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Document type

Journal article | Accepted version

(i. e. final author-created version that incorporates referee comments and is the version accepted for publication; also known as: Author's Accepted Manuscript (AAM), Final Draft, Postprint)

This version is available at

<https://doi.org/10.14279/depositonce-15075>

Citation details

This is the peer reviewed version of the following article: Popova, E. and Popov, V. L. (2019), Science Thriller: The dramatic destiny of Alexander Mohrenstein-Ertel and the history of elastohydrodynamics. Proc. Appl. Math. Mech., 19: e201900097, which has been published in final form at <https://doi.org/10.1002/pamm.201900097>.

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Science Thriller: The dramatic destiny of Alexander Mohrenstein-Ertel and the history of elastohydrodynamics

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Presentation is devoted to the life and work of Alexander Mikhailovich Ertel, the founder of elastohydrodynamics. He was the first to recognize the importance of elastic deformation of partners in lubricated contacts as well as pressure dependence of lubricants. In his dissertation written in Moscow during the Second World War, he suggested a solution of this complicated problem, which was not changed essentially by the later research. However, due to his escape to West Germany and change of identity, the real authorship remained unknown over many years. In West Germany, Mohrenstein-Ertel continued his work by practical implementation of the ideas suggested in his dissertation. He could reveal his identity after the Stalin's death, and could witness the recognition of his contribution through the German Tribological Society and international tribological community.

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1 Historical roots of the theory of elastohydrodynamic lubrication

This short note is devoted to the history of elastohydrodynamic lubrication around the 1940th. But if we would try to find a true starting historical point for elastohydrodynamic lubrication, then we should go even further back, to the 1880th and we would find two of them: the one connected with "elasto" and the second one with "hydro": The theory of elastic contact and the theory of hydrodynamic lubrication. Interestingly both developments happened almost simultaneously. 1882 Heinrich Hertz (Fig. 1a) [1] solved the problem of elastic contact of parabolic bodies. This solution is probably the most important and famous publication in contact mechanics. Only 3 years later, in 1885, Joseph Boussinesq (Fig. 1b) [2] published his book which contained systematic approach to contact mechanics based on the fundamental solution of equilibrium equations of an elastic continuum. In particular, he found solution for flat-ended cylindrical punch and many others.

Fig. 1: The pioneers of contact mechanics and hydrodynamic lubrication: (a) Heinrich Hertz, (b) Joseph Valentin Boussinesq, (c) Nikolay Pavlovich Petrov, (d) Osborne Reynolds.

Almost at the same time, only one year later than Hertz, in 1883, Russian military Engineer, Nikolay Petrov (Fig. 1c) [3], published a paper about hydrodynamic lubrication. Three years later, Reynolds (Fig. 1d) [4] formulated the same theory, a little bit more general and extremely good didactically.

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Elastohydrodynamics brings together contact mechanics and lubrication. This bringing together was more complicated and happened much later, in 1940th, during the Second World War.

2 Foundations of hydrodynamic lubrication

Let us start with the basic equations of hydrodynamic lubrication, following the paper [4] by Reynolds. Reynolds considers two flat surfaces separated by a fluid. The two main possibilities of motion of plane bodies with a fluid between them are (a) simple shear flow (Fig. 2a) with linear velocity profile $v = v_0(z-h)/h$ and (b) the squeezing flow (Fig. 2b) with parabolic profile $v = p' \cdot z(z-h)/(2\eta)$. Here η is dynamic viscosity, $p' = \partial p / \partial x$ is pressure gradient, v_0 is the relative sliding velocity, z is the normal coordinate measured from the lower body, x the tangential coordinate, and h the distance between the plates. In the general case of shear and approach (Fig. 2c), these both solutions are superimposed:

$$v = \frac{v_0}{h}(z-h) + \frac{1}{\eta} \frac{\partial p}{\partial x} \frac{z(z-h)}{2}. \quad (1)$$

Fig. 2: (a) shear flow and (b) squeezing flow, (c) superposition of shear and squeezing. Figs from original paper by Reynolds, [4].

Finally, Reynolds considers the case of non-planar bodies and, using the condition of incompressibility, derives his famous Reynolds equation:

$$\frac{d}{dx} \left(h^3 \frac{dp}{dx} \right) = -6\eta v_0 \frac{dh}{dx}, \quad (2)$$

where now the gap h generally depends on the coordinate x . The one-dimensional Reynolds Equation (2) can be trivially integrated once:

$$\frac{dp}{dx} = 6\eta v_0 \frac{h(x) - h_0}{h(x)^3}, \quad (3)$$

where the integration constant is denoted as h_0 .

One further important point, which was known already to the founders of lubrication theory is the cavitation. Lubricating film fulfils its function only if it is present, that is, it should not be pressed away, even under load. This resistance to the normal load is called load-bearing capacity. The problem is, however, that symmetric or macroscopically plane surfaces have no load bearing capacity. The zero load capacity is due to the fact that the pressure in some parts of the system is positive and in other negative, so that the net normal force at tangential movement is exactly zero. However, the lubrication theoreticians did know that liquids cannot withstand negative pressures. Due to cavitation, the pressure drops practically to zero. This produces an asymmetry in the pressure distribution and courses the final load bearing capacity. One can say: No cavitation – no lubrication! However, this makes the problem of lubrication more complicated as we then leave the domain of classic hydrodynamic theory with its continuity condition. In particular, the Reynolds equation is only valid in the region without cavitation.

