TESTING, ANALYSIS AND COMPARISON FOR CHARACTERISTICS OF AGRICULTURAL FIELD AND ASPHALT ROAD ROUGHNESS

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农田地面与沥青路面不平度特征的测试、分析与比较

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ABSTRACT

Measuring and analysing the roughness of agricultural field and road have great significance for studying the characteristics of tractor dynamic response. This study was designed to analyse and compare the roughness characteristics of agricultural field and asphalt road profiles. A profiling apparatus was developed to measure field and road surface profiles of parallel tracks. The profile measurements were conducted in a grass field, a corn stubble field, a harvested potato field and on an asphalt road. The root mean square value and two spectrum parameters of surface profiles were calculated and analysed to investigate the roughness characteristics of fields and asphalt road. The results of the study indicate that for the values of the agricultural field and asphalt road surface roughness, waviness and roughness index are both positive associated with the root mean square value. Most of the waviness values of all measured field profiles were less than 2 with the average of 1.8, while the waviness values of all measured asphalt road profiles were greater than 2 with the average of 2.08. The roughness of both field and asphalt road profiles can be distinguished by the power spectral density fitting method. However, it has better performance in characterizing asphalt road profiles than characterizing field profiles with the power spectral density fitting method.

ABSTRACT

测量和分析农田和路面的不平度对研究拖拉机动态响应特性具有重要意义。本文为分析和比较农田地面与沥青路面的不平度特征，研制了一种地面不平度测量装置，分别在田间草地、玉米茬地、马铃薯收获地和沥青路面上开展了不平度测试试验。通过分析测试地面不平度的均方根及两个频谱特征参数，研究了农田地面和沥青路面的不平度特性。结果表明，农田地面和沥青路面的不平度频率指数和不平度系数均与不平度均方根呈正相关；测试的三种农田地面不平度频率指数值多数都小于 2，其平均值为 1.8，而沥青路面不平度频率指数值都大于 2，其平均值为 2.08；利用功率谱密度拟合方法可以有效识别农田地面与沥青路面的不平度特征，但用于沥青路面的不平度特征识别具有更好的效果。

INTRODUCTION

The road surface roughness is the main source of kinematic excitation of a moving vehicle, which plays an important role in ride comfort evaluation, dynamic load analysis and vehicle vibration simulation (*Cutini et al., 2017; Zhang et al., 2018*). Agricultural field and asphalt road can be considered as off-road and on-road conditions for dynamic analysis of tractor. There is a significant difference in the amplitude of tractor vibration when it travels on the different roads with the same speed (*Yiliyasi et al., 2016*). Thus, an accurate dynamic simulation of tractor is only possible if the terrain or road profiles tractor traversing on should be accurately acquired and modeled.

A detailed report on how to measure and interpret road surface profiles was introduced in *Sayers and Karamihas (1998)*. Road surface roughness, which plays a major role in vehicle ride dynamics, can be specified with the use of the Root Mean Square (*RMS*) elevation in the time domain or the Power Spectral Density (*PSD*) in the frequency domain (*Gorsich et al., 2003*). Some approaches based on *RMS* or spectrum parameters of typical roads and terrains were proposed in the past (*Lu et al., 2005; Phillip et al., 2014; Johannesson et al., 2016*).

However, limited research has been conducted on analysing the relationship between the profile parameters in characterizing the road surface roughness. An early research on measuring and modeling road surface roughness on bridge in spectral characteristics showed the integral of a filtered profile's *PSD* was the profile's *RMS* (*Honda et al., 1966*). A study about predicting *RMS* surface roughness using fractal dimension and spectrum parameters was carried out in (*Phillip et al., 2011*).

This study was intended to derive a proposal for comparing the roughness characteristics of agricultural field and asphalt road by measuring and analysing *RMS* and *PSD* parameters of surface profiles. The effect of characterizing field and asphalt road roughness with *PSD* fitting method was evaluated from the perspective of analysing the relation between the time-domain *RMS* and the spectrum parameters.

