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A computationally efficient mass-conservation-based, two-scale approach to modeling cylinder liner topography changes during running-in

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ABSTRACT

In an internal combustion engine, the surface topography of the cylinder liner changes continuously during running-in. The wear rates at different locations of the cylinder liner can vary greatly. These changes will significantly affect the lubrication and localized wear rate within the piston ring pack-liner system. In this paper, a computationally efficient, two-dimensional, two-scale homogenized mixed lubrication and wear model is developed to predict cylinder liner surface topography evolution during running-in. It takes cavitation effects into consideration by the mass-conservation-based Elrod-Adams model. To reduce computing costs, the Fischer-Burmeister-Newton-Schur (FBNS) algorithm was used to solve the cavitation model. To the author's knowledge, for the first time, this approach accurately predicts the wear rates at different locations along the stroke of a cylinder liner which has been divided into thirteen zones. The effects of the surface topography evolution on the lubrication, friction and wear properties are analyzed. The simulated wear results seem to be consistent with experimental results obtained by other researchers.

1. Introduction

Running-in is a transient process that occurs between interacting surfaces in relative motion [1]. During running-in, the friction and wear rate between two rough surfaces evolve with time. In an internal combustion engine, running-in is the beneficial wear and can enhance the piston ring pack friction performance, thus reducing the friction loss and oil consumption [2,3]. It also facilitates the enhancement of wear resistance and scuffing resistance between mating surfaces [4].

The honed cylinder liner surface topography is a critical factor affecting lubrication, friction and wear of piston ring pack-liner system. The cylinder liner is generally produced by the honing process to enhance performance. During mass production of cylinder liners, plateau honing process is commonly incorporated in order to reduce the expensive running-in period and the wear amount [5]. The final honed liner surface is composed of plateaus and valley components. These two elements play different roles in the ring-liner system. The plateau roughness is related to friction and wear, and the valley component is related to lubricant circulation and retention. During running-in of an internal combustion engine, cylinder liner wear measurement is highly challenging when compared to piston ring wear measurement. The cylinder liner wear occurs over a significantly larger surface area; therefore, the wear rate varies substantially at different locations of the liner. Measuring the wear depth by gauging the variation in bore diameter before and after wear is significantly affected by the cylinder liner distortion [6]. The estimation of cylinder liner wear by collecting radioactive wear debris from retrieved lubricant does not reflect the wear information at different locations [7,8]. Therefore, a more precise method of cylinder liner wear measurement during running-in is to evaluate the surface topography changes [9,10]. Gara et al. measured the cylinder liner wear using a replication method, and they proposed that wear volume could be computed by evaluating bearing ratio parameters before and after engine test [11]. Several researchers calculated the wear volume and depth by comparing bearing area curve before and after wear [6,12].

During running-in process, the cylinder liner surface topography evolves with time. However, real-time monitoring of the cylinder liner surface wear is remarkably challenging. Simulation of the surface topography evolution during running-in becomes a better option as it ensures decrease of cost and time of experimental investigations. Surface topography changes affect the lubrication properties of the ring-liner system, which, in turn, affects the wear process of the cylinder liner surface topography. Therefore, when simulating the running-in process of the ring-liner system, it is necessary to consider the mutual dependency of mixed lubrication and wear.

Deterministic simulation method [13] represents the surface topography to a high degree of accuracy and divides the computational domain into extremely small elements. However, the main drawback of

