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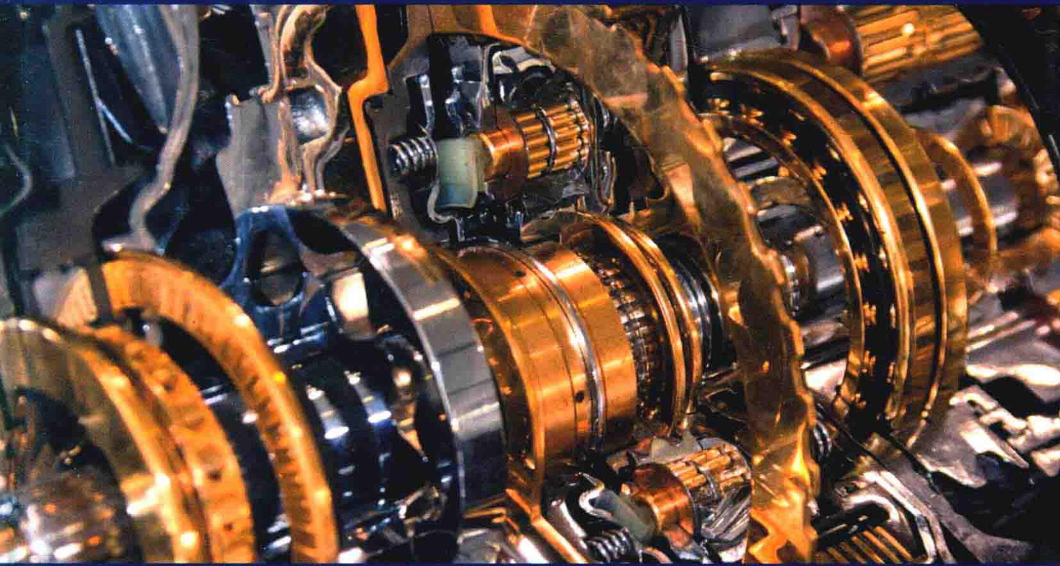

Hydrodynamic Bearings

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Hydrodynamic Bearings

Foreword by J.F. Booker

Hydrodynamic lubrication is a remarkably simple concept: solid surfaces separated by a thin fluid film, thus minimizing friction and wear.

By the last quarter of the 19th Century the concept had been validated experimentally by such engineers as Gustave-Adolphe Hirn (France), Beauchamp Tower (Britain), and Robert Thurston (United States).

Not long afterward, the British engineer and physicist, Osborne Reynolds, had derived the governing partial differential equation that bears his name. (The Reynolds equation is the 2-dimensional result of applying thin-film approximations to 3-dimensional Navier-Stokes and continuity equations.) By the very beginning of the 20th Century Reynolds himself and later the German physicist, Arnold Sommerfeld, had worked out many of the most obvious and simple steady-state solutions.

Why now, early in the 21st Century, do we need a new four-volume series entitled, "Hydrodynamic Lubrication"? The design methodology of the early 20th Century is still perfectly satisfactory for many bearings operating under steady conditions of low loads and speeds. However, the design analysis of many modern bearings must address unsteady response to dynamic loads, high temperatures, thin fluid films, surface finish limitations, structural compliance, and exotic inlet configurations (together with cavitating, piezoviscous, thermoviscous, highly non-Newtonian lubricant behavior), all in the effort to reduce power loss, wear, and cost.

Some of the most extreme demands have come from designs for internal combustion engines, which face continuous pressure for greater efficiency, lower weight, and higher power density.

In the second half of the 20th Century came gradual development of advanced design analysis techniques made possible by steady advances in computer resources and numerical methods.

Spatial discretization methods gradually came to include finite difference (FD), finite element (FE), and finite volume (FV) methods. Temporal integration techniques became more elaborate and more capable of dealing with such difficulties as "stiff" systems.

Lubrication problem categories progressed with increasing complexity (and lengthening acronyms) through hydrodynamic (HD), elastohydrodynamic (EHD), thermohydrodynamic (THD), and thermoelastohydrodynamic (TEHD).

While there is still a place in initial design studies and/or extended whole-engine system dynamic analyses for much faster (but much more approximate) methods, detailed design analysis now requires the powerful methods of numerical analysis developed by such specialists as the authors and previously reported in multiple research publications distributed widely over time and space.

