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A robust piston ring lubrication solver: Influence of liner groove shape, depth and density

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ABSTRACT

A multigrid code using Alcouffe's [1] ideas has been written to solve the hydrodynamic lubrication equation for the piston ring–cylinder liner contact with a textured liner. The new program shows good convergence, even for deep grooves. Results are compared with a simplified 1D analytic model proposed by Biboulet [2]. Then a 2D analytic model of cross hatched grooves with a small angle is studied and compared with the 1D analytic model.

1. Introduction

In internal combustion (IC) engines, the piston ring cylinder liner (PRCL) contact is an important source of mechanical friction. For ecological reasons, oil consumption has to be limited. For both aspects, the piston ring pack plays a crucial part because of its sealing and lubricating functions. Therefore, the piston ring pack has been the subject of many studies. Analysis of the piston-ring pack can be found in [3–6] where the effects of relative ring locations, tension and design of oil-control ring, ring conformability, bore distortion, etc. are investigated.

Cylinder liner texturing is also an important factor to improve load carrying capacity, friction coefficient and oil consumption. They can serve as local pressure generators, lubricant reservoirs or debris traps. Surface texture is necessary to generate pressure in the case of flat rings such as the oil control ring [6–12].

The interest of cross-hatched grooves for good oil redistribution and friction reduction was shown in [13–15]. In [16], the honing process is studied and its effects on the surface topography and henceforth on the PRLC performance are developed. Dynamic effects also play a role in the PRCL contact as studied in [17].

The influence of the groove parameters, density, depth and angle for a cross hatched texture was studied in [18,19,8]. In order to obtain a more precise model of the PRCL contact, it is necessary to solve the transient hydrodynamic lubrication of the contact, requiring millions of points of a measured surface and thousands of time steps. Hence, the use of an efficient and robust solver for the Reynolds equation is a must. Because of the surface roughness, the film thickness term in the Reynolds equation shows huge variations, making the problem quite difficult to solve. Different approaches have been applied in the past such as the stochastic methods using the Patir and Cheng flow factors [20] or homogenization methods [21]. Our approach is based on a deterministic model and measured surfaces. As such a detailed description requires very fine grids, it requires long computing times. Multigrid techniques are used to accelerate the convergence. However, the equation to be solved must be properly represented on the coarse grids. In our case this was not obvious because of the deep grooves. Using ideas developed in [1], it has been possible to overcome this difficulty.

2. Algorithm

The hydrodynamic lubrication of the piston ring–cylinder liner contact can be described by the Reynolds equation. Because of cavitation, the following dimensionless complementary problem must be solved:

$$\frac{\partial}{\partial X}\left(H^3\frac{\partial P}{\partial X}\right)+\frac{\partial}{\partial Y}\left(H^3\frac{\partial P}{\partial Y}\right)-\frac{\partial H}{\partial X}-\frac{\partial H}{\partial T}=0 \quad \text{and} \quad P>0 \;\; P=0$$

where H represents the film height and P the pressure. The geometry H is defined by the macroscopic ring shape and by the liner texture. In this work, only analytic models of the cross-hatched surfaces have been considered:

$$H(X,Y)=1+\frac{X^2}{2}+R(X,Y)$$

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Notation[1]

a	groove depth
d	distance between grooves
e	ring half width
h	film thickness
h_0	minimum film thickness
p	pressure
R_x	reduced radius in direction of sliding
u_m	mean surface velocity
t	time
x	coordinate in direction of sliding
y	coordinate perpendicular to direction of sliding
A	dimensionless groove depth $= a/h_0$
D	dimensionless distance between grooves $= d/\sqrt{h_0 R_x}$
E	dimensionless ring half width $= e/\sqrt{h_0 R_x}$
H	dimensionless film thickness $= h/h_0$
P	dimensionless pressure $= p h_0 \sqrt{h_0}/(12\eta u_m \sqrt{R_x})$
T	dimensionless time $= u_m t/\sqrt{h_0 R_x}$
W	dimensionless load $= w h_0/(12\eta u_m R_x)$
X	dimensionless coordinate in direction of sliding $= x/\sqrt{h_0 R_x}$
Y	dimensionless coordinate in direction perpendicular to sliding $= y/\sqrt{h_0 R_x}$
α	angle between groove and Y-axis
λ	groove width
Λ	dimensionless groove width $= \lambda/\sqrt{h_0 R_x}$
η	viscosity

where R describes the liner texture. An example of such a surface is given in Fig. 1. The sliding direction is the X direction. In this work, the transient part is simulated as described in [2] where it is shown that

$$\frac{\partial H}{\partial T} = -2\frac{\partial H}{\partial X}.$$

In dimensionless form, it amounts to solving

$$\frac{\partial}{\partial X}\left(H^3\frac{\partial P}{\partial X}\right) + \frac{\partial}{\partial Y}\left(H^3\frac{\partial P}{\partial Y}\right) = \frac{\partial H_1}{\partial X}$$

where

$$H_1(X,Y) = 1 + \frac{X^2}{2} - R(X,Y).$$

In order to correctly describe the lubricant flow interactions with the liner texture, very fine grids are required. Therefore multigrid techniques have been used to build an efficient algorithm to solve this problem. A description of multigrid methods can be found in [22,23] or in [24] which mainly treats the lubrication problem.

