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Mechanical vibration — Road surface profiles — Reporting of measured data

National foreword

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Mechanical vibration — Road surface profiles — Reporting of measured data

Vibrations mécaniques — Profils de routes — Méthode de présentation des résultats de mesures

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Contents

Page

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

The committee responsible for this document is ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

This second edition cancels and replaces the first edition (ISO 8608:1995), of which it constitutes a minor revision. The following changes have been made:

- normative references have been updated;
- subclause numbering has been adjusted;
- figures have been made language independent;
- bibliography has been updated;
- editorially revised.

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Introduction

The purpose of this document is to facilitate the compilation and comparison of measured vertical road profile data from various sources. It therefore specifies a uniform method of reporting data from one-track and multiple-track measurements.

It specifies how measurements are to be reported, but not how the measurements are to be made. The measuring equipment can influence the results of the measurement; therefore certain characteristics of the measuring system have also to be reported.

Annex A is an example of a report which meets the minimum requirements of this document.

Annex B gives means of approximately characterizing specific road profiles in order to facilitate the division of road profiles into general classifications. A general classification is also given. A curve fitting method is presented for characterizing spectral data.

Annex C provides general guidance for the use of road profile statistical data for simulation studies and for related studies such as evaluation of comfort, suspensions and road profiles.

Annex D discusses the processing of the power spectral density (PSD) with the fast Fourier transform (FFT) technique. A discussion on the statistical precision is also given.

Mechanical vibration — Road surface profiles — Reporting of measured data

1 Scope

This document specifies a uniform method of reporting measured vertical road profile data for either one-track or multiple-track measurements.

It applies to the reporting of measured vertical profile data taken on roads, streets and highways, and on off-road terrain. It does not apply to rail-track data. Measurement and processing equipment and methods are not included.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61260-1, *Electroacoustics — Octave-band and fractional-octave-band filters — Part 1: Specifications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
spatial frequency
reciprocal of the wavelength

Note 1 to entry: The spatial frequency is expressed in cycles per metre (cycles/m).

3.2
power spectral density
PSD
limiting mean-square value of a signal per unit frequency bandwidth

Note 1 to entry: For a one-sided spectrum, the area located between the graphic plot and the horizontal axis in a linear plot should be equal to the variance σ^2 of the original signal for the evaluated frequency range. This leads to a doubling of the spectral amplitude when the calculation process is only estimating the spectrum for positive frequencies.

3.3
displacement PSD
power spectral density of the vertical road profile displacement

3.4
velocity PSD
power spectral density of the rate of change of the vertical road profile displacement per unit distance travelled (slope of the vertical road profile)

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3.5
acceleration PSD

power spectral density of the rate of change of the slope of the vertical road profile per unit distance travelled

3.6
decolouring

procedure to eliminate the influence of the transfer function of the measuring system on the power spectral density

Note 1 to entry: The raw power spectral density should be decoloured before any further processing by dividing it by the square of the modulus of the measuring equipment transfer function.

3.7
smoothing

averaging process in which a data block is shifted and averaged

Note 1 to entry: In this document, “unsmoothed PSD” means the power spectral density as calculated from the measured data, i.e. with the bandwidths used in or following from the calculations and which are different from those indicated in Table 2. The term “smoothed PSD” is the power spectral density which is obtained after using the averaging process described in 5.1.2.

4 Symbols

The symbols used in this document are given in Table 1.

Table 1 — Symbols

Symbol	Description	Unit
B_e	Frequency resolution	cycles/m
f	Time frequency	Hz
$G_d(.)$	Displacement PSD	m^3
$G_v(.)$	Velocity PSD	m
$G_a(.)$	Acceleration PSD	m^{-1}
$G_1(.)$	PSD of track 1	—
$G_2(.)$	PSD of track 2	—
$G_{12}(.)$	Cross spectrum between tracks 1 and 2	—
l	Wheelbase	m
n	Spatial frequency	cycles/m
t	Time	s
v	Vehicle speed	m/s
γ^2	Coherence function	—
σ^2	Variance	
ω	Angular frequency (= $2\pi f$)	rad/s
Ω	Angular spatial frequency (= $2\pi n$)	rad/m

NOTE The indication (.) means that the parameter of the function can be spatial frequency (n) or angular spatial frequency (Ω).

5 Uniform method of reporting

5.1 One-track data

5.1.1 Description of the road profile

5.1.1.1 General

The road profile shall be described by one or both of the following methods, with preference for the first, the displacement PSD.

The reporting of the non-smoothed data is always required.

5.1.1.2 First method — Displacement PSD: $G_d(.)$

The road profile shall be described by the power spectral density (PSD) of its vertical displacement. The report shall include the displacement PSD versus (angular) spatial frequency, both on logarithmic axes. The dimensions are metres cubed (m^3) versus reciprocal metres (cycles/m and rad/m).

Two scales shall be given on the ordinate, one for $G_d(n)$ and one for $G_d(\Omega)$. Both n and Ω scales shall be indicated in the abscissa. The grid, however, shall only be drawn for $G_d(n)$ and n (see Figure A.2, for example).

5.1.1.3 Second method — Acceleration PSD: $G_a(.)$

The acceleration power spectral density (PSD) is an allowed alternative method of reporting data.

In this case, the road profile shall be described as the PSD of its acceleration in terms of the rate of change of the slope of the road surface per unit distance travelled. The dimension of the acceleration PSD is reciprocal metres (m^{-1}).

The scales shall be logarithmic on both axes. Two scales shall be given on the ordinate, one for $G_a(n)$ and one for $G_a(\Omega)$. On the abscissa, both n and Ω shall be indicated. The grid, however, shall only be drawn for $G_a(n)$ and n.

