

Moving textures: Simulation of a ring sliding on a textured liner

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ABSTRACT

Numerical simulations of the ring/liner contact in which the liner exhibits a periodic texture (pockets) are reported. The mass-conservative Elrod–Adams model is used to treat cavitation, and the dynamics of the ring is considered with a linear mass that corresponds to actual engine compression rings. The results, computed at a Stribeck number of 10^{-3} and thus in the hydrodynamic lubrication regime, show that the ring profile determines whether pocketing is beneficial or not. For strongly non-conformal contacts pocketing is detrimental, but for quasi-conformal contacts friction reductions of up to 73% are predicted. The largest reduction in friction was obtained for textures consisting of close-packed arrays of circular pockets of diameter comparable to the size of the contact.

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1. Introduction

Texturing of contact surfaces to reduce friction and wear has attracted much attention in the last years, especially since surface microengineering techniques have become available. One important application is the piston-ring/cylinder-liner contact in combustion engines, which accounts for about 5% of fuel consumption [1].

It is known that some texture is needed to avoid stiction between the ring pack and the liner, and honed liners have been used for many decades for that purpose. Current investigations are aimed at determining the best texture in terms of friction and wear for each working condition.

Numerical and experimental studies on the ring/liner lubrication problem with textured surfaces are recent and quite scarce.

The numerical studies have only considered the texture to be on the ring, and thus stationary with respect to the contact. Kligerman et al. [2] solved the problem for flat textured and partially textured rings using the Reynolds equation and Reynolds boundary condition, which is known not to conserve mass. They concluded that surface texture reduces the friction between the surfaces. On the other hand, Tomanik [3], with the same cavitation model, numerically compared barrel shaped rings (compression

rings), flat rings (oil control rings) and flat partially textured rings, also incorporating experimental data in the analysis. His results (both numerical and experimental) showed that the untextured barrel-shaped rings performed better than their flat, partially textured counterparts, both in hydrodynamic support and in friction coefficient. This finding coincides with recent numerical results of Gadeschi et al. [4] assessing the effect of Laser Surface Texture (LST) pockets on barrel-shaped rings. These authors adopted the Reynolds equation with Gümbel boundary conditions, which are non mass-conservative.

The goal of this paper is to present numerical simulations of hydrodynamic ring/liner contact with a *mass-conservative cavitation model and considering the texture as being on the liner* and thus moving through the computational domain, as sketched in Fig. 1. Similar simulations have only been reported up to now by Yin et al. [5], though with Reynolds cavitation condition (non-mass conservative), and by Tanaka and Ichimaru [6], who considered purely transversal textures, rendering the geometry one-dimensional, and adopted Reynolds cavitation condition.

The crucial importance of mass-conserving boundary conditions at cavitation boundaries has been established by Ausas et al. [7] and confirmed by several authors, among them Zhang and Meng [8] who performed a careful comparison with experiments.

The importance of considering textured liners, instead of textured rings, arises from several practical considerations: (a) All actual cylinder liners are, in fact, textured in some way. (b) The wear of the liner is smaller, and more evenly distributed, than that of the ring; the texture can thus be designed with more confidence in that it will preserve its shape for long operating

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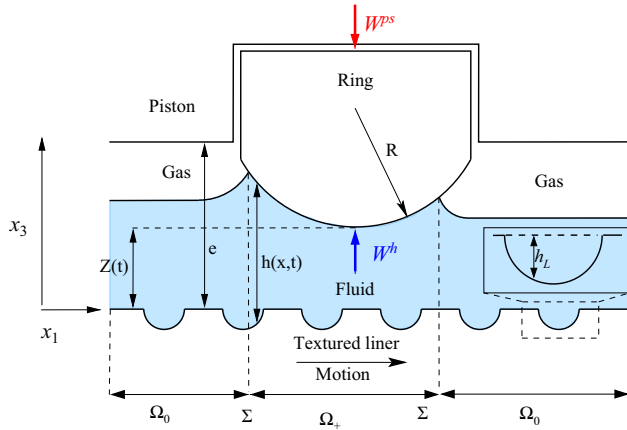


Fig. 1. Scheme of a section of the domain in the piston movement direction, with the forces acting on the ring.

times. (c) Since the rings contact the same axial position of the liner always at the same crank angle, texturing the liner allows one to optimize the texture that contacts the ring independently for each instant of the engine cycle.

The simulation of the ring/liner contact with texture on the liner also constitutes a scientific challenge from the numerical perspective. The dynamical behavior of the system is completely different depending on whether the texture is on the ring or on the liner. In the former case, the texture is stationary with respect to the contact, and thus the ring stabilizes at some position at which force equilibrium takes place. This position only changes with the time scale of variations in the relative velocity or oil-feeding conditions. If the texture is on the liner, the texture cells enter the contact from one side, move under the ring, and leave the contact at the opposite side. In this case the ring exhibits a superposed oscillatory motion with the time scale per/u , where per is the size of the texture cells and u the relative speed. The complexity grows substantially, since the simulation must be transient and must incorporate the rigid-body dynamics of the ring, which is subject to time-varying forces.

