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Simulation of dry and lubricated contacts in multi-body systems

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ABSTRACT. *The present paper investigates the modeling of counterformal elastohydrodynamic lubricated (EHL) contacts in multi-body system (MBS) environments. The aim is to obtain a representation of the dynamic behaviour and characteristic values for lifetime calculations. Two contact models are presented for the study of cam-roller tappet and raceway-roller contacts. The first model is a one-dimensional representation of the EHL contact behaviour. It is based on the calculation of the central lubrication film thickness by means of dimensionless values (functions of the operating conditions) and provides a simplified model of the mixed lubrication. The second one, still under development, investigates the modeling of 3D dry and lubricated contacts. This paper proposes, in the latter case, some perspectives and a discussion of its implementation.*

RÉSUMÉ. *L'article suivant concerne la modélisation de contacts élastohydrodynamiques entre semi-espaces dans les environnements de systèmes multi-corps dans le but d'obtenir une représentation du comportement dynamique de mécanismes complexes et d'évaluer les grandeurs caractéristiques nécessaires aux calculs de durée de vie. Deux modèles de contact élastohydrodynamique sont ainsi présentés pour l'étude de systèmes du type came-roulement ou piste-roulement. Le premier modèle, qui est une représentation unidimensionnelle du contact, s'appuie sur le calcul de la hauteur du film de lubrifiant au centre du contact, donnée à partir de coefficients sans dimension dépendant des conditions de fonctionnement. Il inclut une modélisation simplifiée du frottement mixte. Le second, encore en cours de développement, concerne la modélisation 3D de contacts secs et lubrifiés. L'article contient, à cet effet, une discussion ainsi que quelques perspectives quant à son implémentation.*

KEYWORDS: *elastohydrodynamic, lubrication, mixed lubrication, multi-body system, contact.*

MOTS-CLÉS: *lubrification, élastohydrodynamique, frottement mixte, système multi-corps, contact.*

1. Introduction

Elastohydrodynamically lubricated (EHL) contacts commonly occur in mechanical systems such as gears and cam-roller tappet systems. The calculated pressures of these contacts result from an interaction between the behaviour of the lubrication and the deformation of the structures. The study of this phenomenon is essential for optimizations and lifetime calculations of industrial applications. Due to the increasing complexity of these mechanisms, it becomes necessary to consider all interactions (contacts, joints...) of a system in order to obtain a complete description of the dynamic behaviour of each of his elements. However, the definition of contacts in multi-body system (MBS) environments is often insufficient to represent the complexity of EHL contacts.

EHL line and point contacts have been solved by Moes (2000) with the introduction of dimensionless coefficients to compute the minimal and central lubrication film thickness as functions of several operating conditions. This method is an extension of the principles introduced by Hamrock and Dowson (1976), which includes asymptotic behaviour for a larger applicability. The inverse method was first introduced by Dowson and Higginson (1959) for the solution of the line contact problems and then reworked by Evans and Snidle (1982) and Hou *et al.* (1987) for point contacts. This method solves the complete EHL problem and provides after the solution of the Reynolds and Boussinesq equations a satisfactory description of the pressure distribution and film thickness for a good calculating duration. This method is, however, semi-empirical and may be unstable for lightly loaded cases. The multigrid method, used by Lubrecht, Venner (2000) and others, is nowadays an excellent alternative to direct methods such as Newton-Raphson or iterative methods by offering a better convergence, stability and computation time. This method solves the discrete Reynolds equation by using several levels with different mesh densities.

The aim of this paper is to propose different adaptations of these methods to MBS environments in order to obtain a better dynamic representation of EHL contacts and provide the main characteristic values for lifetime studies.

2. One-dimensional EHL contact solution

The following mathematical model aims the calculation of the dynamic behaviour of heavily loaded line contacts of cam-roller tappet or raceway-roller systems. During the MBS simulation, only a few contact characteristics are available. The system consists of rigid bodies and thus does not contain any deformation. Only the mutual approach between two contacting bodies and general kinematic values are known. The contact model is implemented as a user-subroutine which computes the contact forces and the lubrication film thickness.