5.1.1.4 Relationship between the two reporting methods

The relationship between the two reporting methods (see 5.1.1.2 and 5.1.1.3) is given by Formulae (1) and (2):

$$G_a(n) = (2\pi n)^4 \cdot G_d(n) \tag{1}$$

$$G_a(\Omega) = \Omega^4 \cdot G_d(\Omega) \tag{2}$$

5.1.1.5 Spatial frequency range

The reported PSD shall be restricted between the limits allowed by the measuring equipment. For the report, the user may select any spatial frequency range appropriate to his/her particular road surface, problem and product.

The measured surface depends on the measuring equipment, which has a certain smoothing effect. This equipment is to be reported (see Note 4 and 5.3.5.2.1).

NOTE 1 Figure C.1 gives the relationship between the vehicle speed, the spatial frequency and the time frequency. Knowledge of the frequency and speed characteristics for a given class of vehicles makes it possible to choose the useful limits for that class of vehicle (e.g. on-road or off-road vehicles).

NOTE 2 For the lower limit, the spatial frequency need not in general be measured lower than 0,01 cycles/m for on-road vehicles and 0,05 cycles/m for off-road vehicles.

NOTE 3 The enveloping effect of the tyre acts as a low-pass filter for the road vibration input to the vehicle. This effect depends on the size and construction of the tyre. For general on-road measurements, this results in a recommended upper limit of 10 cycles/m. Of course for suspension vibration purposes, the interesting upper limit depends on the maximum allowed speed on the particular road. For noise purposes, the interesting upper limit may be much higher, and may go as high as 1 000 cycles/m.

NOTE 4 Due to the tyre width there is also an enveloping effect in the lateral direction. This means that for vibration purposes, the mean of the footprint is usually measured. The width depends on the problem (e.g. vibration, noise) and the product (e.g. motorcycle tyres, truck tyres). For general on-road measurements not intended for a specific product, a track of about 100 mm wide is often used for vibration purposes. For noise purposes, a point measurement is often used.

NOTE 5 For off-road measurements, care needs to be taken when interpreting the high frequencies. For soft (e.g. sandy) surfaces, short undulations could be flattened by the wheel load and filtered out. For hard (e.g. stone) surfaces, however, only the enveloping effect of the tyre acts as a filter. In this situation, the surface needs to be described accurately in the data sheet (see 5.3.5.3.2).

NOTE 6 Annex B gives recommended methods for the characterization of the road profile and for the fitting of the measured data.

5.1.2 Presentation of the smoothed power spectral density

When the power spectral densities are calculated with a constant bandwidth method, their representation in a log-log diagram give an appearance or visual impression at high frequencies which over-emphasizes the fluctuations of the PSD generated by the real power distribution and by the statistical noise.

For this reason, the PSD shall also be represented in a smoothed form, i.e. by the mean PSD in the following frequency bands:

- octave bands from the lowest calculated frequency (except zero) up to a centre frequency of 0,031 2 cycles/m (0,196 3 rad/m);
- one-third-octave bands from the last octave band up to a centre frequency of 0,25 cycles/m (1,570 8 rad/m);
- for the rest of the frequency range, one-twelfth-octave bands up to the highest calculated frequency.

The centre frequencies to be used for the calculation of the smoothed PSD are given in Table 2.

Table 2 — Centre frequencies and cut-off frequencies for PSD smoothing, expressed in spatial frequency n

Exponent EXP	**Lower cut-off frequency** n_l cycles/m	**Centre frequency** $n_c = 2^{EXP}$ cycles/m	**Upper cut-off frequency** n_h cycles/m
Octave bands			
–9	0,001 4	0,002 0	0,002 8
–8	0,002 8	0,003 9	0,005 5
–7	0,005 5	0,007 8	0,011 0
–6	0,011 0	0,015 6	0,022 1
–5	0,022 1	0,031 2	0,044 2

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Table 2 *(continued)*

Exponent EXP	**Lower cut-off frequency** n_l cycles/m	**Centre frequency** $n_\mathrm{c} = 2^{\mathrm{EXP}}$ cycles/m	**Upper cut-off frequency** n_h cycles/m
One-third-octave bands			
−4,333	0,044 2	0,049 6	0,055 7
−4	0,055 7	0,062 5	0,070 2
−3,667	0,070 2	0,078 7	0,088 4
−3,333	0,088 4	0,099 2	0,111 4
−3	0,111 4	0,125 0	0,140 3
−2,667	0,140 3	0,157 5	0,176 8
−2,333	0,176 8	0,198 4	0,222 7
−2	0,222 7	0,250 0	0,280 6
One-twelfth-octave bands			
−1,833	0,272 6	0,280 6	0,288 8
−1,750	0,288 8	0,297 3	0,306 0
−1,667	0,306 0	0,315 0	0,324 2
−1,583	0,324 2	0,333 7	0,343 5
−1,500	0,343 5	0,353 6	0,363 9
−1,417	0,363 9	0,374 6	0,385 6
−1,333	0,385 6	0,396 9	0,408 5
−1,250	0,408 5	0,420 4	0,432 8
−1,167	0,432 8	0,445 4	0,458 5
−1,083	0,458 5	0,471 9	0,485 8
−1	0,485 8	0,5	0,514 7
−0,917	0,514 7	0,529 7	0,545 3
−0,833	0,545 3	0,561 2	0,577 7
−0,750	0,577 7	0,594 6	0,612 0
−0,667	0,612 0	0,630 0	0,648 4
−0,583	0,648 4	0,667 4	0,687 0
−0,500	0,687 0	0,707 1	0,727 8
−0,417	0,727 8	0,749 2	0,771 1
−0,333	0,771 1	0,793 7	0,817 0
−0,250	0,817 0	0,840 9	0,865 5
−0,167	0,865 5	0,890 9	0,917 0
−0,083	0,917 0	0,943 9	0,971 5
0	0,971 5	1	1,029 3
0,083	1,029 3	1,059 5	1,090 5
0,167	1,090 5	1,122 5	1,155 4
0,250	1,155 4	1,189 2	1,224 1
0,333	1,224 1	1,259 9	1,296 8
0,417	1,296 8	1,334 8	1,374 0
0,500	1,374 0	1,414 2	1,455 7
0,583	1,455 7	1,498 3	1,542 2
0,667	1,542 2	1,587 4	1,633 9