The simulations reported in this paper consider barrel-shaped rings in which the contact surface is cylindrical of radius R . Several values of R are considered, ranging from 2 mm to nominally conformal contact (R very large), so as to contribute to the interpretation of experimental findings.

Experimental studies of textured surfaces have mainly focused on conformal contacts (nominally flat pin or ring on nominally plane disk) [8–13]. Experiments in non-conformal contact configurations have yielded mixed results up to now. In a recent article, Kovalchenko et al. [14] found that dimpled disks accelerated the wear of the contacting ball and only as a result thereof some friction reduction could be attained. Their explanation focused on a change of regime from boundary to mixed lubrication. Ali et al. [15] performed ball-on-disk experiments and found that dents did not reduce friction in fully flooded conditions, whereas significant reduction was attained under severe starvation. Similar experiments by Li et al. [16] on PDMS disks lead them to conclude that texturing only reduces friction at low sliding velocities, consistent with a boundary or mixed lubrication regime. Other experimental studies of non-conformal contacts in the boundary lubrication regime have been reported by Kim et al. [17], Peterson and Jacobson [18,19].

The hydrodynamic lubrication regime was studied by Costa and Hutchins [20] by means of cylinder-on-plane experiments in which the texture was on the plane. For a cylinder diameter of 16 mm they found that all textured surfaces performed worse than the untextured one. For a cylinder diameter of 200 mm, on the

other hand, they observed that the *average* film thickness, as measured by capacitance techniques, was improved by some non-zero textures. Unfortunately, they did not measure the *minimum* film thickness or the friction coefficient. Tomanik [21], on the other hand, used the compression ring of a heavy duty Diesel engine ($R \approx 50$ mm) on several textured liners (pocketed and honed liners) and obtained that the untextured liner presented less friction than the textured ones. Some further information on the effect of the liner's striation patterns has been published by Grabon et al. [22] and by Yuan et al. [10], among others.

The plan of this paper is as follows: In Section 2 we describe the mathematical model, which is essentially based on the Elrod–Adams model for lubrication and cavitation [23]. Though the Elrod–Adams model has some deficiencies for this problem [24], there is no better general mass-conserving algorithm for cavitation problems [25]. Section 3 contains the numerical results. They correspond to fully flooded, hydrodynamic contact conditions at fixed relative velocity, and with atmospheric pressure (assumed equal to the cavitation pressure) on both sides of the ring. The texture is on the liner and its geometry corresponds to pockets inspired in those produced by Laser Surface Texturing (LST) [26], with depth, diameter and area density in the range of those recommended in LST applications. The mass assigned to the ring is typical of compression rings of car engines. By exploring hundreds of cases, a picture of the effect of textures on ring/liner friction emerges in which texturing is beneficial only for rings with sufficiently large R . This picture coincides with the one recently put forward by Gadeschi et al. [4] for non-moving textures (texture on the ring) on the basis of a non-mass-conservative model. Conclusions are drawn in Section 4.

2. Modeling

2.1. Geometrical model

We consider a configuration in which a single ring is in contact with the liner. The surface of the liner is developed along the x_1 – x_2 plane, x_1 being the axial direction (coincident with that of the motion) and x_2 the circumferential one. The curvature along x_2 is neglected.

It is assumed that the ring is only allowed to move along x_3 , its position being parameterized by Z . The origin of Z is chosen so that $Z=0$ corresponds to the ring touching the x_1 – x_2 plane. The ring profile, $h_U(x_1, x_2)$ satisfies $\min_{(x_1, x_2)} h_U(x_1, x_2) = 0$ and is shown in Fig. 2. Its analytical expression is the one corresponding to an arc of circumference of radius R .

The liner is assumed to coincide with the x_1 – x_2 plane ($x_3 = 0$) when it is smooth (untextured). In the textured case, it is given by

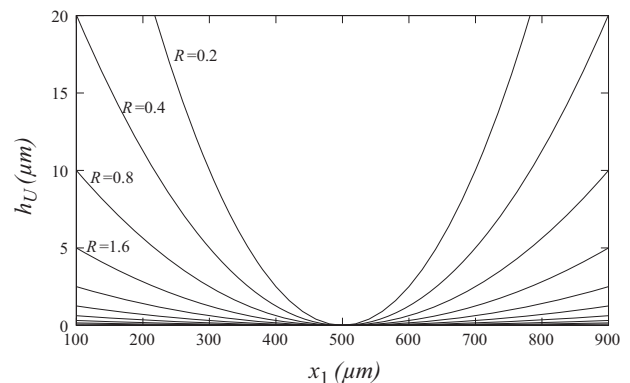


Fig. 2. Ring profiles for curvature radius ranging from $R=0.2$ to $R=102.4$ cm, in powers of 2.

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