An important set of these is now gathered together in one place in the form of an extended monograph — a distillation of some 25 years of work at the very forefront of the subject area carried out by the distinguished authors and others at the University of Poitiers in France. Though each chapter includes a bibliography appropriate for its subject matter, the book is not an extensive review of the work of others, except as it furthers the central development of the subject.

The previous two-volume series edition in French was largely inaccessible to Anglophones (such as myself). This new English edition should thus be welcomed by a much expanded audience. Division into a sequence of four smaller and more narrowly focused volumes seems a logical and convenient way to meet the needs of a diverse audience.

The first volume lays out in detail most of the necessary ingredients for modern design analyses of hydrodynamic bearings: lubricant rheology, fundamental equations of hydrodynamic lubrication and elasticity, and numerical solution techniques.

The second volume takes on the inter-related matters of surface finish, mixed lubrication, and wear.

The third volume extends modeling and solution techniques to include thermal effects.

The fourth volume addresses the specific challenges of hydrodynamic bearings in internal combustion engines, beginning with the kinematics and dynamics of the block-crankshaft-connecting rod-piston linkage, proceeding to detailed hydrodynamic lubrication analyses for each of the bearings in the chain, and culminating in a study of the application of formal experimental design to the bearing design optimization process. This approach allows the possibility of considering many more design variables and operating conditions than with conventional optimization techniques without overwhelming computing resources.

Professor Jean Frêne, also of the University of Poitiers, put it perfectly in his Foreword to the French edition:

> "The authors should be thanked and warmly congratulated for putting together in one comprehensive book their extensive knowledge on the complex topic of the mechanism of internal combustion engines and the lubrication of various highly loaded bearings operating under transient conditions."

It is an honor and a pleasure to second the motion.

J.F. BOOKER

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Fellow, American Society of Mechanical Engineers (ASME)
Fellow, Institution of Mechanical Engineers (IMechE)

June 2014

Foreword by Jean Frêne

The crankshaft–rod–piston system has significantly contributed to the development and success of internal combustion engines. However, this mechanism has also always been one of the weak points of these engines, owing firstly to bearing damage and secondly to significant energy losses from friction in the bearings.

Throughout the first half of the 20th Century, the design of these bearings has essentially been based on empirical methods largely derived from the experience and expertise of the designers of internal combustion engines, since no-one knew how to apply and solve the equations describing the operation of these bearings. In fact, in order to solve the Reynolds equation simply, using a direct method, the form of the lubricant film needs to be known, as does the geometry and the kinetics of the bearing. However, in the case of connecting rods and crankshaft bearings elastic deformations of structures play an important role, and it is the load applied to the bearing, which is generally known.

From 1950, various researchers in Europe and United States proposed semi-graphical and numerical solutions to try to describe the behavior of these bearings but it was only in the early 1980s that the first numerical approaches taking the elastic deformations of the structures into account were suggested. These approaches, based on cumbersome and time-consuming iterative methods, have furthered understanding of the importance of elastic deformations and their effects on the behavior of the bearings.

Since the 1980s, the authors of these books have applied the essence of their research efforts to the study of many problems of lubrication, and particularly those arising from the operation of the connecting rods and crankshafts of internal combustion engines. Thus, it was truly useful and necessary that the authors bring together the essence of their work in the form of these comprehensive books, which are well researched and particularly well organized.

The books begin with a comprehensive presentation of the characteristics of lubricants, which are generally non-Newtonian and whose behavior depends heavily on the temperature, on pressure and shear rate existing throughout in the bearing lubricant film.

Chapter 2 of Volume 1, importantly, is devoted to the equations of fluid film lubrication and in particular to the Reynolds equation and the equations to calculate pressures and flows in the film, and the frictional torque and the load on the bearing. The boundary conditions and the circulation conditions of the lubricant in the bearing are explained as they play an essential role in determining the characteristics of the mechanism.

Chapter 3 presents in detail the different numerical methods that can be used to obtain the solution of the Reynolds equation and associated equations. The choice of the finite elements method is favored because, in addition to its excellent performance, this method takes into account in a very efficient way the deformation of the elastic structures. This point concerning elastohydrodynamic lubrication is very well described in Chapter 4 of Volume 1.

Two important aspects are then explained in detail. The first aspect concerns mixed lubrication, whose importance is paramount when the thickness of the lubricant film is of the same order of magnitude as the height of surface roughnesses. The second aspect involves thermal effects in the lubricant film and in the materials, which form the contact. These two aspects strongly affect the operation of the mechanism.