Our present algorithm is mainly based on a paper by R. Alcouffe [1]. In this paper, an adaptation of the multigrid method for the diffusion equation with strongly discontinuous coefficients is proposed.

The equation considered is

$$-\nabla \cdot (D(X,Y)\nabla U(X,Y)) + \sigma(X,Y)U(X,Y) = f(X,Y)$$

The functions D, σ, f can have strong discontinuities on the domain Ω. Without cavitation, the equation we considered is of the same type taking $U = P$, $D = H^3$, $\sigma = 0$ and $f = \partial H/\partial X$. The liner texture induces large variations of the function H. Therefore we have adapted their ideas to our problem.

The domain Ω is a rectangle $[X_a, X_b] \times [Y_a, Y_b]$. It is decomposed into elementary cells with straight lines that are parallel to the axes. The equation is integrated over each cell Δ to get a discretized problem $LU=F$ with an operator L whose stencil at the point (i,j) reads:

$$L(i,j) = \begin{bmatrix} 0 & A_{i,j} & 0 \\ B_{i-1,j} & -A_{i,j} - A_{i,j-1} - B_{i,j} - B_{i-1,j} & B_{i,j} \\ 0 & A_{i,j-1} & 0 \end{bmatrix}$$

where the coefficients $A_{i,j}$ and $B_{i,j}$ are evaluated in terms of the values of the function $D = H^3$ at the center of the cells. They can be viewed as an analog of electrical conductances, respectively between nodes (i,j) and $(i,j+1)$ and between nodes (i,j) and $(i+1,j)$.

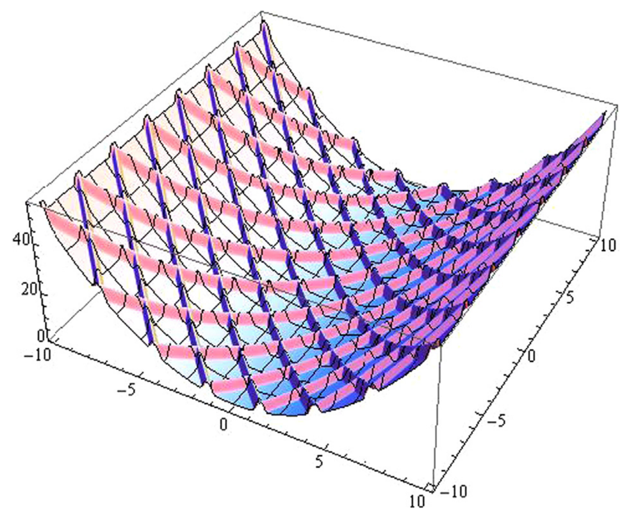

Fig. 1. Liner geometry model.

In what follows a superscript k will be used for a fine grid and $k-1$ for the next coarser grid. Electrical conductance rules with resistance in parallel or in series are used to determine the coarse grid coefficients $A^{k-1}_{i_C j_C}, B^{k-1}_{i_C j_C}$ of grid $k-1$ in terms of the fine grid coefficients $A^k_{i_F,j_F}, B^k_{i_F,j_F}, \ldots$ of grid k. The following notation is used below: $U^k = I^k_{k-1}U^{k-1}$ with I^k_{k-1} the interpolation operator; (i_C,j_C) designates a coarse grid point and (i_F,j_F) designates the associated fine grid point.

The interpolation operator I^k_{k-1} is first built using the continuity of $D\partial U/\partial X$ and of $D\partial U/\partial Y$. This is the main difference with the classical codes as described in [24] where the interpolation operators are based on the continuity of U. It yields a much better physical representation of the fine grid problem on the next coarser grid.The fine grid points corresponding to coarse grid points are injected. For the other points, the previously mentioned continuities enable us to derive interpolated values for $U^k_{i_F+1,j_F}$, $U^k_{i_F,j_F+1}$ and $U^k_{i_F+1,j_F+1}$. They finally amount to average weighted values of the surrounding coarse grid values whose weights are defined by the $A^k_{i,j}$ and $B^k_{i,j}$ coefficients. Details can be found in [1].

The restriction operator I^{k-1}_k is then determined by $I^{k-1}_k = (I^k_{k-1})^T$. A nine point stencil is obtained at the coarse grid point (i_C,j_C) associated with the fine grid point (i_F,j_F). Galerkin coarsening is used on the coarser grids. The operator L^{k-1} on grid $k-1$ is deduced from L^k by:

$$L^{k-1} = I^{k-1}_k\, L^k\, I^k_{k-1}$$

[1] Upper case letters generally represent dimensionless parameters.