EHL-Squeeze in Highly Loaded Contacts: The Influence of Fluid Rheology on Pin-Pulley Interaction in CVT Transmission

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SUMMARY. We analyze the influence of non-Newtonian fluid behavior on the strongly non stationary squeeze process of an oil film sandwiched between the chain-pin and pulley in continuously variable transmission (CVT). As recently demonstrated [7], the spatial pressure distribution is characterized by a non central annular pressure peak, which first appears in the external region of the contact domain and after moves toward the center of the pin with rapidly decreasing speed. In this paper we show that the non-Newtonian visco-elastic rheology of the lubricant plays a crucial role in determining the actual value of pressure peaks and leads to a strong reduction of such pressure spikes in comparison to a perfect Newtonian (piezo-viscous)lubricant. Even more, if the threshold value of shear stress, which characterizes the shear thinning transition of the lubricant, is sufficiently small the annular pressure peak may even disappear. In this case the squeeze process occurs faster, the film thickness is reduced and the lubricant may not be able to avoid direct asperity contact between the two approaching surfaces [8].

1 INTRODUCTION

For the past decades continuously variable transmissions (CVTs) have attracted a steadily increasing interest of the scientific and industrial community as a consequence of their potential to reduce vehicle fuel consumption, greenhouse gases, and polluting emissions. CVTs may also increase the vehicle ride comfort and, in the case of best controlled solutions, also its drivability. Indeed, this kind of mechanical transmissions may enable the engine to follow the so-called economy line: For any given power request the CVT speed ratio can be adjusted to get the highest possible thermal efficiency of the engine [1]-[3]. This is particularly interesting under the perspective of the environmental question. However, the mechanical efficiency of CVTs is still smaller compared with that of the stepped transmissions. Thus, a great deal of research is being carried out in order to improve CVT efficiency and/or utilize CVTs at the best of their performances [4]-[6]. One way to improve the mechanical efficiency is that of optimizing the local traction performances at the chain-pulley contact. This approach requires a deep understanding of the lubrication conditions at the interface [7]-[9], as a first step toward an optimization of the micro- and macro-geometry of surfaces, with the final aim to increase the amount of torque per unit normal force that can be locally transferred through the pin-pulley interface with the minimum wear. In this paper we focus on the Gear Chain Industrial B.V. (GCI) chain belt CVT (see Fig. 1 for a schematic of the GCI chain).

In [7] the authors have shown that the pin-pulley interaction is characterized by a squeezing motion of the oil interposed in between the mating surfaces, which occurs as soon as the pin enters the pulley groove and is determined by a sudden step variation in the normal force acting on the pin (of area of order $\approx 1\ \mathrm{mm}^2$), from zero (on the free strand of the chain) to a finite value of order 1 kN. This step change of the pin-pulley normal force has been demonstrated by independent investigations both theoretically level [5], [10], [11] and experimentally [12].

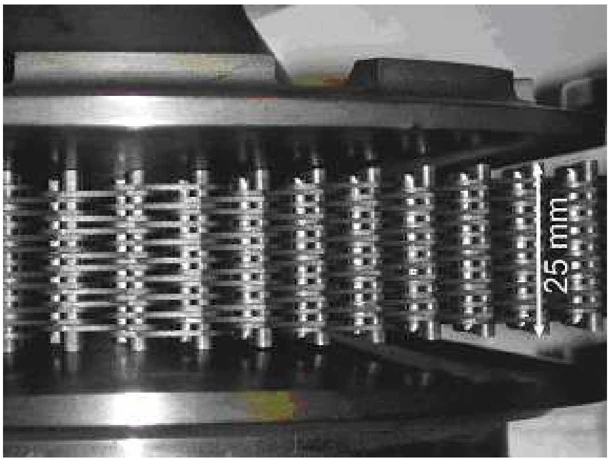

Figure 1: The Gear Chain Industrial B.V. (GCI) chain with the pins entering the pulley groove.