MATERIALS AND METHODS

Instrumentation

A surface profiling apparatus (profiler), which was mounted on the front counterweight of a tractor shown in Figure 1, was developed for the measurement of agricultural terrain and road profiles with parallel tracks. The surface profiles can be measured dynamically during tractor driving. The design and validation of the profiler was presented in a previous study (*Yan et al., 2019*) in detail. The overall accuracy of the profiler, expressed by the root mean square error (*RMSE*) value, was 3.6-4.7 mm and 4.5-5.1 mm with profiling speeds of 1.02 km/h and 2.56 km/h, respectively.

Fig. 1 - Profiling apparatus mounted on the front counterweight of a tractor

Profile measurements of agricultural field and asphalt road

The location of the profiling tests was situated at 40.21°N latitude and 111.34°E longitude in Hohhot, China, and the test was completed on October 7, 2019.

The profiling tests took place in a grass field, a corn stubble field (average stubble height of 10 cm), a harvested potato field and an asphalt road, as shown in Figure 2. During all profiling tests, the tractor was maintained at constant forward speeds of 2.56 km/h, which was verified by the RTK-GNSS system. The measurements for each type of field included five treatments, which were conducted on different tracks with test distances of around 100 meters. The average values of the field surface soil penetration resistance of the grass field, corn stubble field, harvested potato field were 187.6 $N \cdot cm^{-2}$, 246.3 $N \cdot cm^{-2}$ and 130.2 $N \cdot cm^{-2}$, respectively, while the average values of the field surface soil moisture content of the grass field, corn stubble field, harvested potato field were 3.24%, 1.82% and 4.26%, respectively (soil penetration resistance and soil moisture content were determined using a digital soil compaction meter and a digital soil moisture meter).

a) Grass field b) Corn stubble field

c) Harvested potato field d) Asphalt road

Fig. 2 - Agricultural field and asphalt road profiling measurement

THEORY

Spectrum parameters of profile PSD

The *PSD* representation is widely used either to assess the road roughness or as an input to vehicle dynamics (*Ma et al., 2013*). Previous proposals suggest the vertical displacement *PSD* of road or off-road terrain profiles can be represented by equation (1) in assumption that profiles are considered to be stationary random signals with a Gaussian distribution and zero value (*prEN, 2015; Múčka, 2016*).

$$G(n) = Cn^{-W} \tag{1}$$

where:

$G(n)$ is the *PSD* of vertical road profile displacement, [m^3];

C is the roughness index, [m^{3-W}];

n is the spatial frequency, [m^{-1}];

W is the wavelength distribution, named waviness, which is the exponent of the fitted PSD.

According to Eq. (1), the distribution of road surface *PSD* in spatial frequency domain can be approximated by means of a straight line in the log-log chart, which can be called the *PSD* fitting method. Two spectrum parameters, waviness W and roughness index *C* of vertical profiles can be determined by the *PSD* fitting method.

From Eq. (1), two spectrum parameters, roughness index *C* and waviness W, determine the characteristics of road surface roughness. Parameter *C* is proportional to the roughness variance, while W quantifies the distribution of the road profile wavelength content between particular spatial frequency bands.

Relation among RMS and two spectrum parameters

According to Parseval's relation (*Steven, 1999*), since the time and frequency domains are equivalent representations of the same signal, they must have the same energy. When the mean value of road profile sample is zero, the variance of the profile is equal to the mean square value. Also, the RMS of road profile is equal to the standard deviation, which determine the relationship between the *RMS* and the *PSD* of the road surface profile. That is the *RMS* of the vertical displacement of the profile and the square root of the area under the displacement *PSD* should result in the same value, which represent the energy of the vertical profile. The calculation formulas are as follows:

$$RMS = \left(\int_{n_1}^{n_2} G(n)dn\right)^{1/2} \tag{2}$$

Eq.(1) can be substituted into Eq.(2), resulting in Eq.(3).

$$RMS = \sqrt{\frac{C(n_2^{(1-W)} - n_1^{(1-W)})}{1-W}} \tag{3}$$

where: n_1 is lower spatial frequency;

n_2 is upper spatial frequency.

