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Frequency-wise correlation of the power spectral density of asphalt surface roughness and tire wet friction

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ABSTRACT

Modern rubber friction theories predict the friction coefficient of rubber sliding against a rough surface. The key inputs of these theories are the roughness of the surface, the viscoelastic properties of the rubber, and the operating parameters like contact pressure, sliding speed and temperature. With regard to the surface roughness, it is important to know how road surface roughness should be analyzed. To increase the understanding on this topic, the surface topographies of different asphalt surfaces were measured and the roughness results at different spatial frequencies were correlated with wet tire friction results. The surface topographies were analyzed using a top-cutting technique and calculating the power spectral densities, or $C(q)$ functions of the resulting data. The value of the $C(q)$ function at each evaluated spatial frequency was then correlated individually to the friction results using linear regression. The results showed that the highest correlation was found at the highest evaluated frequencies, as limited by the spatial resolution of the measurement. When building a linear least-square fit model with the surface data and road surface temperature information, a good fit between the model parameters and the friction results could be achieved.

1. Introduction

The friction between rubber and road surfaces is of great importance in the context of traffic safety. It is well known that the main contributor to the gradual decrease in rubber-road friction during the lifetime of an asphalt concrete surface is the reduction in the surface micro-roughness, or polishing. Typically, due to methodological limitations, micro-roughness has been evaluated indirectly, using a friction test metric, such as the British pendulum number (BPN). Direct measurements of micro-roughness based on surface topography have typically been confined to laboratory studies, where the methods are easier to apply. This is typically due to restrictions in the portability of the instruments. There are, however, devices available that are portable and that can reach a spatial resolution in the order of 10 μm, while simultaneously having a field-of-view of over 1 cm, which is critical for covering wavelengths introduced by the largest aggregate size in the pavement. Usually these devices cannot be operated from a moving vehicle at traffic speeds, but are instead limited to static measurements. Another possibility is to take core samples of real road surfaces and then perform the topography measurements in a laboratory. This is of course a destructive method, which limits the number of possible applications.

In addition to the limitations in data acquisition, another constraint originates from the data analysis. Most studies where surface data are correlated to friction rely on simple surface metrics, such as the root-mean square roughness of the height profile, asperity sharpness, or relief angle. Surface profiles have also been analyzed qualitatively, but re-measuring the same exact line in a 2D-profile has proven to be difficult, even in laboratory measurements [1]. Often some level of correlation is indeed found, but typically it applies only to a limited set of surfaces [2,3].

In the context of modern rubber friction theories the height-difference correlation function and the power spectral density denoted here as $C(q)$ have been used as surface roughness metrics [4–6]. The benefit of these methods is that they characterize the roughness of the surface on all measured length scales, none of which can be a priori excluded from contributing to friction [6]. The power spectral density of the surface roughness can be defined as [4,6] follows:

$$C(q) = \frac{1}{(2\pi)^2} \int d^2x h(x) h(0) e^{-i\mathbf{qx}},$$

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where x is a two-dimensional vector in the mean plane of the surface and q is a two-dimensional wave vector, or spatial frequency. The corresponding wavelength for each value of q can be calculated as $2\pi/q$. The $C(q)$ function is essentially the Fourier transform of the autocorrelation function of the surface height data.

This spatial frequency-dependent description of the surface roughness is a central part of the calculation of kinetic friction by Persson, as can be seen in the following formula [6]. This version of the formula does not account for the flash temperatures presented in [7].

$$\mu = \frac{1}{2}\int_{q_L}^{q_1} dq q^3 C(q) P(q) \int_0^{2\pi} d\phi \cos \phi Im \frac{E(qv \cos \phi)}{(1-\nu^2)\sigma_0},$$

where q_L and q_1 are the limit spatial frequencies for the surface roughness, φ is the direction of the wave vector in relation to sliding, E is the complex viscoelastic modulus of the rubber, v is the sliding velocity, ν ("nu") is the Poisson's ratio of the rubber, and σ is the mean perpendicular pressure in the contact. $P(q)$ is the relative contact area and is in itself a function of all the above-mentioned variables, including $C(q)$. Because of the central role in this very promising rubber friction theory the $C(q)$ function was used in this study to characterize the asphalt surface roughness.

An aggregate gradation study including a power spectral density analysis has been done by Himeno et al. [8]. Other signal processing methods have also been applied to surface data, such as the Hilbert–Huang transformation [9] by Rado and Kane [10]. The results reported in these articles are compared to the ones from this study in Chapter 5. Wavelet analysis has also been employed to characterize surface roughness [11], albeit for longer wavelengths than the range covered here.

