic derivations. The complex mathematical integration required for solving the pressure wave in fluid-film bearings is replaced in many cases by a simple numerical integration, which the students and engineers may prefer to perform with the aid of a personal computer. The complex calculations of contact stresses in rolling-element bearings are also presented in a simplified practical form for design engineers.

The second objective is that the text be self-contained, and the explanation of the material be based on first principles. This means that engineers of various backgrounds can study this text without prerequisite advanced courses.

The third objective is not to dwell only on theory and calculations, but rather to emphasize the practical aspects of bearing design, such as bearings arrangement, high-temperature considerations, tolerances, and material selection. In the past, engineers gained this expert knowledge only after many years of experience. This knowledge is demonstrated in this text by a large number of drawings of design examples and case studies from various industries. In addition, important economical considerations are included. For bearing selection and design, engineers must consider the initial cost of each component as well as the long-term maintenance expenses.

The fourth objective is to encourage students to innovate design ideas and unique solutions to bearing design problems. For this purpose, several case studies of interesting and unique solutions are included in this text.

In the last few decades, there has been remarkable progress in machinery and there is an ever-increasing requirement for better bearings that can operate at higher speeds, under higher loads, and at higher temperatures. In response to this need, a large volume of experimental and analytical research has been

conducted that is directly related to bearing design. Another purpose of this text is to make the vast amount of accumulated knowledge readily available to engineers.

In many cases, bearings are selected by using manufacturers' catalogs of rolling-element bearings. However, as is shown in this text, rolling bearings are only one choice, and depending on the application, other bearing types can be more suitable or more economical for a specific application. This book reviews the merits of other bearing types to guide engineers.

Bearing design requires an interdisciplinary background. It involves calculations that are based on the principles of fluid mechanics, solid mechanics, and material science. The examples in the book are important to show how all these engineering principles are used in practice. In particular, the examples are necessary for self-study by engineers, to answer the questions that remain after reading the theoretical part of the text.

Extensive use is made of the recent development in computers and software for solving basic bearing design problems. In the past, engineers involved in bearing design spent a lot of time and effort on analytical derivations, particularly on complicated mathematical integration for calculating the load capacity of hydrodynamic bearings. Recently, all this work was made easier by computer-aided numerical integration. The examples in this text emphasize the use of computers for bearing design.

[Chapter 1](#) is a survey of the various bearing types; the advantages and limitations of each bearing type are discussed. The second chapter deals with lubricant viscosity, its measurement, and variable viscosity as a function of temperature and pressure. [Chapter 3](#) deals with the characteristics of lubricants, including mineral and synthetic oils and greases, as well as the many additives used to enhance the desired properties.

[Chapters 4–7](#) deal with the operation of fluid-film bearings. The hydrodynamic lubrication theory is presented from first principles, and examples of calculations of the pressure wave and load capacity are included. [Chapter 8](#) deals with the use of charts for practical bearing design procedures, and estimation of the operation temperature of the oil. [Chapter 9](#) presents practical examples of widely used hydrodynamic bearings that overcome the limitations of the common hydrodynamic journal bearings. [Chapter 10](#) covers the design of hydrostatic pad bearings in which an external pump generates the pressure. The complete hydraulic system is discussed.

[Chapter 11](#) deals with bearing materials. The basic principles of practical tribology (friction and wear) for various materials are introduced. Metals and nonmetals such as plastics and ceramics as well as composite materials are included.

Chapters 12 and 13 deal with rolling element bearings. In Chapter 12, the calculations of the contact stresses in rolling bearings and elasto-hydrodynamic lubrication are presented with practical examples. In Chapter 13, the practical aspects of rolling bearing lubrication are presented. In addition, the selection of rolling bearings is outlined, with examples. Most important, the design considerations of bearing arrangement are discussed, and examples provided. Chapter 14 covers the subject of bearing testing under static and dynamic conditions.

Chapter 15 deals with hydrodynamic journal bearings under dynamic load. It describes the use of computers for solving the trajectory of the journal center under dynamic conditions. Chapters 16 and 17 deal with friction characteristics and modeling of dynamic friction, which has found important applications in control of machines with friction. Chapter 18 presents a unique case study of composite bearing—hydrodynamic and rolling-element bearing in series. Chapter 19 deals with viscoelastic (non-Newtonian) lubricants, such as the VI improved oils, and Chapter 20 describes the operation of natural human joints as well as the challenges in the development of artificial joint implants.