Table 2 *(continued)*

Exponent EXP	**Lower cut-off frequency** n_l cycles/m	**Centre frequency** $n_c = 2^{EXP}$ cycles/m	**Upper cut-off frequency** n_h cycles/m
0,750	1,633 9	1,681 8	1,731 1
0,833	1,731 1	1,781 8	1,834 0
0,917	1,834 0	1,887 7	1,943 1
1	1,943 1	2	2,058 6
1,083	2,058 6	2,118 9	2,181 0
1,167	2,181 0	2,244 9	2,310 7
1,250	2,310 7	2,378 4	2,448 1
1,333	2,448 1	2,519 8	2,593 7
1,417	2,593 7	2,669 7	2,747 9
1,500	2,747 9	2,828 4	2,911 3
1,583	2,911 3	2,996 6	3,084 4
1,667	3,084 4	3,174 8	3,267 8
1,750	3,267 8	3,363 6	3,462 1
1,833	3,462 1	3,563 6	3,668 0
1,917	3,668 0	3,775 5	3,886 1
2	3,886 1	4	4,117 2
2,083	4,117 2	4,237 9	4,362 0
2,167	4,362 0	4,489 8	4,621 4
2,250	4,621 4	4,756 8	4,896 2
2,333	4,896 2	5,039 7	5,187 4
2,417	5,187 4	5,339 4	5,495 8
2,500	5,495 8	5,656 9	5,822 6
2,583	5,822 6	5,993 2	6,168 8
2,667	6,168 8	6,349 6	6,535 7
2,750	6,535 7	6,727 2	6,924 3
2,833	6,924 3	7,127 2	7,336 0
2,917	7,336 0	7,551 0	7,772 3
3	7,772 3	8	8,234 4

NOTE A small overlap exists between the lowest one-twelfth-octave band and the highest one-third-octave band. This overlap maintains the values 0,5; 1; 2; 4 as centre frequencies in the one-twelfth-octave bands. This makes it convenient to calculate the road characterization (see B.4) immediately from the one-twelfth-octave band smoothing.

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The mean PSD in a defined band should be calculated as given by Formula (3):

$$G_s(i)=\frac{\left[\left(n_L+0,5\right)\cdot B_e-n_l(i)\right]G\left(n_L\right)+\sum_{j=n_L+1}^{n_H-1}G\left(j\right)\cdot B_e+\left[n_h(i)-\left(n_H-0,5\right)\cdot B_e\right]G\left(n_H\right)}{n_h(i)-n_l(i)} \tag{3}$$

where

$G_s(i)$	is the smoothed PSD in smoothing band i;
$n_H=\text{INT}\left(\frac{n_h(i)}{B_e}+0,5\right)$	(n_h: see Table 2);
$n_L=\text{INT}\left(\frac{n_l(i)}{B_e}+0,5\right)$	(n_l: see Table 2).

The other symbols are as defined in Table 1. INT is the integer function.

The first and the third terms of the right hand side of Formula (3), respectively, calculate the parts of the original n_L and n_H in the calculated smoothing band i.

If this scheme cannot be followed, due to the calculations, the differences shall be noted in the report.

The same rules shall be followed when the smoothing is to be done in angular spatial frequency.

The same rules shall be followed for analogue computation.

A small and easy supplementary calculation following the processing of the smoothed PSD leads to the characterization of the road profile as described in Annex B.

5.2 Multiple-track data

The multiple-track road profile data shall be described as the PSD curves of each track as described in 5.1, and their relationship curves expressed as their coherence function [see Formula (4)].

$$\gamma^2=\frac{G_{12}^2(.)}{G_1(.)\cdot G_2(.)} \tag{4}$$

When more than two tracks are measured, the most travelled track near the edge of the road shall be taken as the reference track for the calculation of coherence functions.

The curve shall be smoothed as described in 5.1.2.

5.3 Report

5.3.1 General

The report shall contain one or more curve sheets and general information.

5.3.2 One-track data curve sheet

The curve sheet for one-track data shall contain the non-smoothed PSD and the smoothed PSD. When the information is given on one sheet, the separate curves should be carefully differentiated.

The PSD curve sheet shall also include the information given in 5.3.4.1.3, 5.3.4.1.4, 5.3.4.1.5, 5.3.5.3.1 and 5.3.5.3.2.

It is also recommended to indicate on the data sheet the road profile characterization described in Annex B, i.e. the general and octave-band characterization of the road and the fitted PSD (see Figures A.3 and A.5 for examples).

5.3.3 Multiple-track data curve sheet

For multiple-track data, the sheets of each PSD shall be reported as described in 5.3.2, together with a similar curve sheet for their coherence function. This sheet shall contain the smoothed coherence curve. The track width shall be indicated on this sheet.

When the information is given on one sheet, the separate curves should be carefully differentiated.