The relation among the W, *C* and *RMS* determined by the Eq. (3) is simulated in Figure 3. The spatial frequency is selected from 0.011 m^{-1} to 2.83 m^{-1} according to the ISO 8608 standard (*ISO 8608, 1995*). The coordinate variable *C* in the Figure 6 covers the range of eight roughness index grades which is from 16×10^{-8} to 262144×10^{-8} in the ISO 8608 standard, while coordinate variable *W* changes from 1 to 3.5 which covers a wide range of road profiles (*Múčka and Kropáč, 2009*). Figure 3 shows *RMS* is positive related with *C* and W, which codetermine the energy of road roughness. Therefore, W is an important parameter which should be investigated in the testing and analysis of road surface roughness, although the ISO 8608 suggests W =2 in the road classification.

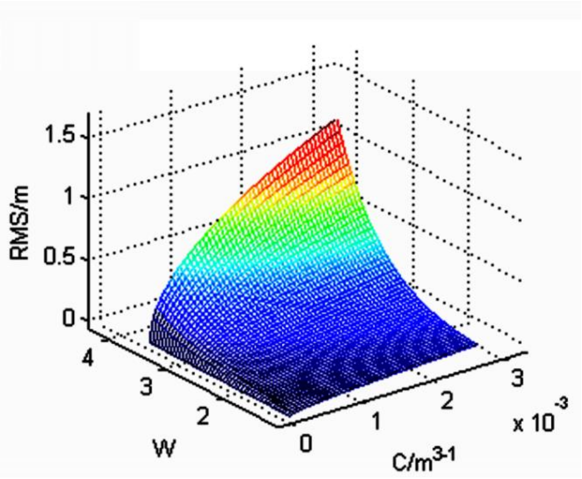


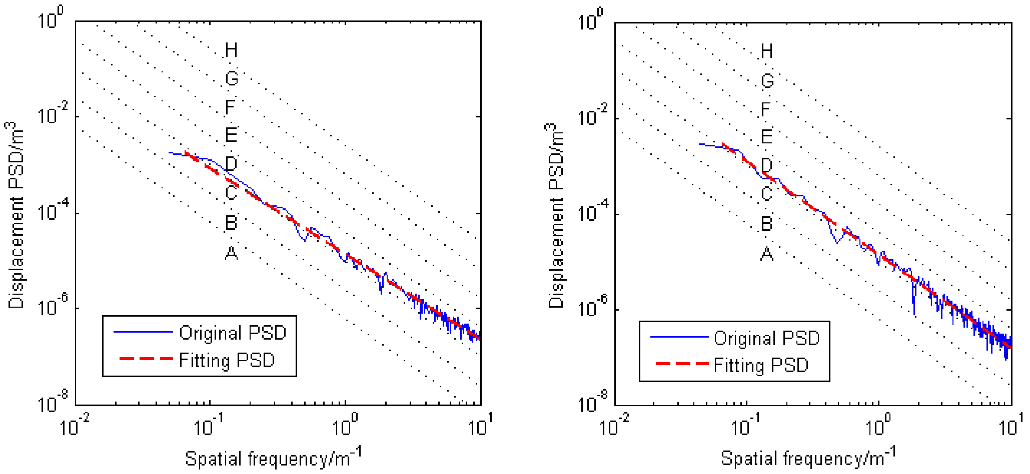
Fig. 3 - The relation between the *W*, *C* and *RMS*

Relation between *RMS* and two spectrum parameters of surface profile is established by Eq. (3). Theoretically, root mean square of measured profile (RMS_m) and root mean square calculated (RMS_c) by W and *C* according to Eq. (3) should be equivalent with the assumption of *PSD* characterization fulfilled. However, the profiles of road or terrain can't totally meet the assumption, which cause the deviations between RMS_m and RMS_c. Therefore, it can be concluded that the closer the RMS_c is to RMS_m, the better profile data meets the assumption condition of *PSD* characterization, which can be used to check the effect of characterizing the profiles with the *PSD* fitting method.

