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Influence of measurement and filtering type on friction predictions between cylinder liner and oil control ring

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ABSTRACT

It is of a vital importance to reduce the frictional losses in the engines and hence the fuel/energy consumption. The major contributors to this are the oil control ring and cylinder liner interactions difficult to understand when comparing the experimental and theoretical results. The latter largely depend on the liner surface measurement and filtering type used in the simulations. Therefore, low-pass and high-pass filtrations were applied and the friction behaviors between the filtered liner surfaces and a perfectly flat ring surface were simulated for different engine speeds. The surfaces low-pass filtered by lower cutoffs showed higher friction, while the type of de-noising revealed about two and a half times higher friction. Stylus surfaces showed larger friction than the interference ones.

1. Introduction

The engineering surfaces are of a multiscale nature which consists of form, waviness and roughness. The form has been extensively studied elsewhere [1–4] and it is not a subject of this paper. The most of the models used to simulate the ring-liner interactions input 3D measured liner topographies which are filtered in a number of different ways to capture the effects of the surface features. Different measurement types/sizes/resolutions are used, either small size-high resolution or larger size-sparser resolution to reduce the computation time to a reasonable level. However, the measurement types/sizes/resolutions and most importantly the filtering techniques used affect the ratio between the boundary and hydrodynamic friction which in turn changes the friction prediction. The effect of the waviness and filtering seems to be overlooked and the researchers try to adjust the boundary friction to match the experimental results [5,6]. Optical white light interference and tactile stylus measurements are the most commonly used methods to measure the liner surfaces and simulate their function. The former has the advantage of high speed acquisition and better representation of the waviness but it generates artificial spikes because the surface has too high a gradient (such as the side of a honing groove) or there is a deposit on the surface that fails to reflect enough light. The latter does not generate spikes but it has: (i) long acquisition time, (ii) mechanical high frequency noise which is often suppressed by low-pass filtering and (iii) no reliable waviness representation in the stylus' lateral direction. To cope with the artificial spikes on the interference measurements, usually the data are filled in by interpolation based on the nearest neighbors and processed by median de-noising filter and/or morphological filters [7] or by Delaunay triangulation [8]. However, this modifies the asperities which come into contact and consequently affect the boundary friction. Obviously, the both measurement types are not perfect because they contain artifacts and the filtration is necessary. In addition, the most of the researchers use high-pass filters to filter out the waviness (i.e. to make the surface as flat as possible) [5,6,9,10] which also affects the boundary friction due to the more even contact distribution (see Fig. 1). In Figs. 1 and 3, there is no particular reason for choosing a threshold of 10% material ratio, selection of any percentage would illustrate the effect of filtering: the smaller the cutoff is, the more even contact distribution is. Unlike the stylus measurement (Fig. 3 left), the interference measurement (Fig. 3 right) has a reliable waviness representation and filtering out the waviness would mean filtering out the effect of the longer wavelengths on friction. The aim of this study is to map the differences among the instruments and filtrations for a proper identification of the "dominant scale" by a subsequent future comparison with the experimental friction. The best correlation between calculated and observed friction would pinpoint the "dominant scale" which eventually could be corrected in the

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Nomenclature

h	Film thickness, in m
Sa	Arithmetic mean height, in m
Sdq	Root mean square slope
Sds	Density of summits, in $1/m^2$
Sk	Core roughness depth, in m
Spk	Reduced summit height, in m
Sq	Root mean square height, in m
Ssc	Arithmetic mean summit curvature, in 1/m
Ssk	Skewness of height distribution, in m
Svk	Reduced valley depth, in m
Sz	Maximum height, in m

manufacturing of the liner surface for reducing the friction. The cutoffs used for quality control of the liners are not necessarily the "best ones" since the friction occurs at all the scales and finding the "dominant scale" would suggest what cutoff would be better to choose. More precisely, this paper seeks answers to the following questions: (i) How do the filtering techniques affect the overall friction? (ii) Are the friction changes significant and how much? (iii) How does the measurement type affect the friction prediction? These questions are crucial to understand the ring-liner friction before comparing with the experiments and will be addressed in this paper.

