A Numerical Approach to Investigate Mixed Friction Systems in the Micro-scale by means of the Coupled Eulerian Lagrangian Method

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Abstract. An approach for numerical investigation of mixed lubricated systems is presented in this article. By means of the Finite Element Method, a two dimensional model is built and composed of one fluid lubricating two sliding rough surfaces. The challenge of such a model resides in the complexity of interactions between the fluid and the solid structure. The used meshing method called Coupled-Eulerian-Lagrangian is utilized for high contact topology changes, a phenomenon occurring in case of large translation of rough surfaces in contact with another viscous body.

A model based on a two dimensional axial bush bearing is developed in order to evaluate the abilities of such an approach in calculating a contact pressure and the friction coefficient between both lubricated solids. The main friction coefficient is separated into solid-solid and fluid-solid friction part. The present approach gives the opportunity to identify the influence parameters on the tribological behaviour of mixed friction systems.

Introduction

In a current context of global warming, improvements in energy saving are highly demanded. Friction effects occurring in mechanical systems, responsible for up to 10% loss of the overall worldwide produced energy [1], need to be reduced. That would be possible if the knowledge of the different friction phenomena is increased. To improve the understanding of such phenomena, a numerical approach principally based on mathematical models is developed.

An advantage of such an approach in comparison with experimentations remains in a better modularity when systems become complex. Indeed, only the CAD data of the studied system are needed whereas experimentations require the building of a prototype which is more expensive. In the contrary to real experimentations; the numerical approach are better adapted for investigations at the microscopic scale necessary conditions for presented mixed lubricated systems analyses.

This paper aims at evaluating the potential of the most recent implemented coupling method of the Finite Elements (FE) code ABAQUS in modelling complex fluid structure interactions like in mixed lubricated systems. Analyses of are then provided to determine the influence of the different parameters on the friction behaviour. Results are compared to the literature with a view to validate the model. Finally the outgoing results are synthesized and an outlook of upcoming experimentations is given.

1 Numerical Model

1.1 Phenomenon

A friction system is submitted to mixed lubrication (see Figure 1) when the lubricating fluid is broken and some solid-solid contacts occur in addition to fluid-solid contacts. The occurring mixed lubrication configuration described as in [2] where R. Stribeck presented the relationship of the friction coefficient μ and the fluid film thickness $log\,h$ in function of the ratio $\eta V/F_N$ where F_N the normal applied load, V the sliding speed and η the lubricant viscosity.

Considering dynamic effects occurring in such system configurations, a transient analysis is required for numerical investigations. The movement of the asperities induces transient fluid flow changes affecting implying dynamic loads.

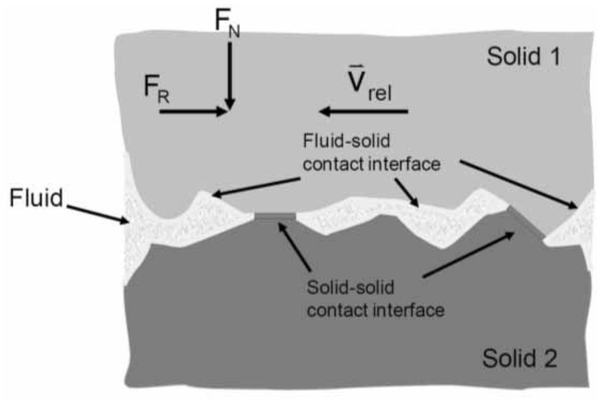

Figure 1: Mixed friction system configuration.

1.2 Coupling method and contact algorithm

The main challenge in this work is to handle with the large fluid mesh distortion provoked by the translation of the upper rough body. To cope with this problem, a remeshing technique, the Arbitrary-Lagrangian-Eulerian (ALE) technique of C.W. Hirt [3] is particularly interesting for such cases. Using this approach, L. Nowicki has modelled in his work [4, 5] Fluid-Structure-Interaction (FSI) with following limitations. When the fluid mesh becomes too small, it is necessary to actualise it manually. To overcome this encountered ALE limitations, the recent approach called Coupled-Eulerian-Lagrangian (CEL) method [6] and based on the volume of fluid technique (VOF) [7] is used for the present investigations.