5.3.4 Parameters of analysis

5.3.4.1 For all forms of spatial analysis, the following information shall be reported.

5.3.4.1.1 The analysis method used, analogue or digital.

5.3.4.1.2 Pre-processing filters shall be reported in terms of cut-off spatial frequency, slope (dB/octave) and type of filter (e.g. Butterworth). In the case of the digital analysis, this includes the anti-aliasing filter.

5.3.4.1.3 The resolution bandwidth: in the case of a relative constant bandwidth analysis, it is sufficient to state the proportion octave bandwidth only.

5.3.4.1.4 The real distance travelled of the data, in metres, analysed and reported.

In order to quantify wavelengths of 100 m with a statistical precision of 60 % at a spatial frequency resolution of 0,01 cycles/m, the distance travelled shall be at least 1 000 m.

In some cases, it may be impossible or perhaps of no interest to reach this limit, e.g. for short roads or for the study of special forms of surfaces. In this case, a remark in the report is required. For a discussion of statistical precision, see Annex D.

5.3.4.1.5 The statistical precision of spectral estimates of the data: in the case of a relative constant bandwidth analysis, the statistical precision of the narrowest bandwidth shall be reported. The statistical precision shall be stated as ± % value, calculated for a 95 % confidence level (i.e. the statistical precision shall be stated as 1,96 times the normalized standard error) on the basis of random error.

5.3.4.2 For analogue spectral analyses, the following information shall be reported, in addition to that specified in 5.3.4.1.

5.3.4.2.1 The class of bandwidth filters in accordance with IEC 61260-1.

5.3.4.2.2 The slopes (dB/octave) and type of constant bandwidth filter.

5.3.4.3 For digital spectral analyses, the following information shall be reported, in addition to that specified in 5.3.4.1.

5.3.4.3.1 The specific method used (such as fast Fourier transform, mean lagged product, continuous digital filter).

5.3.4.3.2 The sampling spatial frequency.

5.3.4.3.3 The sampling window function and correction factor used.

5.3.4.3.4 The reported resolution bandwidth, if it is different from the analysis bandwidth (e.g. when frequency smoothing is used).

5.3.5 Test conditions

5.3.5.1 The date of the measurement shall be reported.

5.3.5.2 The instrumentation used shall be reported as follows.

5.3.5.2.1 Short description of the measuring system.

a) Mechanical design.

b) Scanning device

- in the case of a contacting device (e.g. a wheel): description of the design (e.g. a soft wheel), mass, tyre pressure, tyre dimensions, effective diameter, nominal test load and dimensions of the contact area under nominal test load;
- in the case of a non-contacting device (e.g. a radar system): resolution, dimensions of the effective measured area, etc.

c) The capability of the equipment to take into account slope bias and transverse slope effects over long distances and long wavelengths.

5.3.5.2.2 A flowchart showing transducers, telemetry, recorder, filters, etc.

5.3.5.2.3 The instrumentation and calibration chain of the measuring system should be carefully reported. Details of the design, the guaranteed transfer function and the accuracy should be given, either in the report or in a source reference.

5.3.5.2.4 The cut-off frequencies of any filter used in conjunction with the recording of the data.

5.3.5.3 The road or terrain description shall be reported as follows.

5.3.5.3.1 Definition of the road: country, road number, location, village, direction and, if possible, a small map. Also, traffic density [annual average daily traffic (AADT), when possible], typical vehicle speed and other relevant descriptive information shall be reported.

5.3.5.3.2 The road profile shall be reported with respect to at least the type of surface (concrete pavement, compacted soil, cobblestone, etc.) and the surface condition (new pavement, rutted road, poorly maintained, etc.), the grade (longitudinal slope), the cross-fall (lateral slope) and the curve radius (if any). In the case of off-road measurements, the cone penetration resistance of the soil should be reported together with a reference or a description of the measurement method used (see ISO 22476-1, ISO 22476-3 and Reference [18]).

5.3.5.3.3 Definition of the measured track: distance from the measured track to the near side of the road. A sketch of the road, with indication of the tracks reserved for bicycles, parking and traffic is recommended. All unusual facts should be indicated.

5.3.5.3.4 A photograph of the road shall be included. It shall be taken from a height of 1,4 m (approximately the height of the eyes of the driver of a passenger car). The photograph shall also show a two-dimensional scale indication and the position of the measured tracks.

5.3.5.3.5 If two- or multiple-track data are given, they shall be described as in 5.3.5.3.3. The distance between the tracks shall also be given.

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Annex A
(informative)

Example of a report

A.1 General

This annex contains fictitious data arranged to form an example for two-track reporting which meets the minimum requirements of this document. However, the measuring system description and the photograph are omitted.

The parts of Figure A.3 and Figure A.5 placed in a double frame are the recommended characterizations of the road profile described in Annex B. They are not required, but recommended.

The format of the data sheets is not standardized.

NOTE The numbers in parentheses refer to the subclauses in this document.

A.2 Parameters of analysis

Analysis (5.3.4.1.1, 5.3.4.3.1): FFT

anti-aliasing filter (5.3.4.1.2): 48 dB/octave

Butterworth: 0,5 cycles/m low-pass

Sampling spatial frequency (5.3.4.3.2): 1,4 cycles/m

Sampling window function (5.3.4.3.3): Hanning

Correction factor (PSD) (5.3.4.3.3): $1{,}63^2$

A.3 Test conditions

Measuring system (5.3.5.2.1, 5.3.5.2.3, 5.3.5.2.4): ...1)

Flow chart (5.3.5.2.2), see Figure A.1.

Figure A.1 — Flow chart of the measuring system

---

1) Detailed description or reference given.