Moreover, in [7] the authors have shown that the spatial fluid pressure distribution, as consequence of this load step variation, is characterized by a non central annular pressure peak, which first appears in the external region of the contact domain and after moves toward the center of the pin with rapidly decreasing speed. An highly-pressurized, high-viscosity oil dimple is generated in the middle of the contact zone which is able to avoid direct metal-metal interactions for typical pin-pulley traveling time (PPT) of $\approx 10^{-2}$ s and a combined surface root-mean-square-roughness lower than ≈ 0.1 μm (corresponding to commonly adopted values in such CVTs). Because of combining piezo-viscosity effect and Newtonian rheology in an high shear rate fast squeezing motion, the annular pressure peak is characterized by values of order ≈ 10 GPa [7], which are beyond the strength of steel. This suggest that lubricant non-Newtonian phenomena are experienced during the interaction.

In this work we analyze the effect of non-Newtonian lubricant rheology, namely viscoelasticity (VE) and shear thinning (ST) (which capture most of the physics of the fluid behavior under high-shear, high-pressure operation [8]), on the strongly non stationary squeeze process of an oil film sandwiched between the chain-pin and pulley in continuously variable transmission. Firstly we show, through a linear Maxwell constitutive model, that oil viscoelasticity enables local variations of the fluid pressure field in comparison to the Newtonian fluid model. In particular, a deep smoothing of the annular peak is observed, as consequence of the predominance of oil elastic deformation mode on the viscous deformation mode. Finally, we show, through the Rabinowitsch model, that lubricant shear thinning can completely avoid the highly-pressurized dimple formation for small enough value of shear thinning threshold (STt), so that the squeeze process occurs faster, the film thickness is reduced and the lubricant may not be able to avoid direct asperity contact between the two approaching surfaces [8].

2 THE LUBRICANT VISCOELASTICITY EFFECT

The interaction between pin and pulley is characterized by a fast, high-loaded squeezing of the lubricant film. Contact loads of about 1 kN and pin cross sectional area of about 1 mm^2 (therefore, average pressure of GPa order) suggest an hard-elastohydrodynamic lubrication (EHL) regime as the most suitable to describe the interactions of bodies at the interface, at least until the minimum oil film thickness is large enough to neglect asperity-asperity and asperity-fluid interactions. The Reader is referred to [7]-[9] for details about the contact model and assumptions, and the adopted numerical scheme.

Here we show the calculation results for a piezoviscous and piezodense fluid characterized by a linear Maxwell rheology (linear visco-elasticity) [8]. In order to estimate whether the oil elastic response is actually involved, we should evaluate the Deborah number $D_h = \tau/T$, where τ is a characteristic lubricant relaxation time and can be defined as η/G_s, where η is the (pressure dependent) viscosity and G_s corresponds to the limiting high frequency elastic shear modulus (for mineral oil is of GPa order); T is the perturbation time-scale. For $D_h \approx 1$ the fluid elastic response cannot be neglected if compared to the viscous response.

In an EHL squeeze motion, it is expected a D_h dependent on the squeezing time-instant and on the spatial contact position [8]. Indeed, in Fig. 2 we show the pressure field as function of contact radius, and for different time instants, for a linear Maxwell fluid as compared to the Newtonian solution.

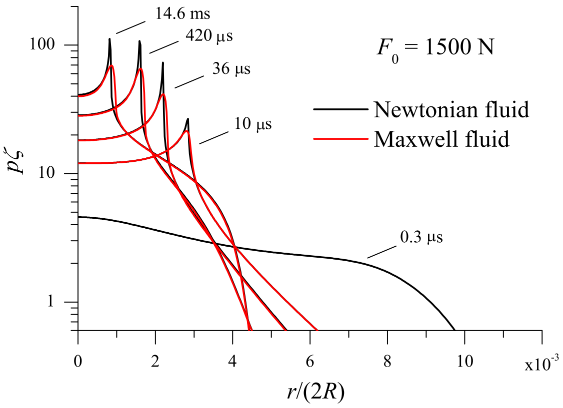

Figure 2: Dimensionless fluid pressure field as function of contact radius at different times for a Maxwell lubricant and an applied squeezing load $F_0 = 1500$ N.

