



# IssyOsborne: transIent Squeeze and Starvation in elastohYdrodynamic - OScillating Bodies sOlving Reynolds oNe-dimensional Equation

Malik Yahiaoui, Denis Mazuyer, Juliette Cayer-Barrio

## ► To cite this version:

Malik Yahiaoui, Denis Mazuyer, Juliette Cayer-Barrio. IssyOsborne: transIent Squeeze and Starvation in elastohYdrodynamic - OScillating Bodies sOlving Reynolds oNe-dimensional Equation. SoftwareX, 2023, 23, pp.101422. 10.1016/j.softx.2023.101422 . hal-04121630

**HAL Id: hal-04121630**

**<https://hal.science/hal-04121630>**

Submitted on 8 Jun 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



## Original software publication

## IssyOsborne: transient Squeeze and Starvation in elastohydrodynamic – Oscillating Bodies solving Reynolds one-dimensional Equation

Malik Yahiaoui<sup>a,\*</sup>, Denis Mazuyer<sup>b</sup>, Juliette Cayer-Barrioz<sup>b</sup><sup>a</sup> Laboratoire Génie de Production, École Nationale d'Ingénieurs de Tarbes, France<sup>b</sup> Laboratoire de Tribologie et Dynamique des Systèmes, CNRS UMR5513, Ecole Centrale de Lyon, France

## ARTICLE INFO

## Article history:

Received 23 March 2023

Received in revised form 17 May 2023

Accepted 21 May 2023

## Keywords:

Tribology

Elastohydrodynamic lubrication

Reynolds equation resolution

Reciprocating sliding

Transient flow

## ABSTRACT

In the field of tribology, many applications operate in the elastohydrodynamic lubrication (EHL) regime e.g., automotive engines, gears and rolling element bearings. In the EHL regime hydrodynamic performances are significantly enhanced by the contact bodies elastic deformations and the lubricant piezoviscosity. IssyOsborne is a procedure package for Igor Pro designed to be used by researchers in the field of tribology and fluid mechanics. It allows to easily calculate the film thickness distribution in lubricated sliding contact in EHL regime under time-varying conditions. This calculation is performed given the contact conditions, the fluid properties and the contact bodies properties. IssyOsborne can be used for deceleration, acceleration and reciprocating motions. In the algorithm, a full-analytical resolution of the Reynolds equation was derived. Validated experimentally, the analytical film thickness equations perfectly modeled the mechanisms behind film formation, such as squeeze due to the transient evolution of the film thickness over time, asymmetry and hysteresis in film distribution.

© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

## Code metadata

Current code version

v1.0

Permanent link to code/repository used for this code version

<https://github.com/ElsevierSoftwareX/SOFTX-D-23-00182>

Code Ocean compute capsule

none

Legal Code License

GPLv3 or later

Code versioning system used

git

Software code languages, tools, and services used

Igor Pro 8

Compilation requirements, operating environments &amp; dependencies

OS X, Microsoft Windows

If available Link to developer documentation/manual

<https://github.com/mlkyh/IssyOsborne.git/README>

Support email for questions

[malik.yahiaoui@enit.fr](mailto:malik.yahiaoui@enit.fr)

## 1. Motivation and significance

Many mechanisms work in lubricated conditions where the velocity, the contact pressure, the surface roughness and the kinematic conditions govern the fluid film thickness separating the solid bodies. Depending on these parameters, the lubricated contact undergoes various lubrication regimes. Amongst these, the elastohydrodynamic lubrication (EHL) regime corresponds to a full-film regime in which elastic deformations of the solids and viscosity pressure-dependence play a major role. In the EHL regime, the classic hydrodynamic lubrication theory, based on the Reynolds equation, was found to be insufficient. Early efforts to

include these effects began in the 1930s, but significant breakthroughs were not seen until the middle of the last century [1]. With the advancement of computer and information technologies, EHL solution methods and experimental techniques have significantly improved, leading to a shift in research focus to thin-film EHL and mixed EHL, with real engineering roughness and transient kinematic being considered.

The presence of surface roughness, heterogeneity of the confined lubricant, boundary film on the surfaces, varying tribological conditions (load or velocity), or transient changes in flooding regimes can lead to a disruption in the lubricant film-forming capabilities. Experimentally, the film thickness distribution can be measured coupling transparent solid, interferometric technique and time and space-resolved cameras and the film forming mechanisms can be further investigated: see for instance, [2,3]

\* Corresponding author.