A.4 Road description

Road definition (5.3.5.3.1), see Figure A.2:

traffic: AADT, 4 200 vehicles/day

typical vehicle speed: 90 km/h

Road profile (5.3.5.3.2):

concrete pavement, 10 years old

grade: 0 %

slope: 0,06 %

no curve

Photograph (5.3.5.3.4): ...[2]

A.5 Road characterization

See Figures A.2 to A.5.

General and octave characterizations for Figures A.3 and A.5 are given in Table A.1.

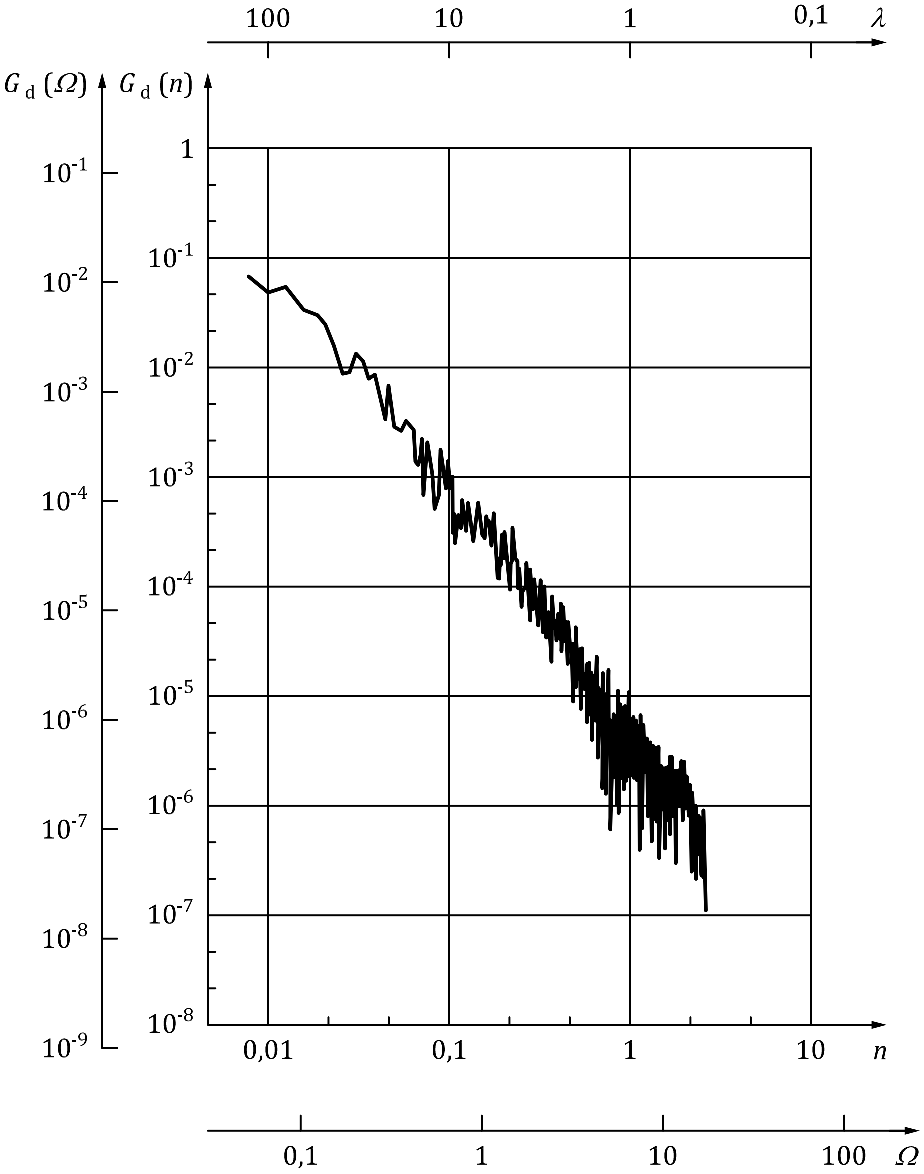
Table A.1 — General and octave characterizations

Centre frequency n_c cycles/m	**Figure A.3** r.m.s. displacement m	**Figure A.3** $G_d(n_c)$ 10^{-6} m^3	**Figure A.5** r.m.s. displacement m	**Figure A.5** $G_d(n_c)$ 10^{-6} m^3
0,007 8	0,020 5	76 157,20	0,021 3	81 768,91
0,015 6	0,023 2	48 894,71	0,020 2	36 987,61
0,031 2	0,016 7	12 599,47	0,012 6	7 164,66
0,062 5	0,011 3	2 895,00	0,013 0	3 827,58
0,125	0,007 7	673,55	0,008 5	819,90
0,25	0,005 5	172,26	0,004 3	106,68
0,5	0,003 4	32,12	0,003 1	26,45
1	0,001 8	4,42	0,001 7	4,21
2	0,001 4	1,46	0,001 2	1,08
General characterization	0,011 cycles/m < n < 2,83 cycles/m; linear fitting			

	r.m.s. displacement = 0,038 4 m;
	r.m.s. velocity = 0,033 7 m/s; w = 2,16;
	G_d(0,1 cycles/m) = 892 × 10^{-6} m^3
			r.m.s. displacement = 0,035 9 m;
			r.m.s. velocity = 0,030 1 m/s; w = 2,22;
			G_d(0,1 cycles/m) = 830 × 10^{-6} m^3	

---

[2] Omitted in this example.