To complete the description of the phenomena, the development of the equations and the numerical methods appropriate to their resolution, the kinematic and dynamic characteristics of the complex mobile system formed by the crankshaft, bearings and connecting rods of internal combustion engines, taking into account the elastic deformations of the structures, are presented in detail.

The last chapters of this work are devoted to the application of these theories and models associated with different bearings permitting transmission of motion and forces from the piston to the crankshaft. Cases of connecting rods–crankshaft, connecting rod–piston, and crankshaft–block bearings in internal combustion engines are successively examined in detail. Solution methods are explained and specific and detailed examples make it possible to understand how these mechanisms function.

These books are of very great interest both for researchers wishing to extend their knowledge of the behavior of connecting rod and crankshafts bearings of internal combustion engines and for engineers aiming to develop equipment that reduces engine energy losses while increasing their reliability. Furthermore, the analysis, modeling and solution methods presented here are sufficiently general to be applied to all reciprocating systems, such as, for example, piston compressors.

The authors should be thanked and warmly congratulated for putting together in one comprehensive work, their extensive knowledge on the complex topic of the mechanism of internal combustion engines and the lubrication of various highly loaded bearings operating under transient conditions.

Jean FRÊNE

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June 2014

Preface

Those who construct and use vehicles and machines have always been faced with a two-fold problem: that of allowing the various elements to move with the greatest possible ease, while still ensuring a level of solidity, which is sufficient to reduce the risk of pieces breaking or wearing out too quickly. Developments over several centuries, which were usually achieved empirically, led to the virtually universal adoption of lubricated bearings to carry rotating shafts or vehicle wheels in the middle of the 19th Century.

However, the operational principle behind these bearings was only truly understood at the end of that century when O. Reynolds presented a model in 1886, which was perfectly in agreement with the experiments carried out in France by G. A. Hirn (1847) and in England by Beauchamp Tower (1883). In Reynolds' theory, a thin lubricant film separates the surfaces of solids moving one with respect to the other. Taking into account the simplifications, which can be made due to the dimensional characteristics, the description of the thin-layer flow of the lubricating film, based on the principles of continuum mechanics, leads to the equation known as the "Reynolds equation". This equation links the film pressure to the film thickness, to the relative velocity of the bounding bodies and to the physical properties of the lubricating fluid. With the exception of a few simple cases, the Reynolds equation cannot be solved analytically. It quickly became apparent that it needs to be handled numerically. With the power rise of computation tools, the second half of the 20th Century saw the development of algorithms for solving equations numerically, which have progressively made it possible to take an increasing number of parameters and phenomena into account in calculations.

Initially, due to the simplicity of their application, finite difference methods became the preferred tool for tribologists. However, starting from the beginning of the 1970s, the finite element method was demonstrated to be highly efficient for solving elliptic partial differential equations similar to the Reynolds equation.

Consequently, much work has been undertaken over the last 40 years on the subject of solving the Reynolds equation using the method of finite elements, giving powerful tools, which have been validated by numerous theoretical studies and by comparison with experimental results. There have not been a great number of these experiments, due to the difficult nature of the environment of lubricating films. More recently, the scope of the finite volume method has been extended to lubrication.

At the end of 25 years dedicated to the study of many problems related to lubrication – in particular those related to the bearings of internal combustion engines – and the resolution of these problems using the finite element method, we considered that the time had come to take stock of the numerical tools available for the calculation of hydrodynamic bearings. An earlier version of this work was published in two volumes in French, in 2011 by Éditions Hermes-Lavoisier (Paris). The current edition in four volumes has been revised, with an added chapter on optimization techniques applied to the calculation of bearings. The content of these books is based largely on our own experience. Even if the applications developed mainly concern internal combustion engine bearings, the methods presented in them may equally be applied to other types of bearings subject to severe and/or non-stationary loadings.

The lubricant is the central element in the operation of these bearings. In Chapter 1 of Volume 1, we describe the physical properties that play an essential part in the hydrodynamic phenomenon; first among these is viscosity. When the lubricating fluid is an oil (organic, mineral or synthetic), it may be considered to be virtually incompressible. As a result, we have deliberately not mentioned the issues linked to aerodynamic lubrication, where the lubricant is air or any other gas, nor have we mentioned the effect of any possible turbulence within the lubricating film. However, variations in viscosity in function of pressure (piezoviscosity) and temperature (thermo-viscosity) are phenomena essential to the applications we discuss. The non-Newtonian behavior of lubricants at high shear rates is also an important matter, especially for the bearings of high-performance engines.

