THEORY AND PRACTICE OF LUBRICATION FOR ENGINEERS

Dudley D. Fuller

SECOND EDITION



THEORY AND PRACTICE OF LUBRICATION FOR ENGINEERS

Second Edition

DUDLEY D. FULLER

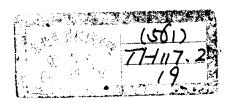
Stevens Professor Emeritus of Mechanical Engineering,

Columbia University

International Tribology Gold Medal Laureate 1978

Engineering Consultant

TH117.2/21



A Wiley-Interscience Publication

IOHN WILEY & SONS

New York • Chichester • Brisbane • Toronto • Singapore

0168134

Copyright © 1984 by John Wiley & Sons, Inc.

All rights reserved. Published simultaneously in Canada.

Reproduction or translation of any part of this work beyond that permitted by Section 107 or 108 of the 1976 United States Copyright Act without the permission of the copyright owner is unlawful. Requests for permission or further information should be addressed to the Permissions Department, John Wiley & Sons, Inc.

Library of Congress Cataloging in Publication Data:

Fuller, Dudley D.

Theory and practice of lubrication for engineers.

"A Wiley-Interscience publication." Includes bibliographical references and index.

1. Lubrication and lubricants. I. Title.

TJ1075.F8 1984

621.8'9 83-27394 ISBN 0-471-04703-1

Printed in the United States of America

10987654321

THEORY AND PRACTICE OF LUBRICATION FOR ENGINEERS

This book is dedicated to the memory of the late Professor George B. Karelitz of the Department of Mechanical Engineering at Columbia University.

Although George Karelitz contributed to many fields in Mechanical Engineering he is particularly known for his basic work in the field of lubrication, in which he was a major pioneer in this country. He was instrumental in establishing basic concepts in hydrodynamic and hydrostatic lubrication.

Through his many publications, he brought the theory of lubrication to the practicing engineer.

PREFACE

This book has been written with several objectives in mind. The first is to present the theory of lubrication to the engineer in the most understandable and usable form.

The second is to systematize and generalize the basic concepts that arise from the theory of lubrication, to permit the development of an organized course of study for both the classroom and the individual.

It has also been a primary objective to demonstrate, through the use of many numerical examples, the wide range of usefulness of lubrication analysis in solving engineering problems and to clarify the restrictions and modifications of lubrication theory that are vital to its successful application.

To gain these objectives, the hydrodynamic and hydrostatic theories have been developed from simple and readily understood principles. This has resulted in greatly increased utility with no significant sacrifice in accuracy or rigor. Every effort has been made to maintain clear physical concepts in the various derivations. As a consequence, the simplest mathematical methods have been employed in preference to those that may be more elegant but less obvious. The motivation in every case has been to establish clearly understood concepts, so that the basic derivations of lubrication theory may be extended by the engineer and used with confidence in meeting the whole spectrum of lubrication problems.

For example, in Chapter 8, dealing with the dynamics of bearings and rotor systems, the methods of analysis are admittedly simplified versions of more complex and involved techniques. They have been developed to provide the non-spe-

cialist with an understanding of the fundamentals of bearing and rotor dynamic behavior and the ability to cope successfully with actual design problems. The experience gained in using these methods over many years with dozens of typical dynamic problems justifies that assertion. However, references to more complete treatises in the literature are also included.

Almost all of the 66 numerical examples used in the text are corroborated either by laboratory or field work.

Emphasis is also given to the restrictive assumptions upon which the hydrodynamic and hydrostatic theories are based. As with all theories, the basic assumptions frequently circumscribe a rather tight circle within which the applicability of that theory is valid. These restrictions on lubrication theory are discussed in detail and demonstrated. For example, hydrodynamic analysis predicts that the load-carrying capacity of a bearing increases as the film gets thinner, rising to infinity as the film thickness approaches zero. In a real bearing, of course, carried to such limits, this becomes entirely unrealistic. The elastic and thermal distortions of the bearing and journal and the effects of misalignment, surface finish, and lubricant contamination establish clearly defined limits on how far the theoretical analysis may be carried.

Heat generation through shearing of the lubricant also imposes absolute restrictions on the performance that may reasonably be expected from any bearing.

