THEORY AND PRACTICE OF LUBRICATION FOR ENGINEERS

SECOND EDITION

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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-specialist 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

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April 1984

CONTENTS

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.