Normalisation of macro-roughness of road and bridge pavements based on natural harmonic analysis

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Abstract. The paper proposes new methods of normalisation of geometrical parameters of macro-roughness of road and bridge pavements on the basis of natural harmonic analysis (in development of Fourier series application), applied, among others, for steel-reinforced concrete and metal orthotropic slabs of bridge structures.

1 Introduction

The paper proposes new methods of normalisation for geometric parameters of macro-roughness of road and bridge pavements on the basis of natural harmonic analysis (in development of Fourier series application), applied, among others, for steel-reinforced concrete and metal orthotropic slabs of bridge structures.

Critical analysis of the existing methods of macro-roughness (macrotexture) determination allows us to draw a conclusion about the strong dependence of the change in the obtained results on the change in the measurement base [1-6]. That is, the measurement result is not invariant with respect to the measurement base. Besides, the question of irregular textures and the application of statistical analysis is not solved. How to determine conversion factors for in-service macro-roughened pavements has not been established in the standards [7-10].

The problem is that the methods of approximation in the form of Fourier harmonic analysis used in the established practice in the problems of evenness and macro-roughness of road and bridge pavements usually give an error of up to 300 % already at the fifth harmonic. Meanwhile, there is a method of approximation of planetary motion, namely natural harmonic analysis, which does not have such disadvantages [11].

2 Materials and methods

Numerical analyses of surface geometry measurements are discussed in ISO 3274, ISO 4287, ISO 4288, ISO 5436-1 and ISO 12085. They define a pavement texture formed in two dimensions when a sensor (the tip of a needle or laser spot) continuously touches or shines

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on the pavement surface then, and moves along a line on the profile surface. Its motion is described along the plane of the surface then, and also in a direction normal to the plane of the surface.

The profile can be viewed as a stationary, random function of distance along the surface. Using Fourier analysis, such a function can be mathematically represented as an infinite series of sinusoidal components of different frequencies (and wavelengths), each with a given amplitude and initial phase. For typical continuous and surface profiles, the profile is analysed by Fourier components and contains a continuous distribution of wavelengths. The texture wavelength in ISO 13473 is the inverse of the spatial frequency.

The deviation of the pavement from a true flat surface with characteristic dimensions along the surface of 0.5 mm to 50 mm is determined, corresponding to texture wavelengths from one third of an octave band, including a range of 0.63 mm to 50 mm from the centre of the wavelengths. The depth of the resulting texture is not based on a 'plane' but on the analysis of a slightly curved surface that mimics the contact of the tyre with the road surface (Figure 1).

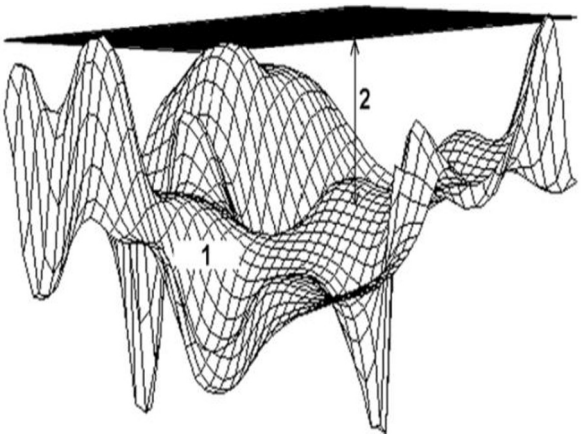


Fig. 1. Three-dimensional texture approximation: 1 - texture (approximation), 2 - distance from the base plane

The average profile measurement (depth) is defined in accordance with ISO 13473-1 and ASTM E1845. The volumetric method of microtexture measurement (patch method) is standardised in ISO 10844: 1994, annex, EN 13036-1 and ASTM E965. The sand patch method has been used worldwide for many decades. The standards state that for mathematically correct definitions of random and periodic signals, it is suggested to refer to random signal processing.