In comparison with conventional FSI analyses, the fluid nodes are not attached onto the solid nodes. This concept allows for the first time the overlapping of a lagrangian and an eulerian mesh. In fact the material domain of the eulerian mesh is determined by using the free surface method. Based on the material ratio criterion the contact forces are only active if the surrounding material is of 50%. When this ratio is lower than this ratio, the fluid penetrates into the structure as shown in the edge on Figure 2.

To avoid any fluid intrusion it is necessary to use round edges and adapt the meshing refinement but this phenomenon cannot always be avoided.

1.3 Material properties and geometry

Using the commercial FE code ABAQUS 6.9-1 [8] a model is made in two dimensions for a question of computing time. The usual lagrangian meshing method is used for the solids whereas the eulerian method is applied to the fluid domain. The Mie-Grüneisen equation of state [9] based on the Hugoniot linear relationship between the particle velocity U_p and the shock velocity U_s is employed to model the fluid.

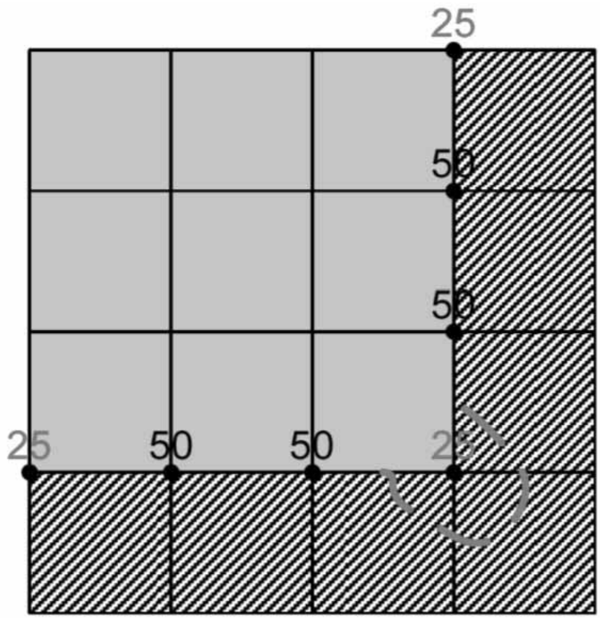

Figure 2: Contact conditions between solid and fluid.

The approximation of constant viscosity in function of the pressure is made because of low hydrodynamic pressure [10]. According to the hypothesis of incompressible fluid the parameters s and Γ are set to 0 which implies that the shock wave velocity is independent from pressure (see Table 1).

For the solid structure, a conventional structural steel is used where plasticization is also taken into account. The developed model is based on two rough simple cast surfaces having a roughness R_a calculated using definition [11].