Equations of hydrodynamic lubrication are discussed in Chapter 2. First, the main assumptions related to thin viscous films which lead to the standard form of the Reynolds equation are recalled. In depressed areas, the lubricant cannot withstand the traction forces and it breaks, leading to the phenomena of separation and cavitation. To determine where the active and non-active zones in the pressure field are, we need a "modified" form of the Reynolds equation, which is also presented in this chapter. The remainder of this chapter discusses the definition of different boundary conditions for the film fringes and the parameters essential to the operation of hydrodynamic bearings (flow, load and friction).

The topic of Chapter 3 is the development of numerical methods for solving the Reynolds equation. The finite difference method and finite volume method are quite simple to apply. They are in particular well suited to uniform width bearings. The comparison of discretization expressions of the Reynolds equation demonstrates that the two methods are very similar. Although it is more complex to apply, the finite element method provides better results for solving the modified form of the Reynolds equation. Chapter 3 provides a detailed description of the developments which lead to the discretization of the equation. The finite element method proves to be superior in the treatment of variable width bearings, of bearings with complex grooves or with uneven bounding body surfaces. The algorithms for these different methods are described in detail. Their respective performances are compared for simple cases for which the data is completely defined, so that they can serve as trial cases.

In high-pressure zones, the fluid exerts levels of pressure on the bounding body surfaces that are high enough to deform them. The reciprocal "elastohydrodyamic" (EHD) dependency between pressure and the film thickness gives the Reynolds equation a strongly nonlinear character, which increases the complexity of solving it, as it must be solved conjointly with elasticity equations. Chapter 4 describes the techniques used to take the deformability of the constitutive elements of the bearing into account, at the bearing level. The case of the deformable bearing is characteristic of the EHD contact problems for conforming surfaces and may serve as a model for solving these.

Volume 2 [BON 14a] is concerned with the study of mixed lubrication. In it, we analyze the role played by surface unevenness from both a hydrodynamic point of view and from the point of view of the contact between the roughnesses on the surfaces, presenting the corresponding numerical techniques in a detailed manner. Volume 2 also handles the issue of surface wear in this context.

Volume 3 [BON 14b] contains the description of several thermo-hydrodynamic (THD) models and thermoelastohydrodynamic (TEHD) problems. It is rounded off by the description of the general algorithms of calculation software for bearings under non-stationary and severe loading.

In Volume 4 [BON 14c], the final volume of the series, we discuss, in detail, the problems specific to the calculation of engine and compressor bearings. This last volume also contains a chapter on optimization techniques for the calculation of bearings with an application for calculating a big end connecting rod bearing for an internal combustion engine.

Acknowledgements

First, our thanks go to our mentor and colleague Jean Frêne, Professor Emeritus at the University of Poitiers (France), who, in the 1980s, suggested that we work on the development and improvement of numerical models for the study of connecting rod bearings. Along with Bernard Fantino, he had, a few years earlier, initiated work on the subject. Without this initial incentive and the constant encouragement that he later offered to us, these books might never have seen the light of day.

Many colleagues and graduate students of the Laboratory of Mechanics of Solids at the University of Poitiers have worked, and some continue to work, on topics related to these books. We have benefited from their contributions and we would like to thank them also. Our structures and interfaces team colleagues located at IUT Angoulême (France), and in particular Bernard Villechaise and Mohamed Hajjam, the team coordinators, have consistently provided us with the best conditions for the realization of our research activity, for which we are grateful. Postgraduate students that we have directed, wholly or partially, occupy a place of privilege for the importance of their contributions. We include here in chronological order: Stephen Mutuli, Toan Nguyen, Joseph Absi, Dominique Guines, Thierry Garnier, Stéphane Piffeteau, Virgil Optasanu, Hervé Moreau, Lê Vuong Hoang, Loubna Jeddi, Philippe Michaud, Frank Gambin, Thi Tan Hai Tran, Marco Spuria, Ramona Dragomir-Fatu and Thomas Lavie.