E-mail address: [malik.yahiaoui@enit.fr](mailto:malik.yahiaoui@enit.fr) (Malik Yahiaoui).

for rough surfaces under steady-state conditions, [4] for complex fluids under reciprocating motions and [5–8] for simple fluids under transient motions. These behaviors directly result from the coupling of the pressure and film thickness distributions as derived by Reynolds [9].

Various numerical methods can be found in the literature to solve the Reynolds equation, mainly based on multigrid and multilevel multi-integration methods [10–12], Newton–Raphson and optimization methods including finite element method (FEM) models (among others [13–16]). Applied to simple fluids under time-varying conditions, these numerical simulations provided estimate of the film thickness distribution and were able to identify features such as the hysteretic nature of the film thickness evolution [17–23].

Otherwise, we provide an open access algorithm, IssyOsborne, based on a fully analytical solution of Reynolds equation in 1D, numerically implemented, that describes and calculates the film thickness under acceleration, deceleration and reciprocating motions for given conditions. This algorithm was experimentally validated in [24].

## 2. Modeling of transient EHL line contact

The Reynolds equation that models the coupling between the film thickness  $h(x, t)$  and the pressure  $p(x, t)$  within a lubricated contact between two solids can be written in one dimension as Eq. (1).

$$\frac{\partial}{\partial x} \left[ \frac{h^3}{\eta} \frac{\partial p}{\partial x} \right] = 6u(t) \frac{\partial h}{\partial x} + 12 \frac{\partial h}{\partial t} \quad (1)$$

where  $u(t) = u_1(t) + u_2(t)$  is the entrainment velocity,  $\eta$  is the viscosity of the fluid under pressure following the Barus law (taken for mathematical convenience),  $x$  is the position in the contact and  $t$  is the time.

Classical assumptions are made on the lubricated contact: Newtonian, piezoviscous, incompressible and isothermal conditions, zero external force and no slip at the solid/lubricant interface. Ertel's hypotheses and Crook's approximation must be assumed to obtain an analytical solution to the Reynolds equation (as detailed in [7]). On the one hand, according to Ertel [25,26], the flow of a piezoviscous lubricant of viscosity  $\eta$ , under the pressure field  $p(x, t)$  can be considered as equivalent to the flow of an iso-viscous lubricant with a viscosity  $\eta_0$  under the reduced pressure field  $q(x, t)$ . On the other hand, the Crook's approximation [27] provides a simplified inlet geometry of the gap between the two surfaces. Both approaches are analytical. Subsequently, the equation was solved by successive integration in the contact inlet and the Hertzian contact, taking fluid entrainment and squeeze contributions into account. This analytical solution was experimentally validated in the case of a linear deceleration over a deceleration time, and it was found that it was essential to include the squeeze contribution and transport effects of the lubricant flow to accurately predict the evolution of the film thickness with time and contact position. It was further used to describe the evolution of the film thickness distribution during forced oscillation [24].

The Reynolds equation was solved analytically in three zones: the convergent, the high-pressure zone and the constriction zone. Accounting for the constriction zone was essential as the outlet zone then became the inlet zone at each change in direction. To model the forced oscillations, a triangular velocity profile was set (as opposed to sinusoidal as in reciprocating sliding experiments) as a first approximation, after an initial step at constant velocity. It is then important to note that, after a deceleration and when the velocity reaches zero, the following acceleration is performed with a change of direction.

In the central contact zone, the pressure field was assumed constant. The Reynolds equation was simplified as follows:

$$u(t) \frac{\partial h}{\partial x} + 2 \frac{\partial h}{\partial t} = 0 \quad (2)$$

This equation was then solved using the method of characteristics. Consequently, three main film thickness equations were calculated during the first deceleration, the following accelerations and decelerations based on the work of [7]. A film thickness reduction factor was added in the algorithm to take into account the starvation effect produced by the change of direction, when the original outlet becomes the inlet and the contact crosses over the previous and persistent cavitation wake. This factor, based on the work of Chevalier et al. [28], was adapted in the case of a variable velocity [24].