To obtain a macro-roughness texture curve it is necessary to remove any slope or long-wavelength component (slope suppression), and to drive the mean level to zero. This is achieved by upper-pass filtering or least-squares subtraction from the profile (ISO 13473-1). An illustration of defining the wheel-macro-roughness interaction by means of an envelope is shown in Figure 2.

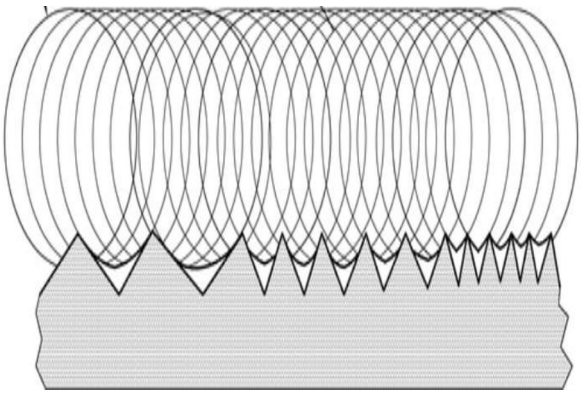


Fig. 2. Illustration of determining the wheel-macro-roughness interaction by means of an envelope

According to the standard, the profile curve is analysed using digital or analogue filtering techniques in order to determine the magnitude of its spectral components at different wavelengths or spatial frequencies.

The European Union standards were chosen as the closest normative analogues: EN ISO 13473-3:2009 Characterisation of pavement texture by use of surface profiles. Part 3. Specification and classification of profilometers and EN ISO 13473-5:2009 Characterisation of pavement texture by use of surface profiles -- Part 5: Determination of megatexture.

According to EN ISO 13473-5:2009, texture is subdivided into micro-, macro- and megatexture according to ISO 13473-2 [7-9]. Surface roughness with longer wavelengths than the megatexture is referred to as bumps and usually takes the form of irregularities in the surface. The profile can be considered as a stationary, random distance dependent function along the surface. Using Fourier analysis, such a function can be mathematically represented as an infinite series of sinusoidal components of different frequencies and wavelengths, each with a given amplitude and initial phase. For typical continuous and surface profiles, the profile of its Fourier components contains a continuous distribution of wavelengths.

According to ASTM E1274-03 Measuring Pavement Roughness Usinga Profilograph, it is possible to extract the macro roughness component from the total measurement signal obtained from the primary measurement transducer [7-10].

An alternative to these methods is natural harmonic analysis of dynamical systems for macro roughness texture analysis [11].

The difference from the conventional Fourier series decomposition is of fundamental importance. By taking an arbitrary interval from the domain of existence of a function, one can decompose not only periodic functions, but also any function, even non-periodic ones, into Fourier series. The problem solved by Fourier series expansion is the approximation of the existing graph of an arbitrary function by a series of periodic functions. Outside the chosen interval, it may not coincide at all with the obtained decomposition.

For the decomposition according to the method of the authors of the article, the existence of natural rather than regular bases of approximation by a harmonic series is fundamental. By determining the return period of oscillations, the problem of determining the inherent natural oscillations of the system is solved.