RESULTS

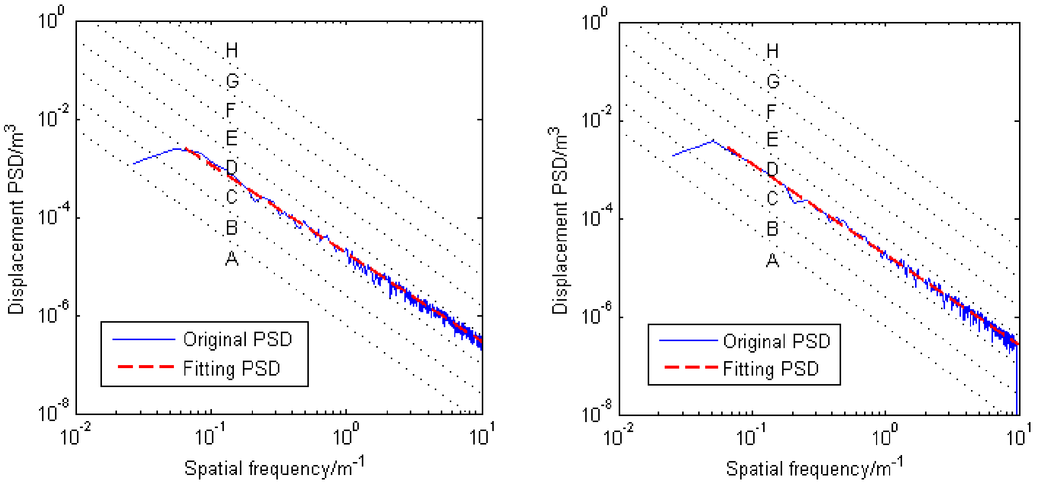
Comparison on the profile values between the agricultural field and asphalt road

The measured data of profile displacements from both wheel tracks were analysed and transformed into the *PSD* of agricultural field and asphalt road roughness by use of the Fourier analysis. Calculated *PSD* curves of tested field profiles are illustrated in Figure 4-6 (Take one group of test data as an example in each kind of the field terrains).



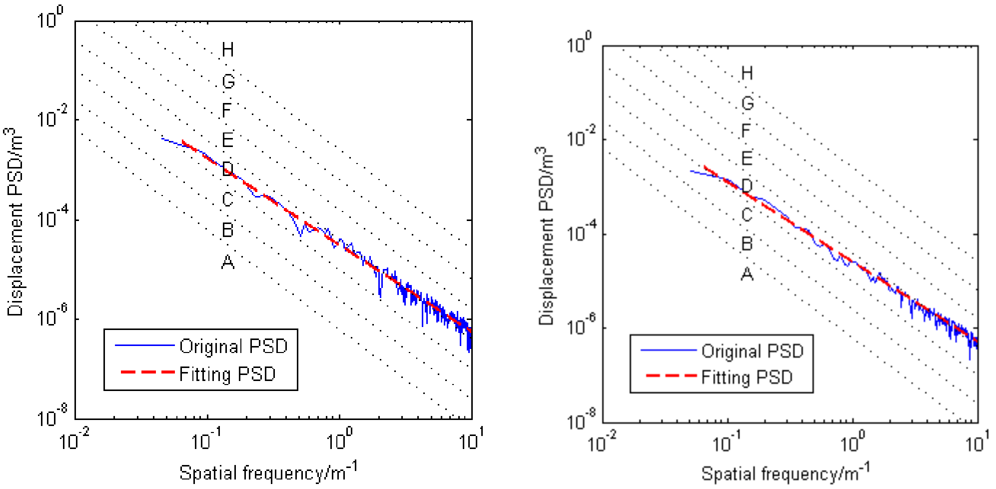
a) Left track ***b) Right track***

Fig. 4 - *PSD* of the measured profiles from one test treatment in the grass field



a) Left track ***b) Right track***

Fig. 5 - *PSD* of the measured profiles from one test treatment in the corn stubble field