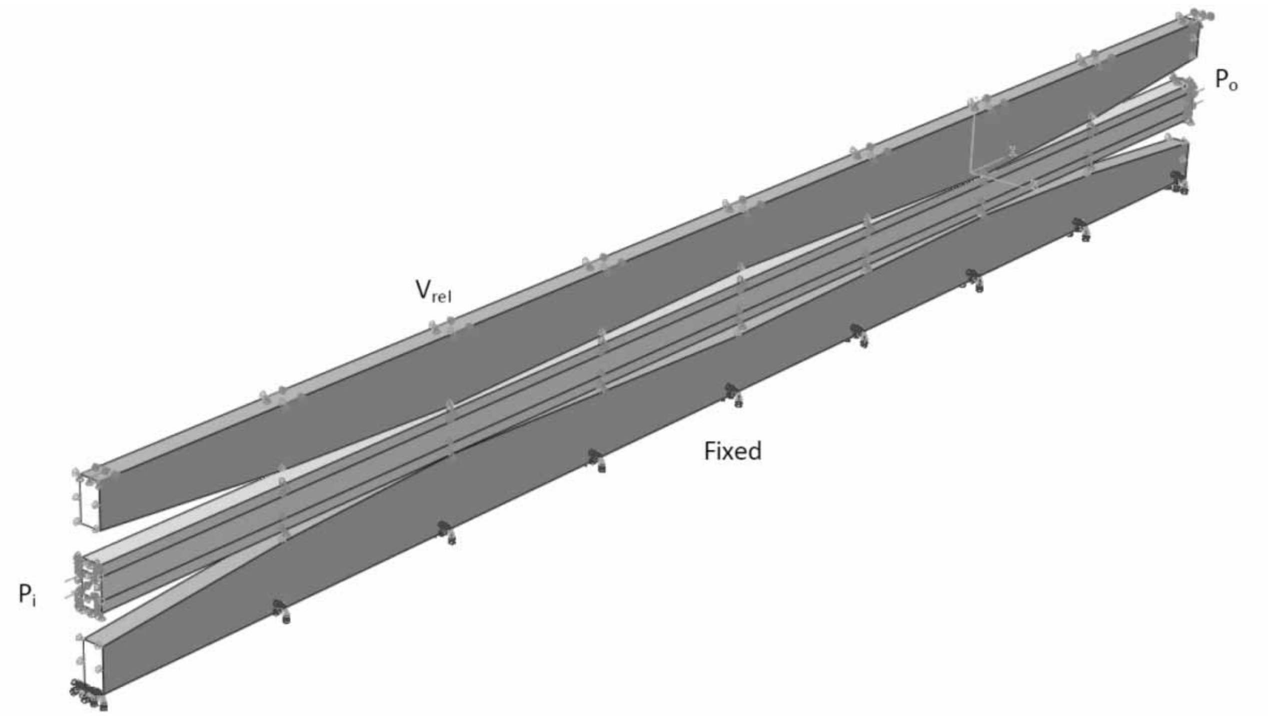

Figure 3: Model with boundary conditions.

Symbol fluid	Quantity	Value	Symbol solid	Quantity	Value
$\boldsymbol{\rho}$	density	880 kg/m^3	ρ	density	7800 kg/m^3
$\boldsymbol{\eta}$	dynamic viscosity	0.088 Pa.s	E	Young coefficient	210.10^9 Pa
$\boldsymbol{c_0}$	sound velocity	2135 m/s	v	Poission coefficient	0.33
$\boldsymbol{\Gamma}$	Grüneisen ratio	0	R_e	Yield stress	234.10^6 Pa
$\boldsymbol{s}$	slope of the $U_s - U_p$ curve	0	ε_e	Yield strain	0.18

Table 1: Fluid structure parameters (on the left) and solid structure parameters (on the right)

1.4 Model configuration and simulation process

The two dimensional model has one rank of elements in the Z direction (see Figure 3). The used boundary conditions are applied in order to fit to the reality. Regarding the objectives, a two dimensional model will not be able to simulate a complete mixed lubricated problems but only a combination of fluid-solid and solid-solid interaction. The aim is to analyze the plausibility of the resulting output in comparison with the real effects.

As the model is a section of a three dimensional one, X and Y rotations, as well as the displacements in the normal direction to the section, represented by the Z axis in Figure 3, are forbidden. The lower body is fixed on the ground at its lower surface. Concerning the fluid, there is the need to avoid fluid loss in the X direction what is also the case in the Y direction whether some fluid parts penetrate into the solid body.