2.1. Lubricated contact conjunctions and mixed friction

According to the heavy loads present in cam-roller contacts of high-pressure pumps, the pressure distribution of EHL (half-)elliptic contacts can be approximated to the elastic one, especially in the central contact area. Thus, the normal contact force F_e may be evaluated for a given mutual approach from the elasticity theory for point contacts (Hertz, 1882) and line contacts (Kunert, 1961). According to Moes (2000), the film thickness may be calculated using dimensionless coefficients. These coefficients depend on the fluid and material properties, the elastic normal force and kinematic values, e.g. the surface velocities. Four asymptotic regimes are introduced from their calculation, which allow a characterisation of the lubrication behaviour: elastic-isoviscous, elastic-piezoviscous, rigid-isoviscous, and rigid-piezoviscous. The central film thickness h can be then calculated from an interpolation formula of these regimes. An estimation of these coefficients leads to the elastic-piezoviscous domain for the cam-roller contact under consideration which means that the film thickness remains essentially constant in the central zone and the elastic deformation must not be neglected.

The simplified mixed lubrication is incorporated by means of the superposition of a hydrodynamic and a boundary lubrication model (Müllers, 2005). In the case of heavily loaded cam-roller contacts, the hydrodynamic friction may be neglected. Thus, its representation is approximated to the viscous shearing of a Newtonian fluid. The boundary lubrication results from the superposition of friction due to local asperity contacts and from the shearing of an extremely thin fuel:

$$F_{R,B}/A = \mu_{Bound} p + \tau_{Eyring} \alpha_C \quad [1]$$

The first term of the equation [1] represents a Coulomb-type law and consists of an empirical local friction coefficient multiplied by the contact force carried by the asperities. The second one results from the product of an empirical Eyring shear stress and the asperity contact area (Teodorescu, 2003). The coefficient α_C is the ratio of the real asperity contact area on the total contact area. In the case of the heavily-loaded contacts, the real contact area may reach more than 50% of the total nominal contact area. Its calculation relies on a generalization the Greenwood/Tripp theory (1971) and the coefficient α_C is determined by:

$$\alpha_C(p) = \tanh(p/p_K) \quad [2]$$

where p_K is a critical pressure depending on roughness and material properties. In the equation [2], the approximation of proportionality between the real contact area and the normal contact force is assumed for low pressure and α_C reaches unity for heavily loaded cases, i.e. for $h \rightarrow 0$ where the asperities merge. Typical values of p_K are in the range from 0.25% to 3% of E' .

2.2. Results and discussion

In the following, some results and comments on the simulation of MBS systems with the one-dimensional mathematical model exposed above are presented. A highly-loaded pump lubricated by diesel fuel is investigated. Half an hour¹ is needed to compute a complete rotation of the cam. Figure 1 confirms the above assumption of the piezoviscous behaviour according to the values of the Moes coefficients L and M.