## 3. IssyOsborne code

The IssyOsborne code has three main algorithms to calculate the film thickness  $h(x, t)$  during the first deceleration, the other decelerations and the accelerations. These algorithms are formed by the Reynolds equation analytical solution obtained by integration in the inlet (i.e.,  $X < X1 = -1$ ), in the contact (i.e.,  $X1 < X < Xm \approx 0.93$ ) and the outlet (i.e.,  $X > Xm$ ). These equations are modulated by the starvation coefficient. For a better understanding, the code is commented in the package's procedure window.

## 4. Illustrative examples

IssyOsborne results obtained with a contact set with a load of 10 N, a sliding frequency of 10 Hz using a PAO lubricant with a viscosity of 1 Pa·s are presented on Fig. 1 displaying the evolution of the film thickness in the contact with time:

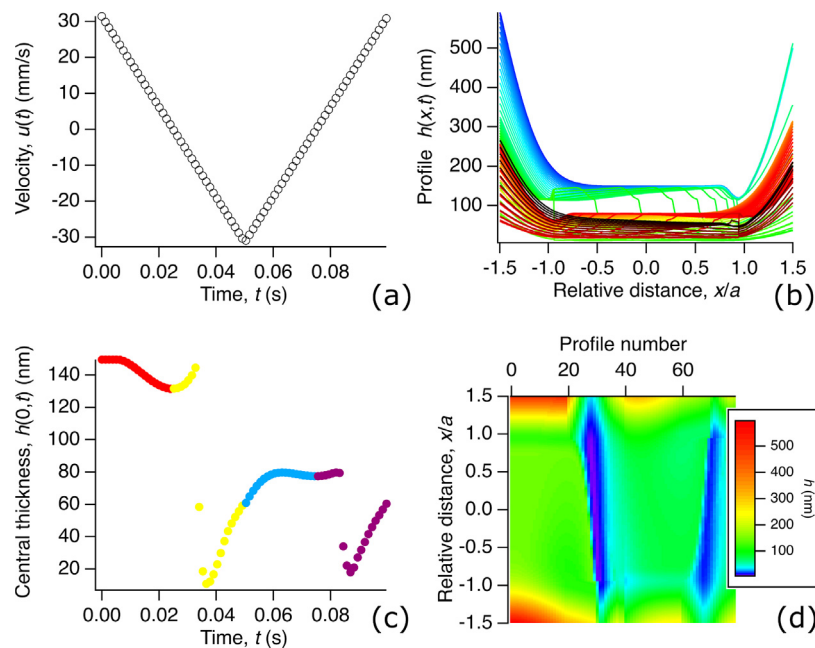
- The Fig. 1a displays the triangular velocity profile  $u(t)$  over one period consisting of one deceleration followed by one acceleration until mid-period and followed by one deceleration and one acceleration to reach a period.
- The Fig. 1b displays the time evolution of the film thickness  $h(x, t)$  profile in the contact considering the position  $x$  relatively to the Hertzian contact radius  $a$ .
- The Fig. 1c shows the film thickness at the contact center  $h, (0, t)$  as a function of the time.
- The waterfall presentation plotted in Fig. 1d concatenates the film thickness profiles over the time period, each color corresponds to a film thickness.

The film establishment mechanisms in EHL regime in forced oscillations are well retrieved by the IssyOsborne algorithm and confirms several experimental observations:

- There is a lubricant film thickness hysteresis in the contact.
- A slight drop of film thickness is observed around the zero velocity.
- Between each deceleration and acceleration, lubricant film thickness inflection or drop is displayed.

## 5. Impact

IssyOsborne algorithm allows one to calculate the film thickness distribution for reciprocating sliding contacts in elastohydrodynamic lubrication regime. Using this code, the calculated film thickness evolution was confronted to experimental results for validation over two decades of fluid viscosity for deceleration ranging from 0.004 to 0.2 m/s<sup>2</sup> for fully flooded contacts [7] and oscillating conditions [24] for frequencies from 5 Hz up to 30 Hz and stroke lengths from 0.2 mm up to 2 mm.



**Fig. 1.** Result example over one period (i.e., four decelerations/accelerations): (a) Triangular velocity; (b) Calculated profiles, each color corresponds to a profile; (c) Central film thickness with each color corresponding to a half period of the cycle; (d) Profiles waterfall.