Volume 2, which deals with mixed lubrication, is based in part on the thesis Ramona Dragomir-Fatu devoted to the study and modeling of mixed lubrication in engine bearings. This thesis was co-supervised by François Robbe-Valloire, professor at the Institute of Mechanics of Paris: his contribution to this work was essential and we want to show him here all our recognition. Our thanks also go to Thami Zeghloul and Arthur Francisco, lecturers at Angoulême University Institute of Technology (IUT), and Pier Gabriele Molari, Professor at the University of Bologna (Italy), for their contributions to the theses of Thi Tan Hai Tran, Thomas Lavie and Marco Spuria.

Much of the work that is the basis for this book has been conducted through close collaboration with industrial partners. Their extensive knowledge of the devices for which the codes are developed has always been of paramount importance. We would like to offer them our special thanks. This applies in particular to Renault, with whom we have worked in uninterrupted partnership over the last 20 years.

Since 1965, when he first proposed the mobility method to address the problem of hydrodynamic bearings submitted to non-stationary loads [BOO 65], and until

today [BOO 14], John (Jack) Booker, Professor Emeritus at Cornell University, has contributed immensely to the development of methods for solving lubrication problems [BOO 14]. The content of this book owes much to earlier work by Jack Booker and colleagues. Jack has done us a great honor by accepting to write a foreword for this first volume. We would like to thank him warmly.

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Nomenclature

Points, basis, repairs, links and domains

M	point inside the lubricant film
M_1	point on the wall 1 of the lubricant film
M_2	point on the wall 2 of the lubricant film
O	origin point of lubricant film repair (developed bearing)
O_c	origin point of the repair attached to the housing (bearing center)
O_a	origin point of the repair attached to the shaft
$\mathbf{x}, \mathbf{y}, \mathbf{z}$	Cartesian basis for the film (developed bearing)
$\mathbf{x}_c, \mathbf{y}_c, \mathbf{z}_c$	Cartesian basis for the housing
Ω, Ω_f	film domain
Ω_0, Ω_r	film domain, non-active zone
Ω_p	film domain, active zone
Ω_S	domain occupied by a solid
$\partial\Omega_0$	boundary of a non-active zone parallel to the circumferential direction
$\partial\Omega_1$	part of an active zone boundary where the pressure is imposed
$\partial\Omega_2$	part of an active zone boundary where the flow rate is imposed
$\partial\Omega_{am}$	up-flow boundary for a non-active zone
$\partial\Omega_{av}$	down-flow boundary for a non-active zone
$\partial\Omega_S$	boundary of a solid

Non-dimensional numbers

$\Re$, Re	$\dfrac{\rho U h}{\mu}$	Reynolds number
$\Re^*$	$\Re \dfrac{C}{R}$	modified Reynolds number

Scalars

B	m	bearing half-width
C	m	bearing radial clearance
C_m		lubricant / external gas mixture density
D	Pa; m	universal variable representing p else $r-h$
E_c		discretized contact equation
E_i		discretized Reynolds equation relative to node i
F	kg m^{-2}	Couette flow rate factor
G	kg $(Pa.s)^{-1}$	Poiseuille mass flow rate factor
H_1	m	level of wall 1 at point with x, z projected coordinates
H_2	m	level of wall 2 at point with x, z projected coordinates
I, I_2	m^2 Pa^{-1} s^{-1}	integrals on film thickness
J, J_2	m Pa^{-1} s^{-1}	integrals on film thickness
L	m	bearing width
L	m	complete film band width that delimits a non-active zone on the bearing edge
M_{xc}	N m	$\mathbf{x}_c$ component for the moment at O_c of $\Im_{pressure}$ torsor
M_{yc}	N m	$\mathbf{y}_c$ component for the moment at O_c of $\Im_{pressure}$ torsor
N		interpolation function
Q_m	kg s^{-1}	lubricant mass flow rate
Q_v	m^3 s^{-1}	lubricant volume flow rate
Q_C	m^3 s^{-1}	lubricant volume flow rate per cycle passing through the bearing extremities
Q_C^+	m^3 s^{-1}	lubricant volume flow rate per cycle outing through the bearing extremities
Q_C^-	m^3 s^{-1}	lubricant volume flow rate per cycle entering through the bearing extremities
R	m	bearing radius
T	$^\circ C$	temperature
U	m s^{-1}	shaft peripherical velocity for a bearing
U_1	m s^{-1}	velocity of wall 1 in $\mathbf{x}$ direction at point (x, H_1, z)
U_2	m s^{-1}	velocity of wall 1 in $\mathbf{x}$ direction at point (x, H_2, z)