I acknowledge the constructive comments of many colleagues and engineers involved in bearing design, and the industrial publications and advice provided by the members of the Society of Tribology and Lubrication Engineers. Many graduates who had taken this course have already used the preliminary notes for actual design and provided valuable feedback and important comments.

I am grateful to my graduate and undergraduate students, whose valuable comments were instrumental in making the text easily understood. Many solved problems were added because the students felt that they were necessary for unambiguous understanding of the many details of bearing design. Also, I wish to express my appreciation to Ted Allen and Marcel Dekker, Inc., for the great help and support with this project.

I acknowledge all the companies that provided materials and drawings, in particular, FAG and SKF. I am also pleased to thank the graduate students Simon Cohn and Max Roman for conducting experiments that are included in the text, helping with drawings, and reviewing examples, and Gaurav Dave, for help with the artwork.

Special thanks to my son, Amir Harnoy, who followed the progress of the writing of this text, and continually provided important suggestions. Amir is a mechanical project engineer who tested the text in actual designs for the aerospace industry. Last but not least, particular gratitude to my wife, Renana, for help and encouragement during the long creation of this project.

Avraham Harnoy

Table of Contents

Preface
Symbols

Chapter 1 Classification and Selection of Bearings

- 1.1 Introduction
- 1.2 Dry and Boundary Lubrication Bearings
- 1.3 Hydrodynamic Bearing
- 1.4 Hydrostatic Bearing
- 1.5 Magnetic Bearing
- 1.6 Rolling Element Bearings
- 1.7 Selection Criteria
- 1.8 Bearings for Precision Applications
- 1.9 Noncontact Bearings for Precision Application
- 1.10 Bearing Subjected to Frequent Starts and Stops
- 1.11 Example Problems

Chapter 2 Lubricant Viscosity

- 2.1 Introduction
- 2.2 Simple Shear Flow

- 2.3 Boundary Conditions of Flow
- 2.4 Viscosity Units
- 2.5 Viscosity–Temperature Curves
- 2.6 Viscosity Index
- 2.7 Viscosity as a Function of Pressure
- 2.8 Viscosity as a Function of Shear Rate
- 2.9 Viscoelastic Lubricants

Chapter 3 Fundamental Properties of Lubricants

- 3.1 Introduction
- 3.2 Crude Oils
- 3.3 Base Oil Components
- 3.4 Synthetic Oils
- 3.5 Greases
- 3.6 Additives to Lubricants

Chapter 4 Principles of Hydrodynamic Lubrication

- 4.1 Introduction
- 4.2 Assumptions of Hydrodynamic Lubrication Theory
- 4.3 Hydrodynamic Long Bearing
- 4.4 Differential Equation of Fluid Motion
- 4.5 Flow in a Long Bearing
- 4.6 Pressure Wave
- 4.7 Plane-Slider Load Capacity
- 4.8 Viscous Friction Force in a Plane-Slider
- 4.9 Flow Between Two Parallel Plates
- 4.10 Fluid-Film Between a Cylinder and Flat Plate
- 4.11 Solution in Dimensionless Terms

Chapter 5 Basic Hydrodynamic Equations

- 5.1 Navier–Stokes Equations
- 5.2 Reynolds Hydrodynamic Lubrication Equation
- 5.3 Wide Plane-Slider
- 5.4 Fluid Film Between a Flat Plate and a Cylinder
- 5.5 Transition to Turbulence
- 5.6 Cylindrical Coordinates
- 5.7 Squeeze-Film Flow

Chapter 6 Long Hydrodynamic Journal Bearing

- 6.1 Introduction
- 6.2 Reynolds Equation for a Journal Bearing
- 6.3 Journal Bearing with Rotating Sleeve
- 6.4 Combined Rolling and Sliding
- 6.5 Pressure Wave in a Long Journal Bearing
- 6.6 Sommerfeld Solution of the Pressure Wave
- 6.7 Journal Bearing Load Capacity
- 6.8 Load Capacity Based on Sommerfeld Conditions
- 6.9 Friction in a Long Journal Bearing
- 6.10 Power Loss on Viscous Friction
- 6.11 Sommerfeld Number
- 6.12 Practical Pressure Boundary Conditions

Chapter 7 Short Journal Bearings

- 7.1 Introduction
- 7.2 Short-Bearing Analysis
- 7.3 Flow in the Axial Direction
- 7.4 Sommerfeld Number of a Short Bearing
- 7.5 Viscous Friction
- 7.6 Journal Bearing Stiffness