a) Left track ***b) Right track***

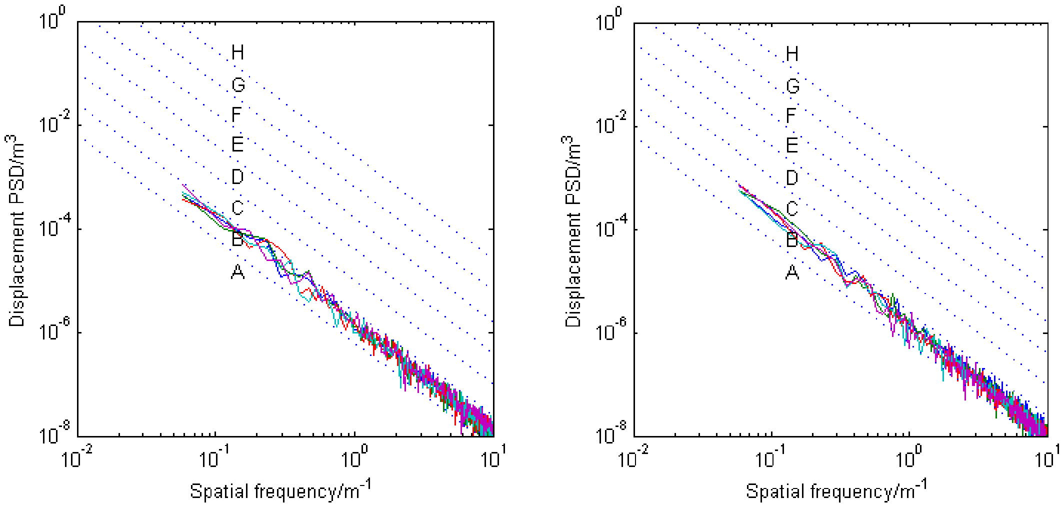
Fig. 6 - *PSD* of the measured profiles from one test treatment in the harvested potato field

In Figure 4, the roughness index C of the grass field profiles at the left and right wheel tracks are 1182×10^{-8} and 1254×10^{-8} respectively, and the waviness W values are 1.78 and 1.95 respectively. In Figure 5, the roughness index C of the corn stubble field profiles at the left and right wheel tracks are 1687×10^{-8} and

1625×10^{-8} respectively, and the waviness W values are 1.8 and 1.84 respectively. In Figure 6, the roughness index C of the harvested potato field profiles at the left and right wheel tracks are 2866×10^{-8} and 2568×10^{-8} respectively, and the waviness W values are 1.74 and 1.69 respectively.

ISO 8608 suggests waviness $W = 2$. However, according to W values of Figure. 4-6, it was found that the W values of the three measured field profiles from both tracks were less than 2 with the average of 1.8. In the case of the asphalt road, *PSD* shown in Figure 7, the irregularities of measured profiles in the asphalt road measurement seem to be close to each other.

Figure 7 shows the *PSD* curves of the tested asphalt road profiles. On each of these figures, the limits of eight roughness levels according to ISO 8608 are also shown for reference. Each *PSD* was fitted with a straight line in log-log scale using the least-mean-square method, then two spectrum parameters W and C of each profile were obtained according to Eq. (1).



a) Left track ***b) Right track***

Fig. 7 - *PSD* of the measured profiles from five test segments on the asphalt road

The spectrum parameters of all measured field profiles and asphalt road profiles were summarized in Table 1. Time-domain profile values RMS_m and RMS_c were also investigated and presented in the Table 1. RMS_m is the root mean square of the measured profile calculated from the test data, while RMS_c is the root mean square calculated by the waviness W and the roughness index C according to the Eq. (3).

By comparing the characteristics of the field surface profiles and asphalt road surface profiles (Table 1), it was found that the differences between the left and right track parameters of field surface roughness, such as W, C, RMS_m and RMS_c were greater than that of the asphalt road in most cases. Meanwhile, most of the W values of all measured field profiles were less than 2 with the average of 1.8, while the W values of all measured asphalt road profiles were greater than 2 with the average of 2.08, which indicates that the ratio of the short wave energy to the all wavelength energy of the field profile is greater than that of the asphalt road. Also, a relatively obvious difference was found in the W values of the same type of field with different test routes or left and right track of the same route, which was particularly evident in the harvested potato field test results. However, no obvious differences could be found between the W values of the asphalt road profiles for different treatments or two tracks with the same treatment. In addition, the W values of the same tested asphalt road were close to each other.

It can be observed from the Table 1 that the roughness values of field profiles including roughness index C, RMS_m and RMS_c, which were tested on the parallel tracks, are significantly higher than those of the asphalt roads. The results show roughness energy of field surface is much larger than that of asphalt road surface. Meanwhile, it was also found that the RMS_m which is positively associated with the roughness energy of surface profile increased with the increase of W and C values. This corroborates the simulation result of Figure 3.