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Nomenclature

TDC	the top dead center
BDC	the bottom dead center
l	the local scale subscript
g	the global scale subscript
t	the slow time scale
τ	the fast time scale
M	the sampling point
$I(M)$	the measured surface profile
$P(M)$	the plateau roughness
$R(M)$	the reference surface or the waviness or form elements
x_1	the global scale coordinate -the axial direction
x_2	the global scale coordinate -the circumferential direction
β	a function of the honing angle
α	the honing angle
h_T	the groove description (m)
h_d	the depth of the groove (m)
w_0	using to adjust the width of the honing groove
$\bar{h}$	the average film thickness at a given separation (m)
p_0	the homogenized pressure solution (Pa)
η	the lubricant viscosity, Pa s
ρ	the lubricant density, kg m^{-3}
U	the speed of moving surface (m/s)
A_0	the homogenized flow factor matrix
a_{ij}	the flow factor in A_0
B_0	the homogenized flow factor vector
b_i	the flow factor in B_0
θ	the cavitation fraction
T_{liner}	the temperature distribution along the liner
T_{TDC}	the measured temperature at the top dead center
T_{BDC}	the measured temperature at the bottom dead center
L_0	the stroke length
L	the distance from the top dead center
x_{in}	the inlet position
x_a	the ring boundary position
p_1	the pressure at the inlet
q_{supply}	the oil supply flow rate at the inlet
h_{supply}	the oil film thickness at the inlet lubrication boundary location
y_1 and y_2	the local scale coordinate
l_1 and l_2	the evaluation length and width of the plateau area
p_{cl}	the asperity contact pressure on the local scale
u	the normal displacement
δ	the gap between the two undeformed surfaces
$\overline{p_c}$	the mean contact pressure
F_T	the applied load (N)
H	the hardness of the soft material (Pa)
K	the dimensionless wear coefficient
Vol	the worn volume (m^3)
s	the sliding distance (m)
k	the dimensional wear coefficient (Pa^{-1})
Δh	the wear depth increment (m)
Δs	the sliding distance increment (m)
p_{cg}	the contact pressure variation with time over one cycle on the global scale (Pa)
n	the zone number
r	the ring number
m	the stroke number
$\Delta\tau_{m,n}$	the time interval required for a piston ring to pass by
Δt	the time step of wear calculation
$\Delta\tau$	the time interval of one cycle
W_r	the ring width (m)
δh	the wear depth increment distribution over one cycle on the plateau (m)

the deterministic approaches is the remarkable amount of computer memory and computation time required, which could be unacceptable when actual surface topography is considered. An approach to solve this type of problems both accurately and efficiently is the multiscale treatment [14].

In the authors' previous work [15], a one-dimensional homogenized mixed lubrication and wear model based on two-scale homogenization technique was developed to study cylinder liner “zero-wear” process. In the model, the effects of the plateau and valley component are considered separately on the local and global scales to ensure high accuracy. Based on the Archard wear model, “zero-wear” of cylinder liner is quantitatively investigated on two scales: on the local scale, considering the superficial plateau wear, and on the global scale, considering the valley component wear. The developed model is verified by conducting experiments on a reciprocating tester. The results demonstrated that the developed model is adequately capable of predicting cylinder liner “zero-wear” process. By using actual measured topography as input, the homogenized mixed lubrication model is likely to be more accurate than the average flow model [16] with statistical parameters as input. In addition, this model is more suitable for non-Gaussian distribution engineering surface such as the honed cylinder liner surface [17]. Furthermore, compared with the deterministic mixed lubrication model [13], the homogenized mixed lubrication model can reduce computation time significantly as well as ensure accuracy [18].

In the present study, the surface topography evolution in different regions of cylinder liner during running-in process is studied considering actual engine conditions. Changes in the lubrication, friction, and wear performance of the ring-liner system owing to cylinder liner surface topography evolution during running-in are also investigated. The main contributions of this study are as follows: Firstly, to completely consider the influence of the cross-hatched texture, a two-dimensional two-scale homogenized mixed lubrication model is developed in this paper instead of the one-dimensional model used in the authors' previous work [15]. Secondly, cavitation in liquid lubrication films is common and directly affects pressure distribution. The Elrod-Adams (EA) [19] implementation of the Jakobsson-Floberg-Olsson (JFO) cavitation model [20,21] is adopted to enforce the conservation of the mass of lubricant. The Fischer-Burmeister-Newton-Schur (FBNS) algorithm proposed by Woloszynski et al. [22] is used to solve the cavitation model efficiently. The FBNS is demonstrated to be substantially faster than the traditional algorithms [23–25], yielding reduction in computation time by approximately two orders of magnitude. By using this algorithm, the computing efforts are substantially reduced, thus enabling the solution of wear problem of ring-liner system by using the two-dimensional model. Thirdly, the developed model is used to predict the evolution of the cylinder liner surface topography during running-in of an actual engine. The cylinder liner is divided into 13 sections along the stroke direction in order to accurately study the surface topography evolution at different locations of the liner. It is noteworthy that this study focuses on the cylinder liner wear during running-in. Moreover, the piston ring surface is typically much smoother and harder than the cylinder liner surface. Therefore, it is assumed that the piston ring is smooth, and the influence of ring wear on the wear process of the cylinder surface topography during running-in is temporarily omitted.

2. Theoretical model

2.1. Statement of the problem and assumptions

The model presented here depicts changes in cylinder liner surface