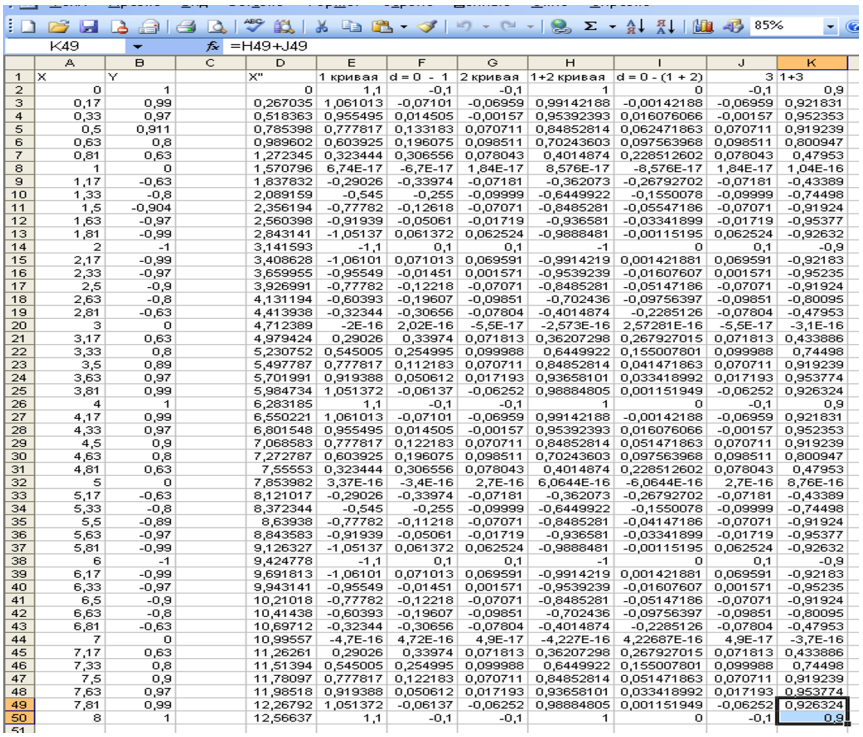
The difference between natural oscillations and arbitrary regular ones is that the periods of natural oscillations are preserved not only in an arbitrary interval, but also beyond it. If on an arbitrary interval a function is decomposed into arbitrary periodic functions, this decomposition is valid only within the interval of the decomposition, and

the series of decomposition into a series of natural oscillations retains its legitimacy for any interval in the past and future. If we take the return period as the interval of the Fourier series decomposition, then the Fourier series decomposition will be as close as possible to the natural oscillation series decomposition. In the general case they may not coincide. The reason for the mismatch is that in the Fourier series expansion not only the intervals of the expansion are arbitrary, but also the parameters of the expansion. So the angular frequencies, and hence the periods of oscillations are taken as a natural series of numbers ω, 2ω, etc. And when decomposing into a series of natural oscillations, the periods are determined not by the formal rules of decomposition, but by the natural properties of the system (macro-roughness textures).

Based on this fundamental difference, it follows that Fourier series expansion can be carried out without preliminary analysis. One can take any interval of existence of any function, no matter whether it is periodic or non-periodic, and purely formally obtain a decomposition into a series of trigonometric functions. In natural harmonic analysis, a function that can be decomposed into a natural harmonic series must be periodic in the whole domain of definition. Before decomposition into a natural harmonic series can begin, "return intervals" must be defined.

The difference between the natural harmonic series decomposition and the Fourier decomposition is that in the Fourier series decomposition the obtained trigonometric functions are obtained in a purely formal way and do not carry any information about the actual vibrations of the dynamic system (macro roughness textures). In natural harmonic analysis, the decomposition proceeds strictly by physically existing vibrations.

An illustration of an example of the application of natural harmonic analysis to the geometry (texture) of macro-rough road and bridge pavements is given in Figures 3-5.