## 6. Conclusions

IssyOsborne is an Igor Pro procedure package (.pxp) for the calculation of EHL film thickness under forced oscillations. The IssyOsborne algorithm is based on a Reynolds equation analytic resolution. IssyOsborne has an easy-to-use interface. To initiate the calculation, the only requirement is to input an initial film thickness profile or at least the contact conditions that will help to build an initial profile. IssyOsborne gives accurate results validated by experiments. These results are displayed on three different graphs: colorized successive profiles with time, colorized central thickness with acceleration/deceleration steps and a waterfall of successive profile with colorized film thickness.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article

## Acknowledgments

This work was performed at the Laboratoire de Tribologie et Dynamique des Systèmes, Ecole Centrale de Lyon, CNRS UMR5513. It was funded by the French Agence Nationale de la Recherche under the Confluence Project No. ANR-13-JS09-0016-01. The present research work was also supported by the Agency for the ecological transition ADEME (France) through the IMOTEP project.

## References

- [1] Zhu D, Wang QJ. EHL history (elastohydrodynamic lubrication). In: Wang QJ, Chung Y-W, editors. Encyclopedia of tribology. Springer US; 2013. p. 832–47. [http://dx.doi.org/10.1007/978-0-387-92897-5\\_625](http://dx.doi.org/10.1007/978-0-387-92897-5_625).
- [2] Brizmer V, Kligerman Y, Etsion I. A laser surface textured parallel thrust bearing. Tribol Trans 2003;46(3):397–403. <http://dx.doi.org/10.1080/10402000308982643>, publisher: Taylor & Francis.
- [3] Touche T, Cayer-Barrio J, Mazuyer D. Friction of textured surfaces in EHL and mixed lubrication: Effect of the groove topography. Tribol Lett 2016;63(2):25. <http://dx.doi.org/10.1007/s11249-016-0713-8>.
- [4] Ernesto A, Mazuyer D, Cayer-Barrio J. From full-film lubrication to boundary regime in transient kinematics. Tribol Lett 2015;59(1):23. <http://dx.doi.org/10.1007/s11249-015-0551-0>.
- [5] Sugimura J, Spikes HA. Technique for measuring EHD film thickness in non-steady state contact conditions. In: Dowson D, Taylor CM, Childs THC, Dalmaz G, Berthier Y, Flamand L, Georges JM, Lubrecht AA, editors. Tribology series. Elastohydrodynamics - '96 Fundamentals and applications in lubrication and traction, vol. 32, Elsevier; 1997. p. 91–100. [http://dx.doi.org/10.1016/S0167-8922\(08\)70439-5](http://dx.doi.org/10.1016/S0167-8922(08)70439-5).
- [6] Ohno N, Yamada S. Effect of high-pressure rheology of lubricants upon entrapped oil film behaviour at halting elastohydrodynamic lubrication. Proc Inst Mech Eng J J Eng Tribol 2007;221(3):279–85. <http://dx.doi.org/10.1243/13506501JET215>.
- [7] Mazuyer D, Ernesto A, Cayer-Barrio J. Theoretical modelling of film-forming mechanisms under transient conditions: Application to deceleration and experimental validation. Tribol Lett 2017;65(1):22. <http://dx.doi.org/10.1007/s11249-016-0801-9>.
- [8] Glovnea RP, Spikes HA. Behavior of EHD films during reversal of entrainment in cyclically accelerated/decelerated motion. Tribol Trans 2002;45(2):177–84. <http://dx.doi.org/10.1080/10402000208982537>, publisher: Taylor & Francis.
- [9] Reynolds O. On the theory of lubrication and its application to Mr. Beauchamp tower's experiments, including an experimental determination of the viscosity of olive oil. Philos Trans R Soc Lond 1886;177:157–234. <http://dx.doi.org/10.1098/rstl.1886.0005>, publisher: Royal Society.
- [10] Lubrecht AA. Numerical solution of the EHL line and point contact problem using multigrid techniques (Ph.D. thesis), University of Twente; 1987.
- [11] Lubrecht AA, Ioannides E. A fast solution of the dry contact problem and the associated sub-surface stress field, using multilevel techniques. J Tribol 1991;113(1):128–33. <http://dx.doi.org/10.1115/1.2920577>.
- [12] Venner CH. Multilevel solution of the EHL line and point contact problems (Ph.D. thesis), University of Twente; 1991. <http://dx.doi.org/10.3990/1.9789090039749>.
- [13] Liu Y, Wang QJ, Wang W, Hu Y, Zhu D, Krupka I, et al. EHL simulation using the free-volume viscosity model. Tribol Lett 2006;23:27–37. <http://dx.doi.org/10.1007/s11249-006-9101-0>.

