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Multiscale roughness analysis of engineering surfaces: A comparison of methods for the investigation of functional correlations

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ABSTRACT

This study investigates the correlations between the topography of different damaged rough surfaces and process conditions. Several surfaces are measured and compared to determine if they can be discriminated. The analysis is performed by using Gaussian Filtering, Wavelet Transform and a more recent approach named Discrete Modal Decomposition. Standardized 3D roughness parameters are computed for each multiscale method, filter (e.g., high-pass, low-pass and band-pass) and available scale. The relevance (i.e., the ability to discriminate surface topographies corresponding to different process conditions) is then investigated using a statistical analysis based on the MesRug™ expert system. The results indicate clear differences between the multiscale methods and show that the Wavelet approach is useful when characterizing localized surface defects while Gaussian Filtering is more appropriate for highly periodic morphological structures. For more complex topographies, this study also clearly shows that the Discrete Modal Decomposition exhibits compelling abilities that fall between those of the Gaussian and Wavelet approaches; this method is clearly more relevant than the Gaussian method in the case of localized defects and less relevant in the case of highly periodical structures and fractal surfaces ($1/f^{\alpha}$ spectrum). This can be explained by the modulated frequency/amplitude descriptors generated via the modal basis.

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1. Introduction

Many surface roughness parameters can currently be used to characterize the relationship between the surface roughness and its behaviour. The evolution of surface measuring machines has enriched the historical 2D parameters [1–3] by adding 3D parameters [4,3] that notably include the ability to better estimate anisotropy. A recurrent issue in functional surface roughness analysis is the ability to determine the relevant parameter(s) with respect to the function studied. The calculation of these roughness parameters also requires low-frequency components filtering (i.e., primary form and waviness). The filtering method choice and the appreciation of the threshold that limits the primary form, waviness,

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roughness and even micro-roughness are often arbitrary and influence the results. The use of a Multiscale Analysis (MA) method provides a more generic approach to this issue, but determining which method, surface parameter, and analysis scale is relevant with respect to an analysed function is still difficult. This paper aims to propose a statistical response to this issue and improve the effectiveness of functional surface topography analysis in tribology.

Three currently available multiscale techniques are compared in this study (Section 2). These techniques are the Gaussian Filtering (GF), the Discrete Wavelet Transform (DWT) and a more recent technique named Discrete Modal Decomposition (DMD). The statistical analysis is performed using the MesRug™ expert system (Section 4), which enables a generic calculation of the relevance indicators for each set of surface parameter, method, filter, and analysis scale. To ensure representative results, a large collection of surface measurements extracted from different tribological processes (Section 2) are analysed, and results are finally presented and synthesized in Section 5 .

2. Spectrum of the study

If surfaces and interfaces roughness analysis are of major interest to study and characterize many functions, the case of vibration phenomena during sliding contact is particularly interesting. For example, the roughness components of total hip implant interfaces induce friction that may be materialized by squeaking [5]. In other cases, an ideal fluid film lubrication regime is sought to minimize the produced vibration; an increased roughness on damaged surfaces can lead to a change in the lubrication regime [6–8]. Another vibration phenomena induced by roughness components is adhesion: Bengisu and Akay [9] have shown that the stick–slip model sums adhesive and deformation forces over all asperities and that the phenomenon was directly linked to roughness slope indicators. In the same way, abrasion modifies the surface morphology [10] and involves a change of vibration characteristics during a sliding process; wheel-raise noise in grinding processes is generally thought to be wheel and rail structural vibrations excited by a combination of the wheel and rail surface roughness components [11]; roller bearing vibrations are induced by excitations from surface waviness and roughness components through a lubricating film [12–14]; during rolling processes (i.e., vibration of the rolling mill structure), a non-steady-state lubrication and friction during rolling involves a change of roughness [15]; in a turning process, the choice of optimized cutting parameters is essential to control the required surface quality, and the difference between real and specified surface roughness is often caused by the influence of dynamic phenomena, such as a built-up edge, the friction of cut surface against tool point and other vibrations [16–18].

As roughness analysis often yields to a better understanding and control of the state of vibration during sliding contact on damaged surfaces, the spectrum of this study was composed by various sliding contact functions of those mentioned below. Each process/function is analysed within two classes of parameters, identified by A and B. Experiments are presented in Table 1, and a brief description of surface processes/function and measuring parameters is presented for each case study. If not mentioned, measurements are made by means of a White Light Interferometer (WLI) *Zygo NewView 7300* equipped with a high-speed camera at 320×240 pixels with a $20 \times$ Mirau objective lens. The working distance is 4.70 mm, the optical resolution is 0.71 μm and the spatial sampling is 1.09 μm for both *X*- and *Y*-axes. To obtain reliable statistical estimation, up to 20 elementary surfaces are measured and stitched together with an overlap of 20% to obtain measurements across surfaces with dimensions of 1.19×0.89 mm. The multi-scale techniques (i.e., GF, DWT and DMD) used in this paper are presented in Section 3.

2.1. Sendzimir cold rolling process

The studied rolling process is used to reduce an austenitic stainless steel strip from 3 to 0.49 mm. The rolling mill is a Sendzimir stand made up of 2 work rolls with diameters below 100 mm that rotate at between 300 and 650 rev/min. During the process, the rolls maintain pressure on the strip to reduce its thickness. The final thickness is obtained after 10 rolling passes, reducing the ratio from 25% to 10%. The roughness gradient between the sheet and blasted cylinder is important. Large crushing asperities occur but are constrained by the trapping of lubricant in the valleys. As the first three rolling passes are critical in the scrub of surface flaws, two specimens are extracted from the industrial process to be analysed, after 1 and 3 passes (Groups A and B, respectively). 700×525 μm measurements are obtained for each group.

Table 1
Surface processes/functions and associated case study.

Process/function	Study	Process/function	Study
Cold rolling	Influence of number of passes	Tribo corrosion	Wear on knee prosthesis
Moderate impact	Sand blasting	Plastic deformation	Cold rolling surfaces
Abrasion	Polishing surfaces	Adhesion	Adhesion on a molding process
Tribometer	Study with different lubricant	Surface polishing	Brushing
Super finishing	Belt finishing process	High impact	Shot peening
Low impact	Super finishing by ultrasonic sand blasting	Fatigue contact	fatigue with different lubricants
Tooled surface	Analyses of high precision turning	Grinding	Super finishing by grinding process

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