K49 =H49+J49

	A	B	C	D	E	F	G	H	I	J	K
1	X	Y		X"	1 кривая	d = 0 - 1	2 кривая	1+2 кривая	d = 0 - (1 + 2)	3	1+3
2	0	1		0	1,1	-0,1	-0,1	1	0	-0,1	0,9
3	0,17	0,99		0,267035	1,061013	-0,07101	-0,06959	0,99142188	-0,00142188	-0,06959	0,921831
4	0,33	0,97		0,518363	0,955495	0,014505	-0,00157	0,95392393	0,016076066	-0,00157	0,952353
5	0,5	0,911		0,785398	0,777817	0,133183	0,070711	0,84852814	0,062471863	0,070711	0,919239
6	0,63	0,8		0,989602	0,603925	0,196075	0,098511	0,70243603	0,097563968	0,098511	0,800947
7	0,81	0,63		1,272345	0,323444	0,306556	0,078043	0,4014874	0,228512602	0,078043	0,47953
8	1	0		1,570796	6,74E-17	-6,7E-17	1,84E-17	8,576E-17	-8,576E-17	1,84E-17	1,04E-16
9	1,17	-0,63		1,837832	-0,29026	-0,33974	-0,07181	-0,362073	-0,26792702	-0,07181	-0,43389
10	1,33	-0,8		2,089159	-0,545	-0,255	-0,09999	-0,6449922	-0,1550078	-0,09999	-0,74498
11	1,5	-0,904		2,356194	-0,77782	-0,12618	-0,07071	-0,8485281	-0,05547186	-0,07071	-0,91924
12	1,63	-0,97		2,560398	-0,91939	-0,05061	-0,01719	-0,936581	-0,03341899	-0,01719	-0,95377
13	1,81	-0,99		2,843141	-1,05137	0,061372	0,062524	-0,9888481	-0,00115195	0,062524	-0,92632
14	2	-1		3,141593	-1,1	0,1	0,1	-1	0	0,1	-0,9
15	2,17	-0,99		3,408628	-1,06101	0,071013	0,069591	-0,9914219	0,001421881	0,069591	-0,92183
16	2,33	-0,97		3,659955	-0,95549	-0,01451	0,001571	-0,9539239	-0,01607607	0,001571	-0,95235
17	2,5	-0,9		3,926991	-0,77782	-0,12218	-0,07071	-0,8485281	-0,05147186	-0,07071	-0,91924
18	2,63	-0,8		4,131194	-0,60393	-0,19607	-0,09851	-0,702436	-0,09756397	-0,09851	-0,80095
19	2,81	-0,63		4,413938	-0,32344	-0,30656	-0,07804	-0,4014874	-0,2285126	-0,07804	-0,47953
20	3	0		4,712389	-2E-16	2,02E-16	-5,5E-17	-2,573E-16	2,57281E-16	-5,5E-17	-3,1E-16
21	3,17	0,63		4,979424	0,29026	0,33974	0,071813	0,36207298	0,267927015	0,071813	0,433886
22	3,33	0,8		5,230752	0,545005	0,254995	0,099988	0,6449922	0,155007801	0,099988	0,74498
23	3,5	0,89		5,497787	0,777817	0,112183	0,070711	0,84852814	0,041471863	0,070711	0,919239
24	3,63	0,97		5,701991	0,919388	0,050612	0,017193	0,93658101	0,033418992	0,017193	0,953774
25	3,81	0,99		5,984734	1,051372	-0,06137	-0,06252	0,98884805	0,001151949	-0,06252	0,926324
26	4	1		6,283185	1,1	-0,1	-0,1	1	0	-0,1	0,9
27	4,17	0,99		6,550221	1,061013	-0,07101	-0,06959	0,99142188	-0,00142188	-0,06959	0,921831
28	4,33	0,97		6,801548	0,955495	0,014505	-0,00157	0,95392393	0,016076066	-0,00157	0,952353
29	4,5	0,9		7,068583	0,777817	0,122183	0,070711	0,84852814	0,051471863	0,070711	0,919239
30	4,63	0,8		7,272787	0,603925	0,196075	0,098511	0,70243603	0,097563968	0,098511	0,800947
31	4,81	0,63		7,55553	0,323444	0,306556	0,078043	0,4014874	0,228512602	0,078043	0,47953
32	5	0		7,853982	3,37E-16	-3,4E-16	2,7E-16	6,0644E-16	-6,0644E-16	2,7E-16	8,76E-16
33	5,17	-0,63		8,121017	-0,29026	-0,33974	-0,07181	-0,362073	-0,26792702	-0,07181	-0,43389
34	5,33	-0,8		8,372344	-0,545	-0,255	-0,09999	-0,6449922	-0,1550078	-0,09999	-0,74498
35	5,5	-0,89		8,63938	-0,77782	-0,11218	-0,07071	-0,8485281	-0,04147186	-0,07071	-0,91924
36	5,63	-0,97		8,843583	-0,91939	-0,05061	-0,01719	-0,936581	-0,03341899	-0,01719	-0,95377
37	5,81	-0,99		9,126327	-1,05137	0,061372	0,062524	-0,9888481	-0,00115195	0,062524	-0,92632
38	6	-1		9,424778	-1,1	0,1	0,1	-1	0	0,1	-0,9
39	6,17	-0,99		9,691813	-1,06101	0,071013	0,069591	-0,9914219	0,001421881	0,069591	-0,92183
40	6,33	-0,97		9,943141	-0,95549	-0,01451	0,001571	-0,9539239	-0,01607607	0,001571	-0,95235
41	6,5	-0,9		10,21018	-0,77782	-0,12218	-0,07071	-0,8485281	-0,05147186	-0,07071	-0,91924
42	6,63	-0,8		10,41438	-0,60393	-0,19607	-0,09851	-0,702436	-0,09756397	-0,09851	-0,80095
43	6,81	-0,63		10,69712	-0,32344	-0,30656	-0,07804	-0,4014874	-0,2285126	-0,07804	-0,47953
44	7	0		10,99557	-4,7E-16	4,72E-16	4,9E-17	-4,227E-16	4,22687E-16	4,9E-17	-3,7E-16
45	7,17	0,63		11,26281	0,29026	0,33974	0,071813	0,36207298	0,267927015	0,071813	0,433886
46	7,33	0,8		11,51394	0,545005	0,254995	0,099988	0,6449922	0,155007801	0,099988	0,74498
47	7,5	0,9		11,78097	0,777817	0,122183	0,070711	0,84852814	0,051471863	0,070711	0,919239
48	7,63	0,97		11,98518	0,919388	0,050612	0,017193	0,93658101	0,033418992	0,017193	0,953774
49	7,81	0,99		12,26792	1,051372	-0,06137	-0,06252	0,98884805	0,001151949	-0,06252	0,926324
50	8	1		12,56637	1,1	-0,1	-0,1	1	0	-0,1	0,9
51											