In the past, the classical concept of hydrodynamic lubrication has often been limited to that of the converging geometric wedge, as found in the tilting-pad bearing and in the plain, clearance journal bearing. This is indeed an unnecessary and highly undesirable restriction of the use of this theory. In this book, hydrodynamic action has been generalized and applied to many different geometries. As a matter of fact, hydrodynamic action is a perfectly natural phenomenon and is frequently found wherever fluids and solid surfaces have some kind of relative motion. A number of very serious problems have actually arisen in industry as a result of the extreme difficulty in suppressing this normal establishment of a hydrodynamic film, when its effects were detrimental.

The difference between lubrication with liquids and lubrication with gas is carefully spelled out in this text. The area of overlap is also defined where equations based on incompressible lubricants may be satisfactorily applied to the compressible case.

The difference on bearing behavior between rigid and flexible surfaces is also identified. The concept of the non-rigid surface is assuming more significance than ever in many phases of our expanding technology.

Another relatively new concept is introduced in this text when a fluid-film journal or thrust bearing, besides supporting its designated load, may simultaneously serve as a pump. It thus performs two functions. The actual pressure and flow rate of the output fluid will of course depend upon the bearing parameters.

Considerable emphasis has been given to hydrostatic lubrication. Although the principle is old, it has been developed and systematized and by suitable analytical methods removed from the empirical, trial-and-error category. Since it has almost

numberless and still unexplored possible applications, ranging all the way from air bearings in the lightest of instruments to heavy rolling-mill bearings, the extensive coverage found in this book is considered justified.

The overall purpose of this book is thus to guide the engineer in his study of the theory of lubrication so as to most effectively implement him in his practice of lubrication.

I would like to thank Captain W. T. Sawyer and Mr. Stanley W. Doroff of the Office of Naval Research (ONR) for their foresight and active support of a coordinated research program on gas-lubrication. For more than twenty years, a coordinating group of individuals from industry, government laboratories, and universities met informally to exchange ideas and comments and share progress reports. The results of this interaction, and the continual motivating support by ONR, have been laudable and most effective in developing this phase of lubrication. It was my great pleasure to have organized and conducted these meetings.

Gratitude should also be expressed to my colleagues at The Franklin Research Center for their collaboration on a broad spectrum of research and development problems. Many of their thoughts have inevitably become my thoughts. A team effort such as we enjoyed often becomes a smooth blend of individual contributions.

Thanks must also be extended to my colleagues at the Mechanical Engineering Lubrication Research Laboratory at Columbia University. Staff and graduate students in very many ways have made possible the achievements that grew out of that activity.

Special recognition should be given to the late Gilbert F. Boeker, a long-time friend and collaborator at Columbia. He was a true pioneer in the field of gas-lubricated bearings and a great source of inspiration. His extraordinary contributions to the field have not yet been publicly recognized.

Many thanks also go to the numerous companies and government agencies with whom I have had the privilege of consulting. They have been the source of many challenging and stimulating problems. A number of those problems, in one form or another, do appear in this text.

Lastly, I should like to acknowledge my indebtedness to my wife, Helen, for patience, encouragement, and help so great and constant as to be beyond measure.

DUDLEY D. FULLER

Lake Hill, New York April 1984

CONTENTS

	INTRODUCTION	1
	References, 4	
1.	FUNDAMENTALS OF VISCOSITY AND FLOW	5
	Viscosity, 5	
	Conversion of Units of Absolute Viscosity, 7	
	Evaluation of Friction Torque, 9	
	Newtonian Fluids, 11	
	Petroff's Equation, 12	
	Viscosity Scale, 15	
	Flow of Viscous Liquid Through a Slot, 16	
	Application of Slot Equation to Hale Telescope, 19	
	Friction Losses in Hale Telescope, 25	
	Temperature Rise in Telescope Oil Pads, 25	
	References, 26	
2.	VISCOSITY AND ITS VARIABLES	27
	Flow Through a Capillary Tube, 27	
	Other Means for Measuring Absolute Viscosity, 31	
	The state of the s	