After setting preceding boundary conditions, it is necessary to follow a global procedure in order to make a parametrical study. Investigations are only relevant when the model is working in quasi-static conditions that means when a constant friction velocity is reached. To do that, a rigorous procedure needs to been chosen. In initial phase an inlet pressure P_i of $110\ MPa$ at the inlet and an outlet pressure P_0 of $109.99\ MPa$ are applied. In order to vary the fluid film thickness a second step is needed for the setting vertical position. Displacements are imposed to the whole bodies because of present high accelerations. After positioning phase, a new step has to initiate the wanted sliding velocity on the upper body. Once the fluid contact is stabilized again, a final step is set to make the relevant quasi-static investigations where the sliding velocity remains constant. When mixed friction is initiated, the solid-solid contact coefficient is of 0.15 is admitted according to the literature.

Due to the high nonlinearity coming from the fluid modelling, the explicit solver is needed. However its computational costs highly depend on the element size according to the stable increment criterion [12] which is depending principally of the characteristic length associated with the elements. This limitation is essential for the simulation duration because the model is made at the micro scale where the global element size is in the order of $0.05\ mm$.

2 Results

Many different investigations where realized in order to analyze the frictional behaviour ofthe system. Three parameters where varied in order to know each of their influence.

2.1 Variation of the film thickness in hydrodynamic lubrication

The main analyses conditions are the same as for the previous one. The friction coefficient is decreasing when the lubricant film becomes thicker. This is explained by the local pressure which decreases when the flow section becomes bigger.

This trend is followed with the three different roughness profiles. A rule could not been defined in order to get the real influence of the roughness.

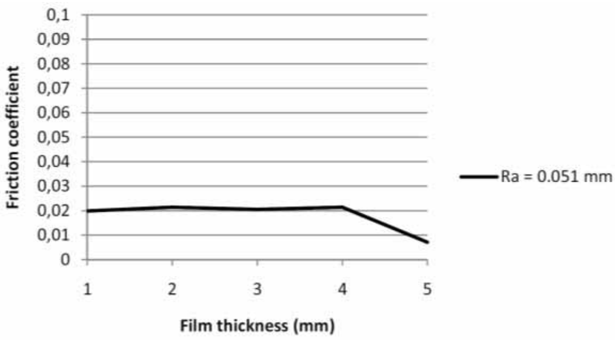

Figure 4: Influence of the film thickness.