3 Lubrication of elastic bodies

Until now we considered rigid bodies. But what if the bodies are elastic? The first scientist who considered elastic bodies, was a young Russian scientist, Alexander Ertel, in 1939, [5]. At that time, he was student at the physical faculty of the Moscow state university. The simplest realization of elastic bearing would be a flexible plate, which is supported by springs creating some given pressure distribution (Fig. 3a). If due to sliding the gap changes, then the pressure still practically does not change and remains determined by the initially created pre-stress distribution. We now can read the Reynolds' equation in the reversed direction: The pressure is known and we look what shape will have the gap. If

this stress distribution is designed in such a way that it increases linearly to the middle of the contact and then decreases linearly (Fig. 3), then during sliding, one constant gap width will be established automatically in one region and another value of the gap in the second region.

Fig. 3: (a) Elastic bearing (schematically reproduced from [5]), (b) pressure peaks at the trailing edge of elastohydrodynamically lubricated contact (from original work [6]).

During the war, Ertel had luck to work at the institute of machine science of the Academy of Sciences, in the department of friction and wear in machines, headed by the famous Russian tribologists Khrushchov. In this department, Ertel continued his work on elastohydrodynamics and produced the famous work, which lead the basics of what we now call elastohydrodynamics. He published the results of his work in 1944 and 1945. The main work was “The Calculation of Hydrodynamic Lubrication of Moving Curved Surfaces under High Loading”, [6]. The contents of this work were reported in five seminars in his department. It was accepted with very great enthusiasm.

Ertel recognized and brought together three points.

(I) First, if the parts are loaded so high that they are elastically deformed, then the pressures in contact also will be very high as for example in gears, and then it is important to consider the dependency of the viscosity on pressure. Ertel considered the simple Barus law $\eta \propto \exp(\alpha p)$. α is here the pressure index, very small, $\alpha \sim 10^6$. But if the pressure is very high, then the viscosity becomes very high too.

(II) After bringing the pressure dependence on the other side of the Reynolds equation, one can integrate the left side of the equation and introduce reduced pressure $\Pi = (1 - e^{-\alpha p}) / \alpha$, which has the property that it vanishes together with the true pressure. With this new pressure definition, the Reynolds equation takes again exactly the same form as it was with pressure independent viscosity:

$$\frac{d\Pi}{dx} = 6\eta_0 v \frac{h(x) - h_0}{h(x)^3}. \quad (4)$$

However, there is some qualitative difference from the case of true pressure. If the reduced pressure approaches some definite value, the true pressure becomes infinite. If the pressure in the contact is very high, then the reduced pressure does not depend on the pressure anymore and is constant. This means that the gap is constant. In addition, this means that the pressure is essentially that which does exist in the not lubricated contact, the Hertz pressure.

(III) The boundary effects were the trickiest part of the whole problem. The gap is constant but how this constant is determined? The answer is: it is determined exactly by the transition from the inside the contact to the outside of the contact, more exactly at the leading edge of the contact. As the pressure outside is almost zero and inside the Hertzian pressure, then the deformation of the body outside the contact should be the same as predicted by the theory of Hertz. This gap can be inserted into the modified Reynolds equation and then integrated from far outside to the first point inside. Here appears some complicated integral of a complicated function. Ertel had luck, as numerical evaluation of this integral shows that in the double logarithmic coordinates this is almost exactly a straight line, so that the integral itself is a power function of the gap. This finally produces an equation for the gap which occurs to be a power function of all parameters:

$$h_0 = 1.90\alpha^{0.727} (\eta_0 v)^{0.727} R^{0.364} E^{*0.091} P^{-0.091}, \quad (5)$$

where P is the normal load per unit length.

The final step made by Ertel was consideration of the trailing edge of the contact. Other than in the case of true Hertzian contact the pressure drops occurs there suddenly. And if an elastic body had a flat support and suddenly loses it, this acts as a sharp edge, e.g. in a contact with a flat punch. It is well known that the pressure distribution produced by a flat punch has a singularity at the edge. This is exactly what Ertel has found in his calculation (Fig. 3b). The first one who could calculate this numerically was Petrusevich, using the method, which we now would call the Boundary Element Method [7].

4 Publication by Grubin and late recognition

After the end of the Second World War A.M. Ertel came to Berlin-Pankow under contract from the Ministry of Heavy Machinery and took over leadership of the Laboratory of Friction and Lubrication. In 1946, seriously ill with tuberculosis, he fled to West Germany and disappeared. He let it look like an accident and changed his identity (as Alexander von Mohrenstein). Therefore, he was considered in the Soviet Union as dead.

1949, the work by Ertel was published by his former head of laboratory, Grubin [8]. This publication became quickly very famous. However, this publication should not be considered as a case of plagiarism. At that time, Grubin just could not cite the name of Ertel, due to political reasons. However, he gave credit to the works "of laboratory" headed by him.

In May 1959, Mohrenstein-Ertel was involved in a severe car accident on the way home from Ebern where he worked in the Firma "Kugelfischer" to Freiburg where he lived at that time. This accident made the continuation of his scientific work no longer possible, although he lived another 40 years.

The details of the true history of appearance of the "Grubin's" theory were first disclosed by Cameron, [9], who also cared for publication of the original work of Ertel in German translation, [10]. In September 1984, for his pioneering works on elastohydrodynamic lubrication, Alexander Mohrenstein-Ertel was awarded the Georg-Vogelpohl Medal by the German Society of Tribology [11].

Alexander Mikhailovich Mohrenstein-Ertel died on October 27, 2001.

A detailed historical recherche related to the history of elastohydrodynamic lubrication can be found in [12].

Acknowledgements The authors acknowledge very exciting and informative conversations with Michael Mohrenstein-Ertel, the son of Alexander Mohrenstein-Ertel, who provided many documents from the family archive Mohrenstein. Further information stems from conversations with Marina Ertel, the granddaughter of Alexander Mohrenstein-Ertel. We appreciate discussions and help by I.A. Buyanovsky.

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