In this study, a portable static high-resolution 3D scanner was used to measure the surface roughness. The roughness was then characterized using $C(q)$ functions after specific post-processing steps. The values of the $C(q)$ at each spatial frequency were then separately correlated to tire wet friction results measured with a skid trailer on the same exact locations as the surface scans. A high number of surface scans were performed to account for the typical high local variations in road surface topography.

2. Surface topography evaluation depth

Roughness metrics from surface data are often calculated using the full range of the measurement. For a truly randomly rough surface it should be a good description of the surface in relation to rubber friction. However, asphalt road surfaces are typically quite skewed due to the compaction process during asphalt manufacturing and to the polishing effect of traffic. During the asphalt manufacturing the surface is compacted to increase the strength of the pavement and to create a smooth surface layer. This is typically done by using a heavy roller with a dynamic load. This process reorients the aggregates so that the top faces of the aggregates at the top of the surface tend to align with the compaction plane, reducing tire-road noise. Due to this alignment, the peaks of the surface profile are truncated, while the valleys remain in a more randomly rough state, which leads to skewness in the surface profile (see Fig. 2).

The topmost layer of the asphalt, which is in direct contact with the tire, therefore consists of aligned stone faces covered with bitumen and smaller sand and filler particles, while the spaces between the larger aggregates are filled with a mixture of bitumen, sand, and filler particles. When shear stresses are applied to the newly created surface, the bitumen and sand on top of and in between the large aggregates gradually starts to be removed, exposing the aggregate surfaces, as shown in [1]. The largest aggregates are typically made of crushed stone, which means that they have cracked surfaces with randomly rough characteristics. However, the polishing effect of tires only acts on the top layer of the surface, again leading to asymmetry in the height distribution. To account for these asymmetries, it has been suggested to cut the surface into two halves at the average plane followed by a division of the resulting $C(q)$ curve by the portion of the data belonging to the top half [12]. In this study, a similar approach is applied, with the distinction that instead of cutting the surface at the mean plane, a much thinner slice of the surface top is used. The thickness of the layer was initially estimated based on the depth of binder removal observed in measured surface data. A thickness of approximately 0.5 times the average root-mean-square (RMS) roughness of all analyzed surfaces was found as an initial estimate and is used throughout this study. The analysis was then repeated at different evaluation depths and a summary of these results is presented in Chapter 4.5 and illustrated in Fig. 11.

Another way to estimate the cutting depth would be to use a theoretical approach by means of *interfacial separation* as described by Persson [13] or *penetration depth* as described by Klüppel and Heinrich [5]. However, a direct implementation of these methods for the asphalt surfaces included in this study is difficult because the information on surface height skewness is not maintained in the surface descriptions used with these methods. For the former, the information is lost when calculating the autocorrelation of the height image. For the latter, it is lost similarly when calculating the height-difference correlation function. However, the asphalt surfaces studied here are quite skewed due to the compaction process during asphalt manufacturing, as seen in Fig. 2. Therefore, an extension of the above methods that takes into account the surface skewness would be highly desirable.

3. Materials and methods

The study was carried out by defining a 30×50 cm^2 rectangle on an asphalt road surface, and performing surface scans, British Pendulum friction tests, as well as tire braking tests with a skid trailer within the defined areas. The study included a total of 17 of such areas, some of which were repeated on different days to evaluate the repeatability of the method. The surfaces are located in three different European countries and the measurements were done between March and July 2013.

3.1. Road surfaces

All road surfaces included in the study had an asphalt concrete surface layer with maximum aggregate sizes ranging between 8 and 10 mm. The aggregate types varied from surface to surface and included, for example, diorite, dolomite, and basalt. The ages of the surfaces varied from a few months to several years. Each surface had been used extensively for braking tests but also less used portions of the surfaces were included in the study.

3.2. British pendulum number

The British pendulum numbers (BPNs) were measured according to the ASTM standard E303-93 using the standard rubber sample. However, for the results used in this study the measured BPN values were used directly without any temperature corrections. The tests were performed at nine different sub-locations within each marked area. The BPN values measured at these sub-locations were then averaged to provide one value for each marked area. It should be noted that each of the nine values is already an average of three tests. The asphalt was kept wet by manually pouring water on the surface before each test as described in the standard procedure.