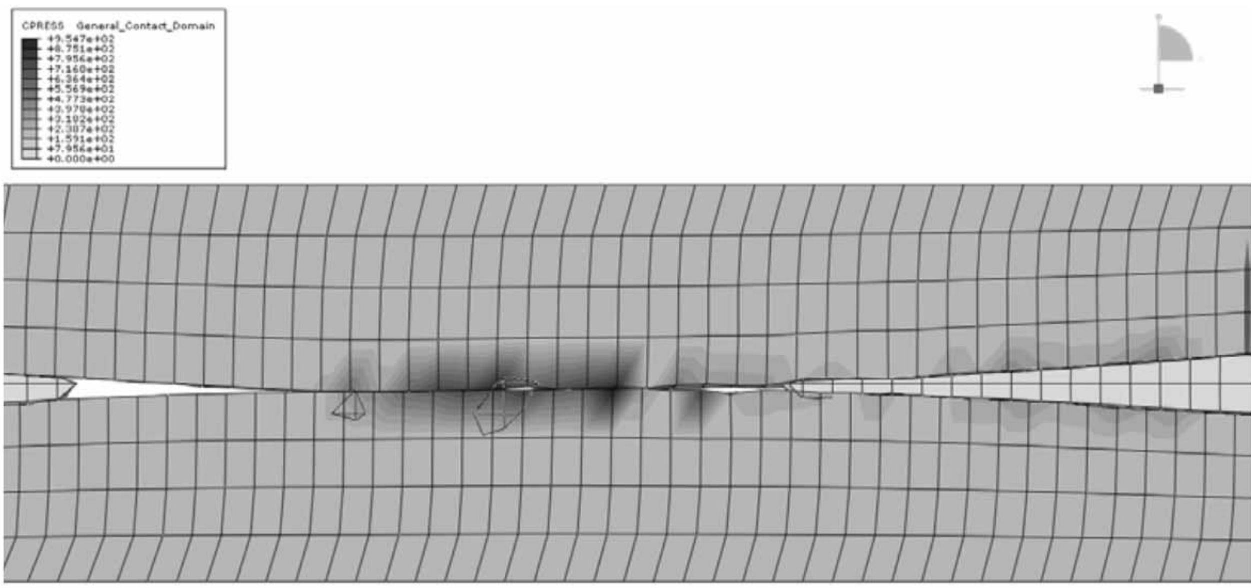

Figure 6: Contact pressure (MPa) in the mixed lubricated system

2.2 Noise effects appearing in using the CEL method

Some noise effects such as vibrations that are a combination of elastic behaviour and fluid vibrations coming from the pressure application (see Figure 5). The three signals are analyzed with the Fast Fourier Transformation (FFT) showing that all signals have the same main frequency of 0.2 peaks pro frame which means a peak each 5 frames. That shows that the frequency is independent of the fluid shock wave because the solid velocity is not influencing this noise. This effect was known by the developers but can only be avoided by using shorter simulation time than the time needed by the wave to reflect against the fluid boundaries.

On Figure 5 oscillations are observed, these ones correspond to the reflecting oscillations of the fluid against both sides where a pressure load is applied.

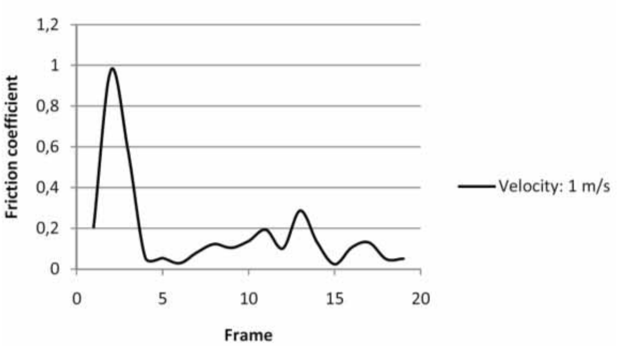

Figure 5: Application of the translation velocity.

2.3 Mixed friction model

The previous presented investigations were made in order to have a basis to investigate more complex system behaviour. In this work the case of mixed friction systems are investigated. Figure 6 shows how the contact pressure is distributed in the contact. The contact pressure goes until 1.1 GPa what is usual for solid-solid contact occurring in mixed friction contacts.

In such systems the solid friction can be separated from the fluid friction into two coefficient μ_s for the solid friction and μ_f the fluid friction. The global coefficient is calculated by the FE solver and its value is of 0.2. The main friction coefficient can be separated into two terms [13].

The adhesion effects issuing from the interaction between the fluid and the structure are calculated with a post processing treatment. The hydrodynamic friction, which is coming from the shear stress of the fluid, is directly taken into account by the software. After post-processing treatment the value of 0.039 as hydrodynamic friction is established which is in accordance with the literature.

3 Conclusion and Outlook

Finally, the new CEL approach offers many possibilities to simulate interactions between fluid and solids. This procedure avoids the difficulty of remeshing fluid structures when contact topologies get too large changes, what is impossible with other methods but with lower precision. Nevertheless, it has to be noticed that the method needs many CPU resources.

The hypothesis to use this method is valid because the outgoing results are very similar to those found in the literature. This method enables investigations of micro structures in order to calculate the local friction coefficient and to understand the phenomena at this scale. The next step will be to develop a method which investigates the phenomena in real three dimensions and enables a design of experiment for determining most influencing parameters.

Then, to complete this method, adhesion models have to be implemented to take into account the adhesion effects between both solids. One last aspect to consider in the modelling is to eliminate and overcome the noise coming from the numerical method.

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