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

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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 elastohydrodynamic 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

Symbols

NOMENCLATURE FOR HYDRODYNAMIC BEARINGS

$\vec{a}$ = acceleration vector
a = tan α, 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
$\bar{t}$ = ωt, 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
β = 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_o = 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 = $3\kappa A_e Q$
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)
$\overline{W}$ = 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