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Book Reviews

Ball Bearing Lubrication (The Elastohydrodynamics of Elliptical Contacts)

B. J. Hamrock and D. Dowson, J. Wiley & Sons, N. Y. (1981).

REVIEWED BY T. E. TALLIAN[1]

General

Since the early 1960's, the phenomena exhibited by an organic fluid lubricant interposed between moving non-conforming contact surfaces under load (Hertzian contacts) are described in terms of Elastohydrodynamics (EHD). This theory describes lubricant films forming in the contact between elastically deforming solids, from a fluid whose rheology is modified by pressure, shearing and heating.

Prof. Duncan Dowson's name has been virtually synonymous with Elastohydrodynamics since 1959. With G. R. Higginson, he published his first trail-blazing paper on the calculation of film thickness, shape and pressure in 1959 and his papers, books, teaching and lectures have given the University of Leeds (U.K.) a dominant position in the field. Prof. Dowson and co-workers are leaders in creating clear, well reasoned and consistent theory on EHD film geometry and pressure distribution. In a joint undertaking, his former student, Dr. B. J. Hamrock, and he have published, from 1974 through 1979, formulations that come very close to being definitive in this field.

The present volume is, first and foremost, an expanded, systematized account of Hamrock and Dowson's joint work, free from the frustrating space limitations of Journal articles, hence much easier, clearer and more satisfying to read. The groundwork necessary for the understanding of EHD analysis is clearly laid out. A chapter of useful and informative application examples is also included. This main body of the book is elegant, comprehensive, a pleasure to study and fills an important need.

Publishing exigencies seem to have added three narrative chapters that address a less specialized audience than does the main body of the book. They are: "History of Ball Bearings," "Introduction to Ball Bearings," and "Lubrication Background." The wish to interest a broad audience may also account for the main title "Ball Bearing Lubrication" which is both less apt and less precise in scope than the subtitle "The Elastohydrodynamics of Elliptical Contacts." The additional material in the three introductory chapters goes into much less depth, and where it refers to current work, is less up-to-date and less completely documented than the core subject, EHD. However, the writing is of the same elegance and high standard as is the main body of the book.

The book may be faulted for two omissions: It contains no chapter on the *theory* of traction in EHD contacts and nothing on elastohydrodynamics on the scale of asperities. A six-page item on traction *measurement* mentions some traction models, and this is the only place EHD traction, as a calculable quantity, comes up. Of course, traction theory is much less advanced than film shape and pressure theory. The physics of EHD traction are quite controversial; the rheological behavior controlling traction is incompletely understood; micro-effects of boundary layers and of asperities are in question; and the role of heating is both major and uncertain. These problems, however, could be presented, and the known or conjectured facts separated from the unknown, much to the disoriented engineering practitioner's advantage. Likewise, the micro-EHD of asperities, while in the development stage, is covered by a sizeable literature and would seem to deserve treatment in the book.

Chapter Review

Leaving off carping over what the book does not contain, a brief overview will now be given of each chapter.

History of Ball Bearings reflects D. Dowson's years of study of the history of tribological devices (and his monumental volume covering this field). To this reviewer, the most intriguing question in the history of rolling contact bearings is why they did *not* develop as practical machine elements much earlier than the late 19th century. The answer, we now know (largely through the efforts of the elastohydrodynamicists) is that a rolling bearing, to survive fatigue, must be of hard material; hard material rolling elements, to survive plastic indentation, must be accurate and, to survive surface distress, need EHD lubrication and, therefore, be smooth. The manufacturing methods to achieve the needed smooth, hard rolling elements came along only through modern alloy steels, heat treating and grinding technology.

Introduction to Ball Bearings is an encyclopedia of general facts about this rolling bearing type. Interspersed with general information are some geometric and kinematic equations which are needed as foundation for subsequently given theory. Sections on materials and manufacturing draw on Hamrock's experience at NASA and, while correct, may grant the specialized NASA aerospace needs and concepts more generality than is justified by bearing usage in industry.

Ball Bearing Mechanics contains the analytic descriptions of contact deformations, stresses, and load distributions. Much of this is classical and well published. However, the presentation excels in clarity and is as simple as this somewhat inelegant subject permits. The "simplified" (read: curve-fitted) expressions Hamrock et al obtained for the ellipticity parameter, the complete elliptic integrals and for Lundberg's parameter $\bar{t}_a$ are a relief to the user who abhors transcendental functions, particularly the computer analyst. It is well to warn here, where such curve fits are given for the first

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[1] SKF Technology Services, SKF Industries, Inc., King of Prussia, Pa. 19406.

time, that these equations have no physical meaning, and that anomalies can result from their uncritical use, particularly at the extremes of the their range. The authors do give error estimates and give, in general, appropriate cautions about their approximations. One point where explicit caution is not given concerns the load distribution integral for radially loaded bearings (Sjovall's integral) discussed under equations 3.43–3.48. The integral formulation assumes infinitely many rolling elements. With deep groove ball bearings having at times as few as three elements in contact, the approximation can be quite crude. Fortunately, full EHD films are rather load insensitive and for EHD film calculation purposes the approximation is acceptable. Once accepted, its closed form is, again, a helpful contribution.

