1

Introduction

Elastohydrodynamic lubrication[a] (ehl) is a comparatively recent branch of tribilogy which only became properly established in the early nineteen sixties. It is the mechanism that describes the separation by a **lubricant** film between two elastic machine elements loaded against each other, and in relative motion. In this context, **machine elements** means two contiguous bodies whose surface geometries would put them in point or line, light touching contact. Furthermore, they are not necessarily purpose-built to be supported by a lubricant film, as are journal or thrust bearings. Examples of machine elements are: a pair of spur gear involute teeth, ("line" contact) or a ball bearing ball and its raceway groove ("point" contact).

Because pairs of machine elements are not specifically designed to have a lubricant film between them, the concept of ehl appeared rather by accident than by design. Suspicion of its existence was prompted by tribologists noting the frequent almost complete absence of wear between pairs of lubricated gear teeth. Two different diagnoses were put forward at the time to explain this observation. As is often the case, the explanations depended considerably upon the previous scientific background of the parties. The views in contention were that the osculating surfaces were protected by boundary films of molecular thickness adhering to them chemically, or that the films were separated by a relatively thick hydrodynamic lubricant film. The followers of the first,

[a]For space considerations, the abbreviations ehl (for elastohydrodynamic lubrication) and ehd (for elastohydrodynamic) will be used. Their choice depends on which is the most suitable in the text.

more traditional school, defended their argument by pointing out, quite rightly, that such a lubricant film could not exist between the surfaces, because current classical hydrodynamic-rigid surface theory predicted that it would be far thinner than the combined surface roughness. What most of them had not realized was that, because of their geometry, the element surfaces cannot retain their undeformed shapes under the normal load in the region of the lubricant films. Furthermore, the lubricant viscosity must increase with the high pressures encountered. At that time, elastostatic concentrated contact theory was well estabilshed, following the pioneering work of Hertz, [1] and so also was a knowledge of lubricant properties, [2]. But it needed someone to be aware that the various states of materials constituting the system, could act concurrently to form a coherent **elastohydrodynamic** film. As late as 1957, there was evidence that the old explanation of non-conforming surface lubrication were still prevalent. See for example the review by Hall in Ref. [3], where hydrodynamic lubrication of gears is mentioned, and in a 1953 paper by Fogg and Webber [4] where there is boundary lubrication of rolling element bearings. All this was despite the appearance of the English translation of a quite brilliant theoretical paper attributed to Grubin in 1949, [5]. In it, he presented a convincing theory of the lubrication of non-conforming machine elements. It embraced all the known characteristics of ehl theory, that is, it included surface elastic distortion, as well as lubricant hydrodynamics and properties.

Another theoretical breakthrough occurred in 1959 when Dowson and Higginson [6] produced the first comprehensive computer-based numerical solution to the ehl problem.

By 1963, the empirical part of ehl became established, following pioneering work by Crook [7] who carried out elegant experiments with disc machines, as well as explaining their frictional behaviour with a theoretical analysis.

Finally, in 1962, using optical interferometry, a tentative proof of the ehl film's existence in a point contact was made Archard and Kirk [8] and in 1963, more clearly, by Gohar and Cameron [9] who used the same method to produce the first definitive pictures of the ehl film contours.

Since then, ehl has become well estabished with a plethora of publications on the subject. Their main thrust has been to refine the initial forecast of the ehd (elastohydrodynamic) film shape, and to study the effect of **real**, as distinct from smooth surfaces, on the ehl film mechanism (partial and micro ehl).

Some discoveries from ehl research that have filtered down to industry are: more efficient seals, improved designs of rolling element bearings and gears, improved feeding of lubricant to the ehd contact, smoother surfaces, tougher materials, more efficient filtration systems and the development of special lubricants. The continously variable traction drive, which depends on an ehd film, now has widespread use in the automotive industry. The ehd theory of approaching surfaces (squeeze films) has led to a better understanding of the mechanism of impact damage to machine elements, as well as its contribution to the damping of rotating machinery supported by rolling element bearings. The more recent comprehensive theories and experiments on the ehl of rough surfaces (micro ehl) has taken the subject out of the laboratory and into the real world of industry.

As ehl is multidisciplinary, the arrangement of the book takes the following form:

— Chapter 2 familiarizes the reader with the properties of the materials that produce the film.
— Chapter 3 dicusses the way the film surfaces distort under elastotatic normal contact loads, whilst in
— In Chapter 4, the equations needed for ehl theory are derived or presented.
— In Chapter 5, some of the equations from Chapter 4 are employed in the classical theory of hydrodynamic lubrication of rigid surfaces and in ehl non-numerical solutions. At this stage, there is introduced a simplified theory for surfaces having regular small amplitude wavy features.
— Then in Chapter 6, all the theories for smooth surfaces of the previous chapters are combined to give a comprehensive review of the basic numerical methods which are used to obtain the ehd film thickness and shape.
— In Chapter 7, the results of numerical solutions of the governing equations, mainly based on Chapter 6, are given, together with design formulae for film thickness.
— In Chapter 8 the frictional behaviour of ehd contacts is discussed. This includes non-linear behaviour of the lubricant (non-Newtonian) in determining the frictional force as well as fundamental differences between Newtonian and non-Newtonian micro ehl for rough surfaces.
— Chapter 9 is devoted to finding the stress distribution within the machine element materials as a consequence of the normal load and friction. These stress levels and their frequencies help to establish the life expectancy of the mechnism of which the machine elements are a part. The close similarity between contact elastostatics and ehl makes the results of Chapter 3

particularly important here. Throughout Chapters 2 to 9, published experimental results are given to support the various theoretical predictions.

— Chapter 10 is solely concerned with the main techniques used to obtain the various experimental results shown previously.
— In the added Chapter 11, recent numerical methods (Multigrid, Multilevel Integration and the Effective Influence Newton Method (EIN), together with some examples based on these methods, are discussed and compared, where possible, with experiments.
— In Chapter 12, some interesting topics directly and indirectly related to ehl, are summarized, with particular stress given to engineering appications by means of case studies.
— Finally in Chapter 13, the book is concluded by a short review of future trends in ehl research and development.

Space limitations have meant that the book concentrates wholly on the ehl of "hard" non-conforming surfaces. The lubrication of soft surfaces, like rubber in contact with a rigid roller, has only passing indirect mention. Likewise, conforming surface ehl, such as elastically distorted journal and thrust bearings or the hip joint spherical pair, are not covered. Fortunately, there are several excellent publications which discuss these topics. See, for example, Refs. [10] and [11].

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