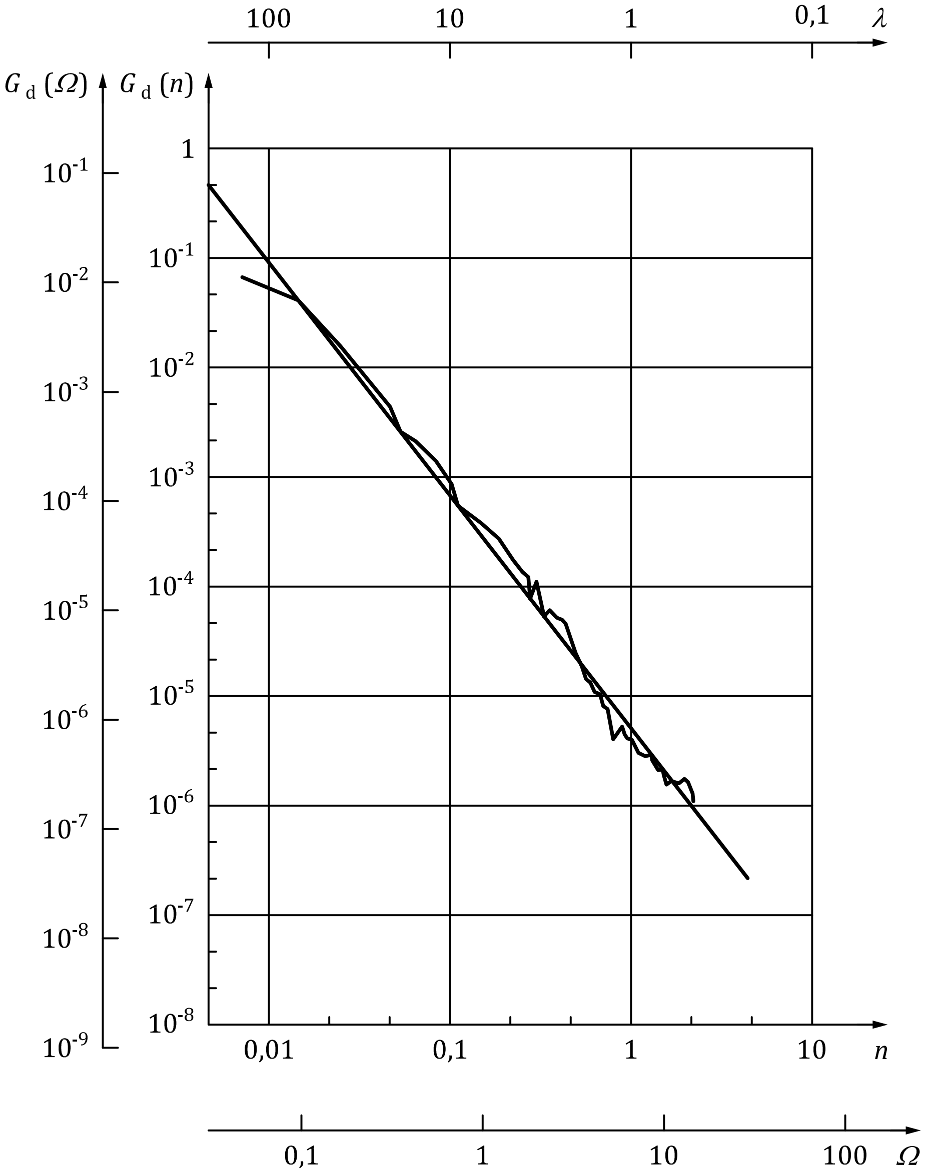


Key

λ	wavelength, m
$G_d(n)$, $G_d(\Omega)$	displacement power spectral density, m^3
n	spatial frequency, cycles/m
Ω	angular spatial frequency, rad/m

NOTE Country: Belgium; Road: N 1000; Place: Xstad; Direction: north to south; Surface: concrete pavement; Distance of track to right road side: 1 m; Distance travelled: 3 571 m; B_e = 0,002 8 cycles/m; ε_r = 0,31; Statistical precision: ±61 %.

Figure A.2 — Non-smoothed PSD of track 1



Key

λ	wavelength, m	n	spatial frequency, cycles/m
$G_d(n)$, $G_d(\Omega)$	displacement power spectral density, m³	Ω	angular spatial frequency, rad/m

NOTE 1 Country: Belgium; Road: N 1000; Place: Xstad; Direction: north to south; Surface: concrete pavement; Distance of track to right road side: 1 m; Distance travelled: 3 571 m; B_e = 0,005 5 cycles/m; ε_r = 0,23; Statistical precision: ±44 %.

NOTE 2 For the octave characterization, see Table A.1; see also Annex B.