Chapter 8 Design Charts for Finite-Length Journal Bearings

- 8.1 Introduction
- 8.2 Design Procedure
- 8.3 Minimum Film Thickness
- 8.4 Raimondi and Boyd Charts and Tables
- 8.5 Fluid Film Temperature
- 8.6 Peak Temperature in Large, Heavily Loaded Bearings
- 8.7 Design Based on Experimental Curves

Chapter 9 Practical Applications of Journal Bearings

- 9.1 Introduction
- 9.2 Hydrodynamic Bearing Whirl
- 9.3 Elliptical Bearings
- 9.4 Three-Lobe Bearings

- 9.5 Pivoted-Pad Journal Bearing
- 9.6 Bearings Made of Compliant Materials
- 9.7 Foil Bearings
- 9.8 Analysis of a Foil Bearing
- 9.9 Foil Bearings in High-Speed Turbines
- 9.10 Design Example of a Compliant Bearing

Chapter 10 Hydrostatic Bearings

- 10.1 Introduction
- 10.2 Hydrostatic Circular Pads
- 10.3 Radial Pressure Distribution and Load Capacity
- 10.4 Power Losses in the Hydrostatic Pad
- 10.5 Optimization for Minimum Power Loss
- 10.6 Long Rectangular Hydrostatic Bearings
- 10.7 Multidirectional Hydrostatic Support
- 10.8 Hydrostatic Pad Stiffness for Constant Flow-Rate
- 10.9 Constant-Pressure-Supply Pads with Restrictors
- 10.10 Analysis of Stiffness for a Constant Pressure Supply
- 10.11 Journal Bearing Cross-Stiffness
- 10.12 Applications
- 10.13 Hydraulic Pumps
- 10.14 Gear Pump Characteristics
- 10.15 Flow Dividers
- 10.16 Case Study: Hydrostatic Shoe Pads in Large Rotary Mills

Chapter 11 Bearing Materials

- 11.1 Fundamental Principles of Tribology
- 11.2 Wear Mechanisms
- 11.3 Selection of Bearing Materials
- 11.4 Metal Bearings
- 11.5 Nonmetal Bearing Materials

Chapter 12 Rolling Element Bearings

- 12.1 Introduction
- 12.2 Classification of Rolling-Element Bearings
- 12.3 Hertz Contact Stresses in Rolling Bearings
- 12.4 Theoretical Line Contact

- 12.5 Ellipsoidal Contact Area in Ball Bearings
- 12.6 Rolling-Element Speed
- 12.7 Elastohydrodynamic Lubrication in Rolling Bearings
- 12.8 Elastohydrodynamic Lubrication of a Line Contact
- 12.9 Elastohydrodynamic Lubrication of Ball Bearings
- 12.10 Force Components in an Angular Contact Bearing

Chapter 13 Selection and Design of Rolling Bearings

- 13.1 Introduction
- 13.2 Fatigue Life Calculations
- 13.3 Bearing Operating Temperature
- 13.4 Rolling Bearing Lubrication
- 13.5 Bearing Precision
- 13.6 Internal Clearance of Rolling Bearings
- 13.7 Vibrations and Noise in Rolling Bearings
- 13.8 Shaft and Housing Fits
- 13.9 Stress and Deformation Due to Tight Fits
- 13.10 Bearing Mounting Arrangements
- 13.11 Adjustable Bearing Arrangement
- 13.12 Examples of Bearing Arrangements in Machinery
- 13.13 Selection of Oil Versus Grease
- 13.14 Grease Lubrication
- 13.15 Grease Life
- 13.16 Liquid Lubrication Systems
- 13.17 High-Temperature Applications
- 13.18 Speed Limit of Standard Bearings
- 13.19 Materials for Rolling Bearings
- 13.20 Processes for Manufacturing High-Purity Steel
- 13.21 Ceramic Materials for Rolling Bearings
- 13.22 Rolling Bearing Cages
- 13.23 Bearing Seals
- 13.24 Mechanical Seals

Chapter 14 Testing of Friction and Wear

- 14.1 Introduction
- 14.2 Testing Machines for Dry and Boundary Lubrication
- 14.3 Friction Testing Under High-Frequency Oscillations
- 14.4 Measurement of Journal Bearing Friction
- 14.5 Testing of Dynamic Friction
- 14.6 Friction-Testing Machine with a Hydrostatic Pad