This chapter contains a section on fatigue life prediction. In the space devoted to it, no more than a brief summary of the classical Lundberg-Palmgren life model can be given. This model is then updated by defining "life factors," i.e. multipliers to correct for lubrication condition, material analysis and processing. Factors are, undeniably, the current conventional approach. This reviewer may be excused if he wishes for mention of the more fundamental life model revisions published since 1971 by Chiu, Tallian, McCool, and van Amerongen.[2]

Lubrication Background. This chapter begins with an (over-brief) review of the surface topography of contacting solids. Of quantitative measures, only height averages are mentioned. For the limited purpose of comparing EHD film thickness (calculated for ideal surfaces) to average roughness, this treatment suffices. If is not sufficient for a discussion of the "mixed" regimes or of surface failure in which the *sharpness* of asperities plays a major role. Most current rolling contact devices operate in the "mixed" (more aptly *partial*-EHD) regime, although continued progress in surface finishing is pushing the Λ ratio higher and higher.

The history of EHD theory, in which the authors are outstanding participants, is given objectively and fully. The history of experimentation concentrates on work done in the U.K.

Basic Lubrication Equations. The basic equations describing the forces and motions in thin lubricant films, formed from organic fluids subject to pressure and temperature ranges, between elastic solids in contact are given, along with the energy balance equation. This reviewer is not an analytic hydrodynamicist and thus cannot comment on the choice of analytic forms except to praise the clarity and conciseness of the presentation. After decades of success in using these equations, the authors surely know best what serves for the analyses they are undertaking.

With "Lubrication of Rigid Ellipsoidal Solids" the book enters the main body of its presentation. This, and the following chapters: "Elastohydrodynamic Lubrication Theory," "Theoretical Results for Elliptical Contacts," "Theoretical Results for Starved Elliptical Contacts," "Elastohydrodynamics of Elliptical Contacts for Materials of Low Elastic Modulus" and, finally, "Film Thickness for Different Regimes of Fluid Film Lubrication" comprise the complete theoretical edifice erected by the authors for predicting film shape, thickness and pressure in *elliptical* contacts. (The two-dimensional limiting case is treated briefly, by reference to earlier work.)

The elegant coherence of the authors' theory is best seen by reviewing these "core" chapters together.

In the strict confines of the smooth-surface isothermal fluid film theory of elliptical contacts, two dependent variables, film thickness and pressure, are calculated at each point in and around the contact, as a function of a number of geometric, elastic and rheological parameters, and of relative velocities and total load in the contact. Prof. Dowson, in all his papers, expresses these quantities in terms of a small, physically intuitive, set of dimensionless variables. The present book follows that practice. The principal dimensionless variables are, for lubricant-flooded contacts: film thickness, speed, load, material parameter and ellipticity. For lubricant-starved contacts, an inlet meniscus location parameter is added. For any given combination of speed, load, material and ellipticity parameters, the theory predicts point-wise film thickness (including the overall minimum) and pressure (including the Hertzian maximum).

Film conditions fall into four regimes, determined by the importance of elastic deflections and viscosity changes under pressure. The rigid, isoviscous regime exists under very light load. As load increases, elastic deflections only (for rubber-like contact material), viscosity changes only (for very closely conforming hard material contacts), or both become important to the results. When both variations are important, full EHD lubrication exists.

To apply the theory, it is first necessary to place the problem in the proper regime of lubrication. The book provides maps for doing this. The concise mapping is possible through a further reduction in the number of dimensionless parameters to only *three*: A viscosity parameter, an elasticity parameter and ellipticity. (Starved lubrication is not accounted for in the maps). The new viscosity and elasticity parameters are neither independent nor particularly intuitive, but they have a unique conciseness, so that three simple regime-maps valid for different ellipticities, with the viscosity and velocity parameters as coordinates yield a good overview of all regimes. For low values of both the viscosity and elasticity parameter, the regime is isoviscous, rigid. If the elasticity parameter increases, the isoviscous elastic regime is reached. High viscosity-parameter values lead to the piezoviscous rigid regime and high values of both (in a band cutting diagonally across the maps) yield full EHD conditions.

For each regime (other than the rare piezoviscous rigid one), the authors provide typical contour maps of film thickness and pressure over the contact. More important for the user, are simple, closed-form, curve-fitted equations for all four regimes, yielding minimum film thickness. For the EHD regime, formulas, are also given for plateau film thickness (the uniform film thickness prevailing over most of the contact area) and a starvation correction is provided.

These formulas are the ultimate result of a decade of the authors' dedicated efforts, and for elegance and comprehensiveness, they leave little if anything to be desired.