Figure A.3 — Smoothed PSD of track 1

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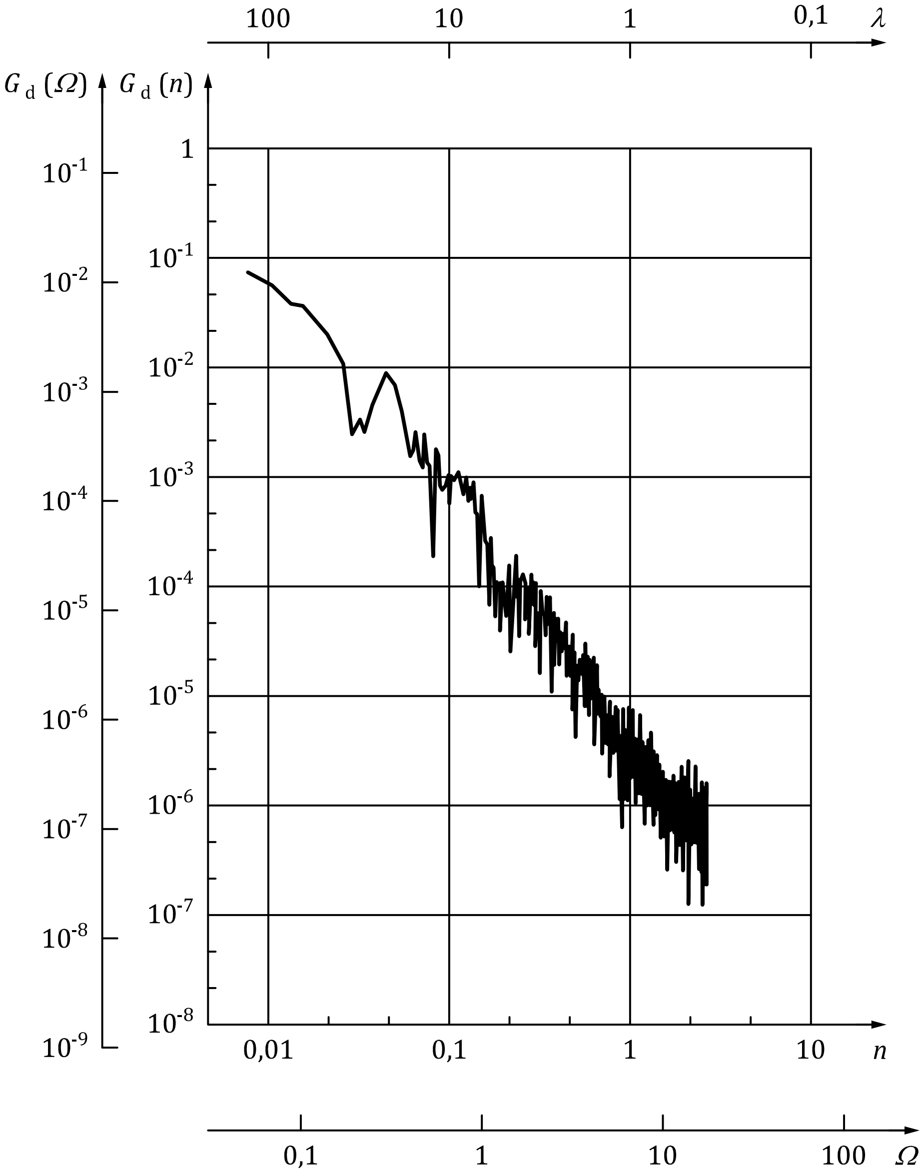
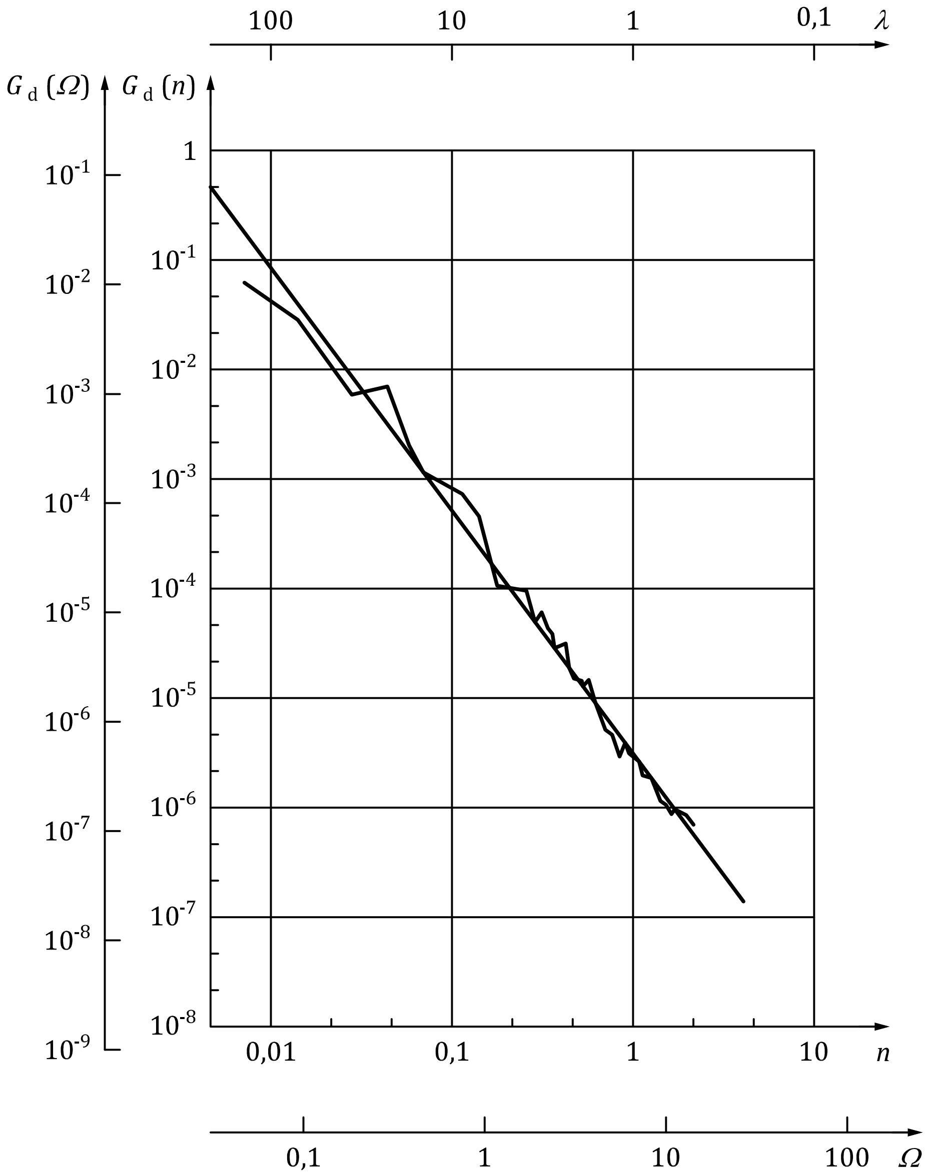


Key

λ	wavelength, m	n	spatial frequency, cycles/m
$G_d(n)$, $G_d(\Omega)$	displacement power spectral density, m^3	Ω	angular spatial frequency, rad/m

NOTE Country: Belgium; Road: N 1000; Place: Xstad; Direction: north to south; Surface: concrete pavement; Distance of track to right road side: 2,4 m; Distance travelled: 3 571 m; B_e = 0,002 8 cycles/m; ε_r = 0,31; Statistical precision: ±61 %.