After an initial hydrodynamic stage with negligible solid elastic deformations, an annular pressure spike is generated with a peak decreased of more than 50% with respect to the Newtonian case. Therefore, the oil VE locally modifies the squeezing pressure field, as consequence of the dominance of the lubricant elastic deformation mode on the viscous deformation mode due to the pressure-induced exponential increase of viscosity, particularly accentuated relatively close to the pressure spike. Moreover, the decrease of the shear modulus G_s determines the spreading (along the radial direction) of the annular pressure spike. In Fig. 3-a we show the pressure distribution for different value of G_s, and two different squeeze time instants, while in Fig. 3-b we show a magnification of the pressure peaks of Fig. 3-a.

In Fig. 3-b the curves for $t = 1.2$ ms clearly show the spreading of the radial domain of dominance of the fluid elastic deformation mode for a decreasing G_s. Being this pressure variation

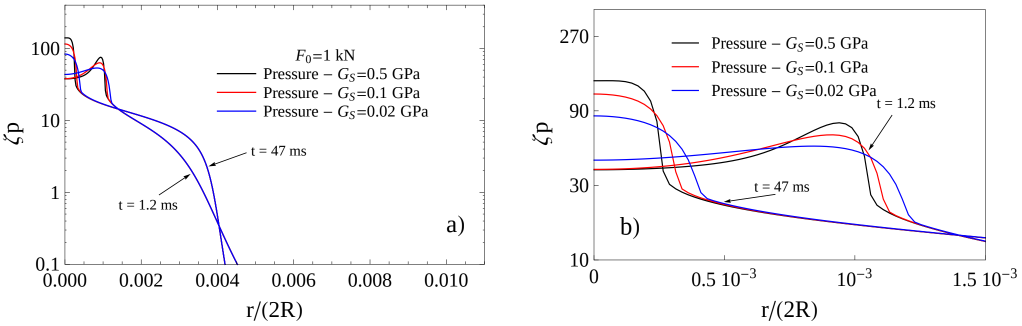

Figure 3: a) Dimensionless pressure distribution for an applied load of $F_0 = 1$ kN and for $G_s = 0.5,\ 0.1,\ 0.02$ GPa. b) Magnification of the pressure distribution close to the pressure peaks.

localized in around the pressure peaks, and considering the singularity behavior of the elastic kernel, it is clear that VE can determine only local variation to the film thickness field. In Fig. 4-a we show the film thickness field corresponding to the simulation parameters of Fig. 3, while in Fig. 4-b we show a magnification of the film thickness of Fig. 4-a.

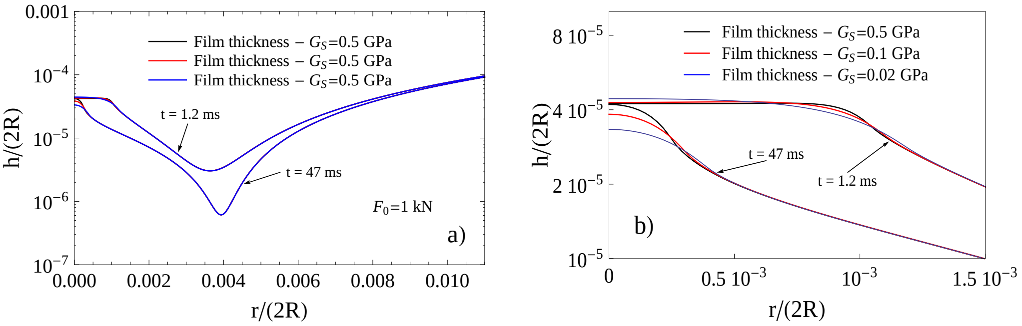

Figure 4: a) Dimensionless oil film thickness as function of contact radius for an applied load of $F_0 = 1$ kN and for $G_s = 0.5,\ 0.1,\ 0.02$ GPa. b) Magnification of the film thickness distribution.