The authors carefully state a number of the limitations of their theory. The most important ones (stated and unstated) are as follows.

1. The theory is *isothermal.* The contact is assumed to be at uniform temperature and controlled by the two (equal temperature) contacting solids. Much experimental evidence shows that this is a tenable simplification for *pure* rolling. As sliding intervenes (and most often it does), the enormous sensitivity of viscosity in organic fluids, to temperature, begins to cause errors.

2. The film thickness equations are curve-fitted within each lubrication regime. Regime boundaries are set so that the film thickness curves approaching the boundary on a regime-map from both sides, intersect at the boundary. However, their *slopes* differ dramatically. Since regime boundaries are just mathematical conveniences, they cannot denote abrupt changes in the physics of the film. Thus, near the boundaries, all curve-fitted equations must be viewed with reserve.

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[2] For the latest summary of this material see Tallian, T. E., "A Unified Model for Rolling Contact Life Prediction," ASME Paper No. 81-Lub-42, 1981 ASME/ASLE Joint Lubrication Conference.

Forbidden bands along the boundaries ought to be drawn, within which the accuracy of the equations is poor.

3. Starved EHD contacts are common, probably more so than flooded ones. Te starvation parameter needed to apply a correction is generally unknown. Therefore, most practical calculated film thicknesses are flooded values, and these are *overstated.* Dowson, and, elsewhere, Chiu[3] have attempted. These have not been verified and their weakness places shifting ground under the edifice of starved film theory.

4. The theory works with ideally smooth surfaces. When roughness is not negligibly low in height compared to minimum film thickness, it creates significant modifications in film profile, minimum film thickness and pressure distribution, which the present theory does not capture.

Two chapters remain to be reviewed: "Experimental Investigations" and "Applications."

Starting with the latter, it contains straight-forward application of the theory to several simple contacts and to three types of practical machine elements: rolling bearings, power transmissions (gears and traction drives) and railway wheels on rails. This chapter is helpful in putting the theory in perspective, by showing what values of the variables are likely to occur. Beyond that, it is reassuring to follow the clearly set out calculations, showing the reader whether he has mastered the use of the formulas. (The virtually flawless proof-reading of the book has slipped in the cylindrical roller bearing section. Such a bearing contains *rollers*, not *balls*, as consistently printed.)

The chapter "Experimental Investigations" reviews, in a few pages, the established arsenal of disc machines and ball machines for EHD film generation. Electrical, X-ray and optical film profile techniques are cited. For film profile observation, the optical interferometry techniques have dominated for years and yield data as precise as the theory. Pressure measurement techniques by resistive evaporated transducers are much less refined, but have served to confirm general features. The short shrift given electrical techniques (particularly contact conduction) in the book is understandable from the theorist's perspective, but ignores the fact that these direct techniques were the basis for the concept of the film thickness/roughness ratio Λ as a prime factor in controlling contact surface endurance and are still indispensable for the practical evaluation of working machine elements.

Comparisons between measured and calculated film thickness are given in detail and show gratifying overall agreement. Nonetheless, individual measurement results can be off the prediction by factors of two and more – and we do not generally know which to trust. Considering that the change from full asperity contact at $\Lambda = 0.4$ to full film at $\Lambda = 3$ covers such a narrow range, and that within it, most of the EHD effect on endurance is compressed between $\Lambda = 1$ and $\Lambda = 2.5$, accuracy is at a premium. Direct measurement of surface separation in working machine elements is still the best assurance of performance.

Temperature and traction are two features of an EHD film which the theory in this book does not reach. The fascinating experimental results of infrared contact pyrometry by Winer's group are concisely presented. A valiant attempt is made to present the topic of traction experiments in EHD films, in a section of six pages. This topic, the next frontier in EHD studies, could itself fill a book – which, unfortunately, is not ready to be written.

Closure

EHD film thickness theory is a major success story of engineering physics. The theory is, by now, clear, compact, accurate and reliable. When a theory is this successful, it owes, second to the brilliance of its creators, much to the "tractability" of the natural phenomena it covers. EHD film thickness is "tractable" because it is determined in the contact *inlet*, where conditions are not too severe. It is largely load independent and, thus, robust against inevitable load fluctuations. It becomes highly starvation dependent only under miserly oil supply. EHD films are real and practically important because there happen to be practical organic fluids with viscosity properties to yield useful film thickness. The films are useful because their thickness is comparable to a level of surface roughness which, after thousands of years of craftsmanship, is now achievable at affordable cost.

Unfortunately for imminent theoretical success, it does not appear that temperature or traction phenomena in contacts are equally "tractable," in the light of current knowledge. One can only hope that future insights will reveal fruitful new approaches to these important aspects of EHD.

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[3] Chiu, Y. P., "A Theory of Hydrodynamic Friction Forces in Starved Point Contact Considering Cavitation," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 96, Apr. 1974, pp. 237–246.