- [14] Touche T, Woloszynski T, Podsiadlo P, Stachowiak GW, Cayer-Barrio J, Mazuyer D. Numerical simulations of groove topography effects on film thickness and friction in EHL regime. *Tribol Lett* 2017;65(3):113. <http://dx.doi.org/10.1007/s11249-017-0896-7>.
- [15] Simon V. Multi-objective optimization of hypoid gears to improve operating characteristics. In: Uhl T, editor. *Advances in mechanism and machine science*, IFTOMM WC 2019, Mechanisms and machine science, Vol. 73. Cham: Springer; 2019, p. 905–14. [http://dx.doi.org/10.1007/978-3-030-20131-9\\_90](http://dx.doi.org/10.1007/978-3-030-20131-9_90).
- [16] Habchi W. Finite element modelling of elastohydrodynamic lubrication problems. John Wiley & Sons, Ltd; 2018, <http://dx.doi.org/10.1002/9781119225133>.
- [17] Hooke CJ. The minimum film thickness in line contacts during reversal of entrainment. *J Tribol* 1993;115(1):191–9. <http://dx.doi.org/10.1115/1.2920975>.
- [18] Sugimura J, Jones Jr WR, Spikes HA. EHD film thickness in non-steady state contacts. *J Tribol* 1998;120(3):442–52. <http://dx.doi.org/10.1115/1.2834569>.
- [19] Sugimura J, Okumura T, Yamamoto Y, Spikes HA. Simple equation for elastohydrodynamic film thickness under acceleration. *Tribol Int* 1999;32(2):117–23. [http://dx.doi.org/10.1016/S0301-679X\(99\)00022-5](http://dx.doi.org/10.1016/S0301-679X(99)00022-5).
- [20] Wang J, Hashimoto T, Nishikawa H, Kaneta M. Pure rolling elastohydrodynamic lubrication of short stroke reciprocating motion. *Tribol Int* 2005;38(11):1013–21. <http://dx.doi.org/10.1016/j.triboint.2005.07.022>.
- [21] Bassani R, Ciulli E, Carli M, Stadler K. Experimental investigation of transient and thermal effects on lubricated non-conformal contacts. *Tribotest* 2007;13(4):183–94. <http://dx.doi.org/10.1002/tt.43>.
- [22] Ciulli E. Non-steady state non-conformal contacts: friction and film thickness studies. *Meccanica* 2009;44(4):409–25. <http://dx.doi.org/10.1007/s11012-008-9178-7>.
- [23] Hultqvist T, Shirzadegan M, Vrcek A, Baubet Y, Prakash B, Marklund P, et al. Elastohydrodynamic lubrication for the finite line contact under transient loading conditions. *Tribol Int* 2018;127:489–99. <http://dx.doi.org/10.1016/j.triboint.2018.06.035>.
- [24] Yahiaoui M, Mazuyer D, Cayer-Barrio J. Transient effects of squeeze and starvation in an EHL contact under forced oscillation: On the film-forming capability. *Tribol Int* 2020;150:106375. <http://dx.doi.org/10.1016/j.triboint.2020.106375>.
- [25] Mohrenstein-Ertel A. Die Berechnung der hydrodynamischen Schmierung gekrümmter Oberflächen unter hoher Belastung und Relativbewegung, Fortschr. In: Lang OR, Oster P, editors. *Fortschrittsberichte VDI, Ser. 1, (115)*, Düsseldorf: VDI Verlag; 1949, First published in 1945 in Russian under the name A.M. Ertel.
- [26] Popova E, Popov VI. On the history of elastohydrodynamics: The dramatic destiny of Alexander Mohrenstein-Ertel and his contribution to the theory and practice of lubrication. *ZAMM* 2015;95:652–63. <http://dx.doi.org/10.1002/zamm.201400050>.
- [27] Crook AW. The lubrication of rollers-II, film thickness with relation to viscosity and speed. *Philos Trans R Soc Lond Ser A Math Phys Sci* 1961;254:223–36. <http://dx.doi.org/10.1098/rsta.1961.0015>.
- [28] Chevalier F, Lubrecht AA, Cann PME, Dalmaz G. Film thickness in starved EHL point contacts. *J Tribol* 1998;120:126–33. <http://dx.doi.org/10.1115/1.2834175>.