Effect of characterizing the field and asphalt road profiles by the PSD fitting method

In order to check the effect of characterizing the field and asphalt road profiles by the *PSD* fitting method, the percentage differences between the RMS_m and RMS_c of the same track profiles were calculated and presented in Table 1. The range of the percentage difference between the RMS_m and RMS_c of the same track field profiles was 0.3%-41.9%, and the mean values of the left and right tracks were 13.1% and 15.8%, respectively. The range of the percentage difference between the RMS_m and RMS_c of the asphalt road profiles was 2.2%-10.6%, and the mean values of the left and right tracks were 6.7% and 6.2%, respectively. Therefore, the percentage difference between the RMS_m and RMS_c of the field profiles is much larger than that of the asphalt road profiles, which illustrates it has better performance in characterizing asphalt road profiles than characterizing field profiles with the *PSD* fitting method.

Table 1

The waviness *W*, roughness index *C*, RMS_m and RMS_c values of profile in each test

Test code	Waviness W		Roughness index *C* [10^{-8} m^{3-W}]		RMS_m [10^{-3} m]		RMS_c [10^{-3} m]		Percentage difference between the RMS_m and RMS_c [%]	
	Left track	Right track	Left track	Right track	Left track	Right track	Left track	Right track	Left track	Right track
A1	1.78	1.95	1182	1254	24.7	26	22.5	30.9	8.9	15.8
A2	1.91	2.25	931	945	22	26.7	24.8	46	11.3	41.9
A3	2.05	1.83	878	968	25.2	26.2	30.8	22.1	18.1	15.6
A4	1.76	1.66	1147	1194	24.1	25.8	21.4	18.6	11.2	27.9
A5	1.68	1.77	1081	1031	21.6	22.3	18.3	20.6	15.3	7.6
B1	1.8	1.84	1687	1625	27.9	29.2	27.7	29.1	0.7	0.3
B2	1.79	1.99	1142	1096	20.7	22.9	22.4	31	7.6	26.1
B3	1.88	1.83	1166	1161	22.4	21.5	26.4	24.2	15.2	11.2
B4	2	1.91	1695	1704	32.1	29.7	39.2	33.6	18.1	11.6
B5	1.77	1.82	1650	1520	26.5	25.7	26.1	27.2	1.5	5.5
C1	1.74	1.69	2866	2568	36.4	35.3	32.7	28.6	10.1	19
C2	1.4	1.57	3541	3063	31.3	30.3	21.9	25.9	30	14.5
C3	1.83	1.98	2290	2114	32	34.9	34	42.2	5.9	17.3
C4	1.29	1.69	3265	1577	23.9	26.7	18.3	22.4	23.4	16.1
C5	1.65	1.85	1428	1044	24.6	25.5	20	23.7	18.7	7
D1	2.1	2.13	20	17	4.8	4.8	5.1	5	5.9	4
D2	2.08	2.14	18	16	4.2	4.4	4.7	4.9	10.6	10.2
D3	2.12	2.09	16	20	4.4	4.6	4.7	5	6.4	8
D4	2.06	2.02	19	20	4.3	4.3	4.6	4.4	6.5	2.2
D5	2.03	2.07	22	17	4.5	4.1	4.7	4.4	4.3	6.8

Different test code letters A, B, C, D indicate the grass field, the corn stubble field, the harvested potato field and the asphalt road, respectively. Different numbers 1, 2, 3, 4, 5 indicate five segments of each profile test.

CONCLUSIONS

Based on the measured data and analysis presented above, the following conclusions have been developed.

For the values of the agricultural field and asphalt road surface roughness, W and *C* are both positive associated with the *RMS*. Most of the *W* values of all measured field profiles were less than 2 with the average of 1.8, while the W values of all measured asphalt road profiles were greater than 2 with the average of 2.08, which indicates the ratio of the short-wave energy to the all wavelength energy of the field profile is greater than that of the asphalt road. The differences between the left and right track values of the field surface roughness, such as W, *C*, RMS_m and RMS_c are greater than that of the asphalt road in most cases, while these values of the same tested asphalt road with different treatments are close to each other.

The effect of characterizing the field and asphalt road roughness by *PSD* fitting method was evaluated from the view of analysing the relation between the time-domain *RMS* value and the spectrum parameters. The result shows the roughness of both field and asphalt road profiles can be distinguished by the *PSD* fitting method. However, it has better performance in characterizing asphalt road profiles than characterizing field profiles with the *PSD* fitting method.

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