Note the film thickness is only locally affected by a decrease of G_s.

Therefore, VE is fundamental in determine the time evolution of the correct viscosity spatial field (which is strictly related to the frictional properties at the interface) but is not relevant in determine the lubrication regime, as the minimum film thickness is unaffected from VE, see Fig. 5. Note in Fig. 5 that, as expected, the central film thickness changes are localized in the squeeze-time range in which the pressure peaks are close to the contact axis.

3 THE SHEAR THINNING EFFECT

In this section we analyze the fluid shear thinning (ST) effect on the EHL squeeze motion. It is well know that Newtonian rheology assumption is well validated, for film thickness calculation (e.g.

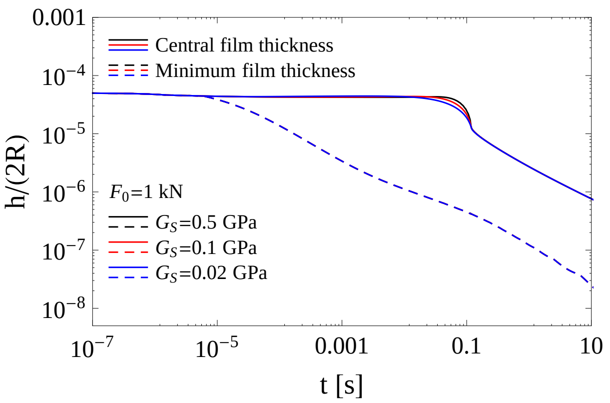

Figure 5: Dimensionless minimum (dashed line) and central (continuous line) film thickness as function of squeezing time. For the same parameters of Fig. 3.

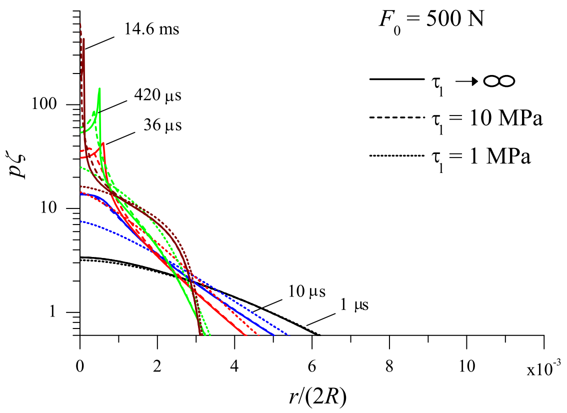

Figure 6: Lubricant dimensionless pressure as function of radial coordinate for different squeeze-time instants, and for STt $\tau_l = 10,\ 1$ MPa, as compared to the Newtonian solution ($\tau_l \rightarrow \infty$). The applied load is $F_0 = 0.5$ kN.

see [13]), for low-molecular weight lubricants, as mineral oil. Nevertheless, specially for automotive applications, mineral oils are generally blended with high-molecular materials, as polymer thickeners (in order to reduce the temperature dependence of viscosity) and frequently nowadays the base stock is of high molecular weight [14]. Here we investigate the ST effect through a Rabinowitsch constitutive model [14]. The reader is referred to [7]-[9] for details about the contact model and assumptions, and the adopted numerical scheme.

In Fig. 6 we show the fluid pressure as function of radial coordinate for different squeeze-time instants, and for STt $\tau_l = 10,\ 1$ MPa in comparison to the Newtonian solution ($\tau_l \rightarrow \infty$). It is

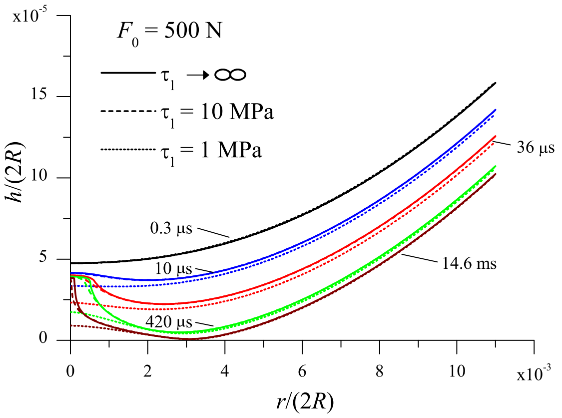

Figure 7: Oil film thickness as function of radial coordinate for different squeeze-time instants. For the same calculation parameters of Fig. 6.