73

Falling-Sphere Viscometer, 33 Rolling-Ball Viscometers, 34 Kinematic Viscosity, 35 Other Forms of Capillary Viscometers, 41 Viscosity Data, 41 Crankcase Oils, 41 SAE and API Ratings, 43 Factors That Affect Viscosity, 45 Temperature, 45 Viscosity Index, 47 Pressure, 50 Leakage through Capillary Seals, 54 Effect of Pressure on Flow through a Slot, 55 Change of Viscosity with Rate of Shear, 59 Turbulence, 60 Reynolds Number for Bearings, 61 Density and Specific Gravity, 66 Expansion of Petroleum Oils, 70 References, 71 3. **HYDROSTATIC LUBRICATION** Hydrostatic Oil Pads, 74 Application to Rocket Bearing Tester, 75 Denver Mile High Stadium, 78 Hydrostatic Step Bearings, 78 Optimization, 84 Application to Pivoted-Pad Thrust Bearings, 91 Application to Ultracentrifuge, 95 Other Applications, 98 Optimization of Hydrostatic Thrust Bearings with Non-Symmetrical Geometries, 101 Electric Analog Solutions, 101 Hydrostatic Bearing Compensation, 110 Hydrostatic Bearing Film Stiffness with Constant Feed Rate, 112 Analytical Evaluation of Film Stiffness, 114 Hydrostatic Bearing Film Stiffness with Capillary and Orifice Compensation, 116 Capillary Compensation, 117 Orifice Compensation, 121 Design Considerations for Hydrostatic Applications with Multiple Bearing and Recess Systems, 127 Application to Radio Telescope, 130 Hydrostatic Bearings with Variable Direction Loads, 135 Hydrostatic Lifts, 142 Electric Analog Solutions, 151

Application to Precision Spindle Bearing, 154 Error-Correcting Capability, 158 Lift-Off with Tilting-Pad Journal Bearings, 160 Application of Grease-Lubricated Hydrostatic Journal Bearings to a Small Rolling Mill, 162 Application to Ball Mill, 165 Application to Synchronous Condenser, 167 Application to Foil Mill, 168 Modification of Hydrostatic Lift for Severe Conditions, 168 General Design Features, 171 References, 172	
HYDROSTATIC SQUEEZE FILMS	174
Circular Flat Plates, 175 Impact Conditions Between Lubricated Solids, 180 Rectangular Plates with Various Width-to-Length Ratios, 181 Journal and Bearing with Various Width-to-Length Ratios, 185 Application to Engine Piston Pin, 190 Squeeze Film Damping, 194 References, 197	
HYDRODYNAMIC LUBRICATION	198
Tower's Experiments, 201 Development of Hydrodynamic Theory, 202 Applications of Hydrodynamic Theory, 206 Hydrodynamic Theory Applied to Tapered Wedge, 217 Pivot Position of Tilting Shoe, 222 Distance from Sliding Surface to Pivot Contact, 224 Effects of Side Leakage, 225 Solution of Reynolds Equation, 228 Effect of Side Leakage on Tapered Wedge, 229 Film Stiffness in Tilting-Pad Thrust Bearings, 230 Friction in Slider Bearings, 232 Air-Lubricated Thrust Bearing, 237 Pivoted-Pad Journal Bearings, 239 Bearing Whirl, 240 Tilting-Pad Bearings with Crowned Profile, 243 Stepped Film Bearing, 252 Spiral-Grooved Thrust Plate, 258 References, 259	
HYDRODYNAMIC LUBRICATION OF JOURNAL BEARINGS	262
Bearings of Infinite Width, 263 Finite-Width Journal Bearings, 271	

4.

5.