- 14.7 Four-Bearings Measurement Apparatus
- 14.8 Apparatus for Measuring Friction in Linear Motion

Chapter 15 Hydrodynamic Bearings Under Dynamic Conditions

- 15.1 Introduction
- 15.2 Analysis of Short Bearings Under Dynamic Conditions
- 15.3 Journal Center Trajectory
- 15.4 Solution of Journal Motion by Finite-Difference Method

Chapter 16 Friction Characteristics

- 16.1 Introduction
- 16.2 Friction in Hydrodynamic and Mixed Lubrication
- 16.3 Friction of Plastic Against Metal
- 16.4 Dynamic Friction

Chapter 17 Modeling Dynamic Friction

- 17.1 Introduction
- 17.2 Dynamic Friction Model for Journal Bearings
- 17.3 Development of the Model
- 17.4 Modeling Friction at Steady Velocity
- 17.5 Modeling Dynamic Friction
- 17.6 Comparison of Model Simulations and Experiments

Chapter 18 Case Study: Composite Bearing—Rolling Element and Fluid Film in Series

- 18.1 Introduction
- 18.2 Composite-Bearing Designs
- 18.3 Previous Research in Composite Bearings
- 18.4 Composite Bearing with Centrifugal Mechanism
- 18.5 Performance Under Dynamic Conditions
- 18.6 Thermal Effects

Chapter 19 Non-Newtonian Viscoelastic Effects

- 19.1 Introduction
- 19.2 Viscoelastic Fluid Models

- 19.3 Analysis of Viscoelastic Fluid Flow
- 19.4 Pressure Wave in a Journal Bearing
- 19.5 Squeeze-Film Flow

Chapter 20 Orthopedic Joint Implants

- 20.1 Introduction
- 20.2 Artificial Hip Joint as a Bearing
- 20.3 History of the Hip Replacement Joint
- 20.4 Materials for Joint Implants
- 20.5 Dynamic Friction

Appendix A Units and Definitions of Material Properties

Appendix B Numerical Integration

Bibliography

Symbols

NOMENCLATURE FOR HYDRODYNAMIC BEARINGS

- \vec{a} = acceleration vector
- $a = \tan \alpha$, slope of inclined plane slider
- B = length of plane slider (x direction) (Fig. 4-5)
- C = radial clearance
- c = specific heat
- e = eccentricity
- F = external load
- F_f = friction force
- $F(t)$ = time dependent load; having components $F_x(t)$, $F_y(t)$
- h = variable film thickness
- $h_n = h_{\min}$, minimum film thickness
- h_0 = film thickness at a point of peak pressure
- L = length of the sleeve (z direction) (Fig. 7-1); width of a plane slider (z direction) (Fig. 4-5)
- m = mass of journal
- N = bearing speed [RPM]
- n = bearing speed [rps]
- O ; O_1 = sleeve and journal centers, respectively (Fig. 6-1)

p = pressure wave in the fluid film
 P = average pressure
 PV = bearing limit (product of average pressure times sliding velocity)
 q = constant flow rate in the clearance (per unit of bearing length)
 R = journal radius
 R_1 = bearing bore radius
 t = time
 $\bar{t} = \omega t$, dimensionless time
 U = journal surface velocity
 V = sliding velocity
 VI = viscosity index (Eq. 2-5)
 W = bearing load carrying capacity, W_x , W_y , components
 α = slope of inclined plane slider, or variable slope of converging clearance
 α = viscosity-pressure exponent, Eq. 2-6
 $\beta = h_2/h_1$, ratio of maximum and minimum film thickness in plane slider
 ε = eccentricity ratio, e/C
 ϕ = Attitude angle, Fig. 1-3
 λ = relaxation time of the fluid
 ρ = density
 θ = angular coordinates (Figs. 1-3 and 9-1)
 $\tau_{xy}, \tau_{yz}, \tau_{xz}$ = shear stresses
 $\sigma_x, \sigma_y, \sigma_z$ = tensile stresses
 ω = angular velocity of the journal
 μ = absolute viscosity
 μ_0 = absolute viscosity at atmospheric pressure
 ν = kinematic viscosity, μ/ρ