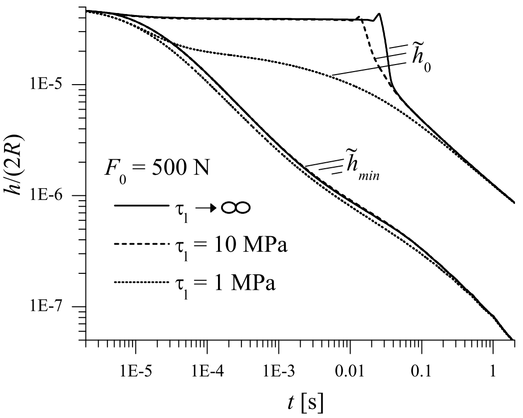

Figure 8: Minimum and central film thickness as function of squeeze time. For the same calculation parameters of Fig. 6.

interesting to notice that for the lowest value of STt, the typical central highly-pressurized oil dimple is mainly not formed, so that the beneficial effect of piezo-viscosity in retarding direct metal-metal interaction may be avoided.

In Fig. 7 we show the film thickness spatial distribution corresponding to the simulation parameters of Fig. 6. The squeeze motion is therefore speeded up by a decrease of STt (for squeezing time comparable to the PPT), which we show to globally affect the solutions fields. Therefore, we state that the exact knowledge of the oil rheology for the high-pressure high-shear transient lubrication is of fundamental importance in determining not only the frictional behavior (which, for a piezo-viscous oil in condition of hard-EHL, is mainly due to the value of viscosity field), but also the film thickness distribution itself. Coherently, ST (as also limiting shear stress phenomena) may determine the lubrication regime in pin-pulley interaction.

Moreover, in Fig. 8 we show the minimum and central film thickness as function of squeeze time for the same calculation parameters of Fig. 6. Note for the lowest value of τ_l how quickly the central-gap curve diverges from the Newtonian solution, as consequence of a reduced oil dimple formation, for finally overlapping, as consequence of a low shear motion. Note also in Fig. 8 the deviation of minimum film thickness curve, for the lowest value of STt, for squeezing time comparable to the PPT. We confirm that, depending on the actual value of mating surfaces roughness, the fluid shear thinning may play a fundamental role in determining the actual lubrication regime, as for decreasing τ_l the exponential pressure-induced increase of viscosity may be not able to avoid asperity-asperity collisions, with strong consequence in the frictional and wear properties at the interface.

4 CONCLUSIONS

In this paper we have investigated the effect of fluid rheology on the elasto-hydrodynamic (EHL) squeeze process at the pin-pulley interface in continuously variable transmission (CVT). The effects of lubricant viscoelasticity and shear thinning behavior have been analyzed separately. We have shown that in both cases the annular pressure peak is strongly reduced of about 50% if compared to the Newtonian solution, and decreases more if the oil threshold shear stress is significantly reduced. However, for low-molecular weight lubricant (as for mineral oil), the threshold shear stress is not small enough to determine significant changes to the solution fields as calculated with the Newtonian approximation. This is even more true if one looks to the oil thickness spatial and time profiles. We have also shown that the scenario outlined so far may strongly change depending on the threshold shear stress of the oil. The threshold shear stress may indeed significantly change as a consequence of contaminants or because of a change of the oil composition. In particular, a strong decrease of the threshold shear stress may lead to a complete disappearance of the annular pressure peak, accelerate the squeeze process and lead to direct metal-metal contact between the two approaching surfaces.

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