6.

xiv CONTENTS

Evaluation Methods, 276
Stiffness, 281
Bearings Operating Under Severe Conditions, 282
Minimum Allowable Film Thickness, 285
Practical Design Considerations, 287
Deformation of Bearing Shell, 287
Length-to-Diameter Ratio, 289
Misalignment, 290
Construction Details, 292
Clearances in Journal Bearings, 293
Hot Clearance Versus Cold Clearance, 293
Bearing Pressures, 294
References, 296

7. FRICTION AND POWER LOSSES IN JOURNAL BEARINGS

297

343

Evaluation of Friction Loss with Laminar Bearing Films, 297 Friction in the Concentric Bearing, 303 Alternate Method for Computation of Friction in 360° Bearings, 305 Friction Loss on the Bearing, 307 Friction Losses as Measured by the McKees, 309 The Significance of the Parameter zN/p, 311 Sommerfeld Number as a Bearing Parameter, 313 Heat Balances in Self-Contained Bearings, 314 Heat Balances in Bearings with Forced-Feed Lubrication, 321 Oil Flow with Circumferential Groove, 321 Flow of Lubricant in a Bearing with a Hole Source, 325 Forced-Feed Oil Flow with Various Types of Grooves, 326 Grooving of Journal Bearings, 327 Typical Grooving Patterns, 329 Bearing Seals, 332 Oil-Feed Requirements for Lubrication of Journal Bearings, 333 Minimum Oil-Feed Requirements to Maintain a Fluid Film in Journal Bearings, 336 The Effect of Turbulent Films on Journal Bearing Friction, 339 References, 342

8. DYNAMICS OF BEARINGS AND ROTOR SYSTEMS

Synchronous Resonant Shaft Whirl, 343
Conical Synchronous Shaft Whirl, 346
Synchronous Translatory and Conical Whirl of the Bearing, 348
Non-Rotating Bearing, 348
Rotating Bearing, 350

Synchronous Shaft Whirl with Flexible Rotors, 353 Stiffness of Rolling-Element Bearings, 354 General Derivation Including Shaft and Bearing Stiffness, 354 System-Critical Speeds, 359 Dunkerley Method, 361 Half-Frequency Whirl Analysis (Translatory Shaft), 362 Conical Half-Frequency Shaft Whirl (Rigid Body Assumption), 381 Conical Half-Frequency Whirl of Bearing, 382 Non-Rotating Bearing, 382 Rotating Bearing, 382 References, 385	
VISCOUS PUMPS	387
Introduction, 387 Simple Plane Geometry, 388 Viscous Pumping Action from a Rotating Unloaded Shaft, 394 Viscous Pumps with Side-Flow Restriction, 397 Efficiency of Viscous Pumps, 400 Efficiency for Pumping Against a Head of Fluid, 402 Pumping with a Helical Groove, 405 Helical Groove Pump Including Back Flow Across the Lands, 408 Helical Pumping Groove Seals, 419 Spiral Pumping Grooves in Face Plate, 419 Spiral-Grooved Thrust Bearing, 424 Journal-Bearing Viscous Pumps, 431 References, 437	
COMPLIANT-SURFACE BEARINGS	439
Introduction, 439 Foil Bearings, 444 Tension Dominated, 445 Bending Dominated (Segmented), 446 Bending Dominated (Continuous), 446 Elastomer Bearings, 452 Hydrostatic Compliant Thrust Bearing, 456 Tilting-Pad Thrust Bearings, 464 References, 468	
SOME TYPICAL INDUSTRIAL BEARINGS	470
Oil-Ring Bearings, 470 Oil-Ring Speeds, 471 Oil Delivery by Ring, 473	

9.

10.

11.

xvi CONTENTS

Collars, 476
Wick and Felt-Pad Bearings, 477
Waste-Packed Bearings, 482
Railroad Journal Bearings, 482
Armature Bearings, 483
Heat Effects, 486
References, 488

12. GAS-LUBRICATED BEARINGS

490

Introduction, 490 Advantages, 492 Disadvantages, 492 Compressibility Numbers, 493 Tilting-Pad Bearings, 495 Effect of Mean Free Path, 500 Rayleigh Step Bearings, 501 Journal Bearings, 502 Gas-Lubricated Journal Bearings, 502 Friction in Gas-Lubricated Journal Bearings, 509 Moment Capacity of Journal Bearing, 512 Synchronous Whirl, 515 Half-Frequency Whirl, 518 Tilting-Pad Journal Bearings, 521 Three-Sector Journal Bearing, 524 Helical-Grooved Journal Bearings, 525 Hydrostatic Gas-Lubricated Thrust Bearings, 526 Pneumatic Hammer, 533 Multiple-Pressure Sources, 535 Hemispherical Air Bearing, 537 Design Procedure, 538 Porous Bearings, 542 Compliant Surface Bearings, 543 Hydrostatic Journal Bearings, 544