Fig. 3. Illustration of the application of natural harmonic analysis. Initial data set. Numerical series obtained as a result of approximation

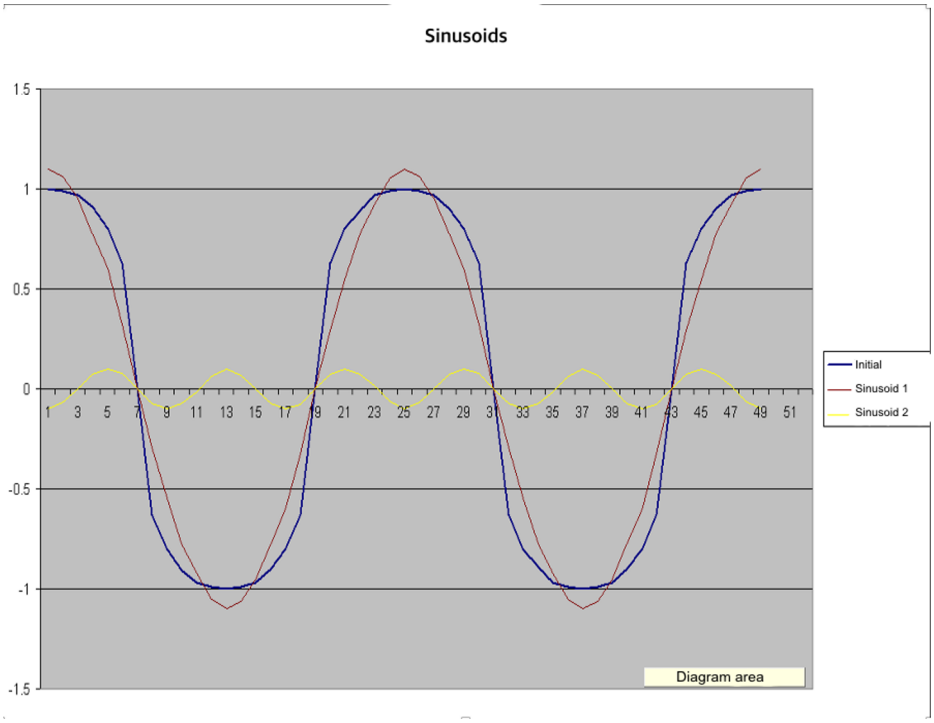


Fig. 4. Illustration of the application of natural harmonic analysis. Graphs of profilogram measurement results, calculations of the first and second harmonics