2. Surface characterization

In order to address the above questions, 3 × 2.5 mm surface measurements of a cylinder liner after a 320 h engine test of a heavy duty diesel truck engine were taken at the same place by using a stylus and a white light interferometer (see Figs. 2 and 3). A stylus instrument of Hommel-Somicronic 3CS with: a 2 μm tip radius, an angle of 90°, a height resolution of 6 nm, and a speed of 0.3 mm/s was used while the interference measurement was taken by a 2.5 × objective of a MicroXAM 100 HR white light interferometer with a height resolution of 3 nm. The lateral resolution of the stylus measurement was 5 μm in the both directions, but for the interference measurement it was 5.2 μm in axial and 4.4 μm in circumferential direction. Fig. 3 shows the difference between the waviness which is in the same time the contact pattern. The form has been removed by fitting a second order polynomial based on the least square method and subtracting it from the measured data (Fig. 2).

Different low-pass and high-pass filtrations, known in the standard ISO 25178, part 2 as S (short wavelength elimination) and L (long wavelength elimination) respectively, were applied. The surfaces were classified mainly into two categories according to the: (i) de-noising type and (ii) waviness suppression type, alluding that the de-noising comes before the high-pass filtering. In the first category, henceforth called **noise removal category**, the noise from the top of the surfaces was handled in three different ways resulting in five different surface types:

I. Stylus measurement with noise removed by a low-pass robust Gaussian filter, cutoff = 2.5 μm (called *Stylus ordinary*)
II. Stylus measurement with noise removed by a low-pass robust Gaussian filter, cutoff = 25 μm (called *Stylus 25um*)
III. Interference measurement without de-noising, only filling in the non-measured points (called *Interf ordinary*)
IV. Interference measurement with noise removed by a median and morphological filter (called *Interf outliers removed*). 7 × 7 pixels for averaging the isolated outliers by the median filter was used and closing followed by opening with a ball has been used for the morphological filter to treat the outliers on the edges.
V. Interference measurement with noise removed by a low-pass robust Gaussian filter, cutoff = 25 μm (called *Interf 25um*)

Regarding the **waviness suppression category**, the measurements were treated by:

1. No waviness suppression, only form removal by using a second order polynomial, surface called *FormRemoved*
2. Form removal + waviness suppression by a high-pass robust Gaussian filter with a 2500 μm cutoff, surface called *2500um*
3. Form removal + waviness suppression by a high-pass robust Gaussian filter with a 800 μm cutoff, surface called *800um*
4. Form removal + waviness suppression by a high-pass robust Gaussian filter with a 250 μm cutoff, surface called *250um*

In total 20 different surfaces, 5(de-noised) × 4(long-wavelength suppressed), were investigated. The surface conditioning for all the surfaces along with the computing of the 3D parameters (see Table 1) was done in the MountainsMap software [7]. The surfaces in Fig. 4 represent the waviness topographies obtained by low-pass filtering the form removed data in Fig. 3. The upper row of Fig. 4 for the stylus measurement stems from Fig. 3 left and the lower row of Fig. 4 for the interference measurement stems from the Fig. 3 right. As the cutoffs decrease from 2500 μm (see the leftmost column in Fig. 4) to 250 μm (see the rightmost column in Fig. 4) the amplitudes increase (see Sq and Sa parameters in the right part of Table 1) and the highest regions of the rightmost topographies correspond to contact patterns marked black in Fig. 3. The high-passed surfaces: *2500um, 800um and 250um* have been obtained by subtracting the respective waviness topographies from the form removed data. It is also interesting to note that the Sk (core roughness depth) and Spk (reduced summit height) parameters of the stylus measurements are greater than their interference counterparts. For example, Sk and Spk of *Stylus ordinary FormRemoved* are greater than Sk and Spk of *Interf ordinary FormRemoved* as well as Sk and Spk of *Stylus 25um FormRemoved* are greater than *Interf 25 um FormRemoved*. These parameters characterize the plateau part of the surface and are closely connected with the contact mechanics because it is the plateau part of the surface which comes first into contact. This also suggests that the high frequency noise on the plateaus of the stylus is higher than that of the interferometer even though the slope parameter Sdq is higher for the interferometer than for the stylus, which is partly due to mechanical–morphological filtering of the stylus tip of 2 μm.

3. Mixed lubrication simulation

A deterministic model described in [11] was used to calculate the contact and oil pressures (see Figs. 5–7) in the mixed lubrication regime. The model considers the full-scale lubrication behavior and the asperity interactions for different separations between a perfectly flat ring land surface and a rough liner topography (a patch extracted from the liner surface measurement). The flat surface emulates the contact land of a twin-land oil control ring, which is one of the major contributors to the engine friction losses of all other rings. From each surface type, 16 patches were extracted with