NOMENCLATURE FOR HYDROSTATIC BEARINGS

A_e = effective bearing area (Eq. 10-25)
 B = width of plate in unidirectional flow
 d_i = inside diameter of capillary tube
 \dot{E}_h = hydraulic power required to pump the fluid through the bearing and piping system
 \dot{E}_f = mechanical power provided by the drive (electrical motor) to overcome the friction torque (Eq. 10.15)
 \dot{E}_t = total power of hydraulic power and mechanical power required to maintain the operation of hydrostatic bearing (Eq. 10-18)
 h_0 = clearance between two parallel, concentric disks
 H_p = head of pump = $H_d - H_s$

H_d = discharge head (Eq. 10-51)
 H_s = suction head (Eq. 10-52)
 k = bearing stiffness (Eq. 10-23)
 K = parameter used to calculate stiffness of bearing = $3\kappa A_c Q$
 L = length of rectangular pad
 l_c = length of capillary tube
 p_d = pump discharge pressure
 p_r = recess pressure
 p_s = supply pressure (also pump suction pressure)
 Δp = pressure loss along the resistance
 Q = flow rate
 R = disk radius
 R_0 = radius of a round recess
 R_f = flow resistance = $\Delta p/Q$
 R_{in} = resistance of inlet flow restrictor
 T_m = mechanical torque of motor
 V = fluid velocity
 W = load capacity
 Z = height
 η_1 = efficiency of motor
 η_2 = efficiency of pump
 κ = constant that depends on bearing geometry (Eq. 10-27)
 β = ratio of recess pressure to the supply pressure, p_r/p_s
 μ = fluid viscosity
 γ = specific weight of fluid

NOMENCLATURE FOR ROLLING ELEMENT BEARINGS

a = half width of rectangular contact area (Fig. 12-8)
 a, b = small and large radius, respectively, of an ellipsoidal contact area
 d = rolling element diameter
 d_i, d_o = inside and outside diameters of a ring
 E_{eq} = equivalent modulus of elasticity [N/m^2]
 \hat{E} = elliptical integral, defined by Eq. 12-28 and estimated by Eq. 12.19
 F_c = centrifugal force of a rolling element
 h_c = central film thickness
 h_{min}, h_n = minimum film thickness
 k = ellipticity-parameter, b/a , estimated by Eq. 12.17
 L = An effective length of a line contact between two cylinders
 m_r = mass of a rolling element (ball or cylinder)

- n_r = number of rolling elements around the bearing
 p = pressure distribution
 p_{\max} = maximum Hertz pressure at the center of contact area (Eq. 12-15)
 q_a = parameter to estimate, \hat{E} , defined in Eq. 12-18
 r = deep groove radius
 R_1, R_2 = radius of curvatures of two bodies in contact
 R_{1x}, R_{2x} = radius of curvatures, in plane y, z , of two bodies in contact
 R_{1y}, R_{2y} = radius of curvatures, in plane x, z , of two bodies in contact
 R_{eq} = equivalent radius of curvature
 R_r = race-conformity ratio, r/d
 R_s = equivalent surface roughness at the contact (Eq. 12-38)
 R_{s1} and R_{s2} = surface roughness of two individual surfaces in contact
 R_x = equivalent contact radius (Eqs. 12-5, 12-6)
 R_d = curvature difference defined by Eq. 12-27
 t^* = parameter estimated by Eq. 12.25 for calculating τ_{yz} in Eq. 12-24
 \hat{T} = elliptical integral, defined by Eq. 12.28 and estimated by Eq. 12-22
 U_C = velocity of a rolling element center (Eq. 12-31)
 U_r = rolling velocity (Eq. 12-35)
 \bar{W} = dimensionless bearing load carrying capacity
 W = load carrying capacity
 W_i, W_o = resultant normal contact forces of the inner and outer ring races in angular contact bearing
 W_{\max} = maximum load on a single rolling element
 N = bearing speed [RPM]
 α = viscosity-pressure exponent
 α = linear thermal-expansion coefficient
 α_r = radius ratio = R_y/R_x
 Λ = a ratio of a film thickness and size of surface asperities, R_s (Eq. 12-39)
 δ_m = maximum deformation of the roller in a normal direction to the contact area (Eq. 12-7, 12-21)
 ξ = ratio of rolling to sliding velocity
 $\tau_{xy}, \tau_{yz}, \tau_{xz}$ = shear stresses
 $\sigma_x, \sigma_y, \sigma_z$ = tensile stresses
 μ_0 = absolute viscosity of the lubricant at atmospheric pressure
 ν = Poisson's ratio
 ω = angular speed
 ω_C = angular speed of the center of a rolling element (or cage) [rad/s]
 ρ = density