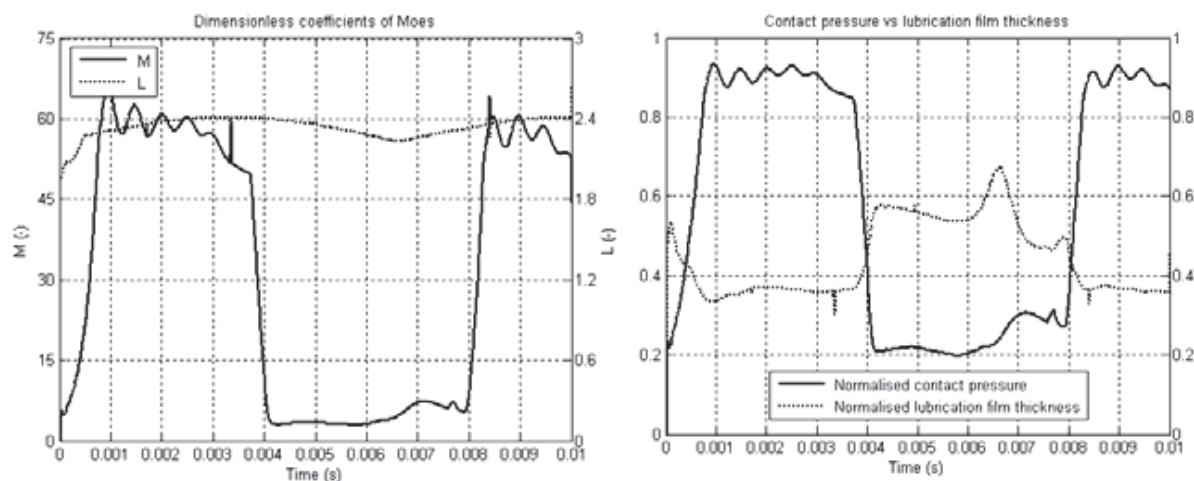


Figure 1. EHL results from a heavily-loaded cam-roller contact for $\frac{3}{4}$ of a rotation

It shows an important influence of the contact load and validates the hypothesis used for the friction model. The main reasons for these results are of course the load properties but also the bad viscosity of the present fuel. It leads to very small contact film thicknesses (about $0,1\mu\text{m}$). Figure 1 clearly shows the influence of the contact load on the film thickness. These results have not yet been confirmed by experimental studies but correspond to the initial predictions of the system behaviour.

3. Three-dimensional contact solution

The objective of the following model is to compute 3D accurate representations of the fluid behaviour and the contact pressure distribution for the contact between half-spaces. The restrictions are identical to those from the previous contact model concerning the MBS environment. A coupled solution of the Reynolds and the Boussinesq equations is in this case required. This task is still under development and only a concept for the Boussinesq equation for dry contacts is investigated here.

1. Intel Xeon 3.20GHz.

3.1. Dry contact

The following numerical model is based on the elasticity theory for half-spaces (Love, 1927). The Boussinesq equation

$$d(x, y) = \frac{2}{\pi E'} \iint_A \frac{p(x', y') dx' dy'}{\sqrt{(x - x')^2 + (y - y')^2}} \quad [3]$$

is solved to compute the pressure distribution for all time steps. The contour of the contacting bodies is discretised and the mutual approach $d(x, y)$ or the intersection volume is evaluated in a reference system associated with the contact plane. Equation [3] is then inverted in a discrete form by means of an iterative process, and the solution is achieved as soon as the real contact area is obtained (Ahmadi *et al.*, 1983). Excellent results were obtained for a low computation time. An improvement of this numerical model may be investigated: the influence of the sliding phenomenon on the contact normal pressure distribution. Therefore, the elasticity theory must be considered in more details (Björklund and Andersson, 1994).

3.2. Discussion of the EHL contact problem

In the following, some comments and perspectives are outlined for the improvement of the above numerical model considering fully lubricated contacts. The fluid-structure interaction arises from the coupling of the elasticity theory and the Reynolds equation. Two methods are distinguished for the present MBS model: the inverse method (Dowson and Higginson, 1959) and the multi-grid method (Lubrecht and Venner, 2000). One of these methods will be firstly adapted to the MBS environment to solve the Reynolds equation for smooth surfaces in order to test the stability and the calculating duration. Many studies have been done to improve and replace the well-known Greenwood/Tripp contact model, e.g. fractal distribution of asperity heights (Majumdar and Bhushan, 1991 and Willner, 2004). However, these models are nowadays still insufficient and the measurement of their characteristic parameters is not practicable for industrial applications. The Greenwood/Tripp model or an empiric internal model is therefore proposed for the present numerical implementation.

4. Conclusion

A simplified one-dimensional EHL contact model for cam contacts is proposed. It provides an approximation of the central film thickness and the friction behaviour and allows, due to the low consumption of computing time, optimisations or fast identifications of dynamical critical operating conditions. The user-subroutine is particularly appropriate for heavily loaded systems and can be rapidly adapted for a

larger application range. A second 3D model is then introduced to overcome the simplified EHL results and provides a better description of the contact behaviour for future lifetime calculations. A comparison with experimental examinations will be conducted to validate the above numerical models.

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