13. DRY FRICTION

References, 545

549

Introduction, 549
Types of Friction, 550
Dry: Static and Kinetic, 550
Boundary: Static and Kinetic, 551
Fluid Friction, 551
Semifluid or Mixed Friction, 551
Dry Friction, 552

Tomlinson's Theory of Molecular Attraction. Cohesive Friction, 554
Fretting Corrosion, 557

Preventing of Fretting, 558

Welding of Clean Surfaces, 560

Present Concept of Friction, 561

Surface Temperatures, 565

Variables in Friction, 569

Cleanliness and Surface Films, 569

Effect of Pressure, 573

Effect of Velocity and Temperature, 573

Effect of Vibration, 578

Conclusion, 579

References, 580

14. BOUNDARY FRICTION

582

Introduction, 582

Oiliness of Boundary Lubricants, 583

Molecular Adherence of Fatty Acids, 586

Effect of Length of Molecule on Boundary Friction, 589

Variables of Boundary Friction, 593

Effect of Roughness, 594

Effect of Moisture, 594

Effect of Temperature, 597

Extreme-Pressure Boundary Lubrication, 599

Characteristics of Good Boundary Lubricants, 600

Standard Test Machines for Evaluation of Boundary Lubricants, 601

Test Methods, 602

Solid Lubricants, 604

Greases, 606

Graphite, 607

Molybdenum Disulphide, 608

Phosphating of Metal Surfaces, 608

Examples, 610

Teflon Coatings, 611

Extreme Temperature Ranges, 612

Exposure to Severe Ambient Conditions, 614

To Avoid Contamination of Surfaces or Materials Adjacent to the Lubricated Areas, 614

Lubrication of Electric Contacts, 615

Situations Where Dust or Lint Collection Is Objectionable, 615

High Unit Pressures, 615

Minimization of Fretting Corrosion, 615

Conclusions, 616

References, 616

15. BEARING MATERIALS

Introduction, 618

Tin- and Lead-Base Babbitts, 619

General Requirements of Bearing Materials, 620

Score Resistance, 621

Mutual Solid Solubility, 621

Compressive Strength, 622

Fatigue Strength, 622

Deformability, 624

Corrosion Resistance, 627

Structure, 628

Structure, 02

Cost, 628

Bronzes, 630

Copper-Lead, 633

Cadmium-Base Alloys, 634

Aluminum Alloy, 635

Silver, 636

Porous Metal Bearings, 637

Cast Iron, 639

Hard Materials, 639

Ceramics and Cermets, 641

Surface Coatings, 641

Glass, 642

Synthetic Sapphires and Jewels, 642

Plastics, 643

Teflon, 644

P-V Factors, 645

Polymer-Metal Combinations, 646

Prosthetic Devices, 647

Internally Lubricated Plastics, 652

Wood, 653

Rubber, 653

Graphite, 655

Conclusion, 655

References, 656

INDEX

661

INTRODUCTION

Lubrication plays a most vital role in our great and complex civilization.

The significance of that statement was dramatically underscored during the Joint Lubrication Conference of the American Society of Mechanical Engineers and the American Society of Lubrication Engineers in October, 1983. At that conference, the 100th anniversary of the publication of the first paper on fluid-film lubrication of journal bearings was observed. This was the pioneering paper by Beauchamp Tower,^{5-1,*} "First Report on Friction Experiments," published in 1883 by The Institution of Mechanical Engineers in London.

As part of the centennial commemoration, I reviewed the extent of the present use of fluid-film bearings across the full spectrum of technological activity—industry by industry.¹

The aggregate of the collected evidence was quite unexpected and overwhelming. It was determined that industry after industry was either partially or totally dependent for its existence upon fluid-film bearings.

Fluid-film bearings were the most pervasive, across-the-board component of industrial activity, to the extent that many industries could not exist without them. The only comparable generic ingredient in our technical world might be electricity itself. Even that, one must recall, is generated by machines, dependent upon fluid-film bearings.

^{*} References are given at the end of each chapter.