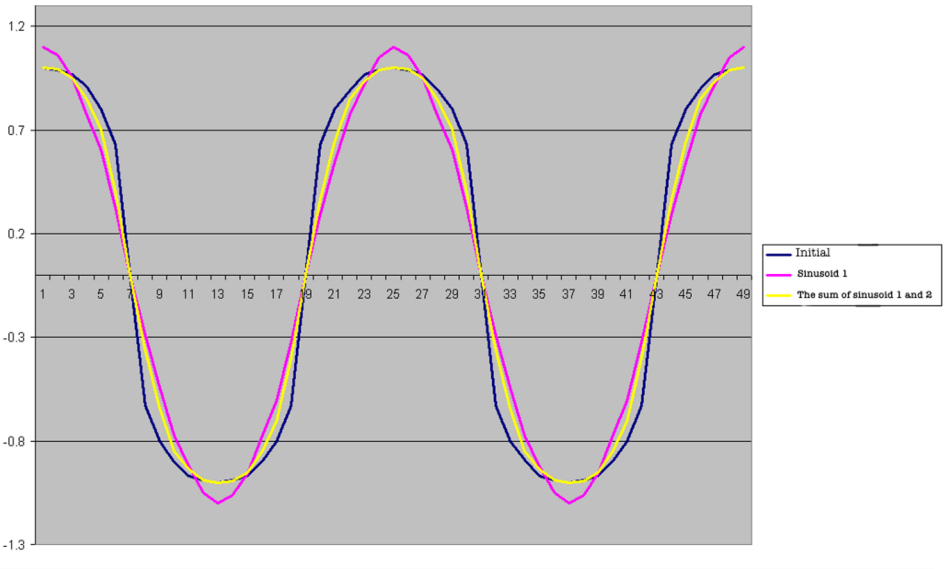


Fig. 5. Illustration of the application of natural harmonic analysis. Graph of the profilogram, first and sums of the first and second harmonics

3 Discussion

The formulas for the application of natural harmonic analysis are formed from the table of Figure 3.

Curve 1:
$s_1 = 1.1* \cos((PI/2)*f)$;
Curve 2:
$s_2 = 0.1 * \cos((3*PI/2)*f)$.
Total sum of the first and second harmonics:
$s = 1.1* \cos((PI/2)*f) + 0.1 * \cos((3*PI /2)*f)$;
here f is frequency of the curve under study.

The maximum deviation (calculation error) was 0.267927. The least squares calculation error was 7.178489 %.

It should be noted that in contrast to the application of Fourier series, where the error accumulates, for natural harmonic analysis the error value remains at the same level.

The example of application of natural harmonic analysis confirms its scope of definition, large period; reliability; meaningfulness and accuracy of calculation, as well as a fundamental difference from the application of Fourier series.

4 Conclusions

1. The results of the analytical review allowed us to justify the prospect of further investigation of macro-rough road surfaces, which are characterised by a relative increased variation in the height of protrusions and variation in the depth of depressions.

2. For the first time a method of technical normalisation of the macro-roughness geometry of road or bridge pavement (including the slab of a bridge structure) on the basis of natural harmonic analysis based on the approximation of the macro-roughness surface texture geometry by the established regular gauges has been proposed.

3. An example of the application of natural harmonic analysis confirms its scope of definition, large period; validity; meaningfulness and accuracy of calculation, as well as a fundamental difference from the application of Fourier series.

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