Figure A.4 — Non-smoothed PSD of track 2



Key

λ	wavelength, m	n	spatial frequency, cycles/m
$G_\mathrm{d}(n)$, $G_\mathrm{d}(\Omega)$	displacement power spectral density, m^3	Ω	angular spatial frequency, rad/m

NOTE 1 Country: Belgium; Road: N 1000; Place: Xstad; Direction: north to south; Surface: concrete pavement; Distance of track to right road side: 2,4 m; Distance travelled: 3 571 m; B_e = 0,005 5 cycles/m; ε_r = 0,23; Statistical precision: ±44 %.

NOTE 2 For the octave characterization, see Table A.1; see also Annex B.

Figure A.5 — Smoothed PSD of track 2

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Annex B
(informative)

Road profile characterization and PSD fitting

B.1 General

This annex gives means of approximately characterizing specific road profiles in order to facilitate the division of road profiles into general classifications. A general classification is also given. A curve-fitting method is presented for characterizing spectral data.

B.2 Symbols

The symbols used in this annex are given in Table B.1.

Table B.1 — Symbols

Symbol	Description	Unit
n	Spatial frequency	cycles/m
n_0	Reference spatial frequency (= 0,1 cycles/m)	cycles/m
$G_d(.)$	Displacement PSD	m^3
$G_a(.)$	Acceleration PSD	m^{-1}
w	Exponent of fitted PSD calculated on $G_d(.)$	—
w'	Exponent of fitted PSD calculated on $G_a(.)$	—
Ω	Angular spatial frequency	rad/m
Ω_0	Reference angular spatial frequency (= 1 rad/m)	rad/m
NOTE The indication (.) means that the parameter of the function can be spatial frequency (n) or angular spatial frequency (Ω).		

B.3 General characterization of the road profile

The root-mean-square (r.m.s.) value between n = 0,011 cycles/m (Ω = 0,063 rad/m) and n = 2,83 cycles/m (Ω = 17,77 rad/m), calculated from the displacement PSD, shall be reported. These limits are band limits for the octave bands to be calculated in 5.1.2 and B.4. These limits were chosen in relation to the frequency data existing in the literature.

However, for off-road data, special studies and limited distances travelled, this spatial frequency range may be reduced. In that case the spatial frequency range shall be reported.

B.4 Characterization in octave bands

In order to obtain surveyable and classifiable data, the spectrum should be divided into octave bands and the r.m.s. values, calculated from the displacement PSD, should be noted for each band. The centre frequencies are given in Table B.2 for both the spatial frequency n and the angular spatial frequency Ω.

The characterizations described in B.3 and B.4 can be calculated with a small and easy supplementary calculation following the processing of the smoothed PSD.

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B.5 Fitted PSD

The smoothed form of the PSD may be fitted by a straight line on the smoothed data (5.1.2) by the least-mean-square method in the spatial frequency range 0,011 cycles/m to 2,83 cycles/m. This fitting may be represented on the general presentation plot. The formula of the fitting shall be reported.

The general form of the fitted PSD is given by Formula (B.1):

$$G_d(n) = G_d(n_0) \cdot (n/n_0)^{-w} \tag{B.1}$$

or by Formula (B.2):

$$G_d(\Omega) = G_d(\Omega_0) \cdot (\Omega/\Omega_0)^{-w} \tag{B.2}$$

where

n_0 (= 0,1 cycles/m)	is the reference spatial frequency;
Ω_0 (= 1 rad/m)	is the reference angular spatial frequency;
w	is the exponent of the fitted PSD.

When the fitting is calculated on the acceleration PSD the exponent is $w' = w - 4$.

NOTE In this annex, only a one-straight line fitting is presented. In the literature, a two- or more-straight line fitting is often used, but then the standardization of a method which guarantees a unique solution is practically impossible.

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Table B.2 — Centre frequencies and cut-off frequencies for PSD characterization in octave bands

Exponent EXP	**Lower cut-off frequency**	**Centre frequency**[a]	**Upper cut-off frequency**	**Centre wavelength** m
	Spatial frequency n, cycles/m			
−9	0,001 4	0,002 0	0,002 8	512
−8	0,002 8	0,003 9	0,005 5	256
−7	0,005 5	0,007 8	0,011 0	128
−6	0,011 0	0,015 6	0,022 1	64
−5	0,022 1	0,031 2	0,044 2	32
−4	0,044 2	0,062 5	0,088 4	16
−3	0,088 4	0,125	0,176 8	8
−2	0,176 8	0,25	0,353 6	4
−1	0,353 6	0,5	0,707 1	2
0	0,707 1	1	1,414 2	1
1	1,414 2	2	2,828 4	0,5
2	2,828 4	4	5,656 9	0,25
3	5,656 9	8	11,313 7	0,125
	Angular spatial frequency Ω, rad/m			
−6,35	0,008 7	0,012 3	0,017 4	512
−5,35	0,017 4	0,024 5	0,034 7	256
−4,35	0,034 7	0,049 1	0,069 4	128
−3,35	0,069 4	0,098 2	0,138 8	64
−2,35	0,138 8	0,196 3	0,277 7	32
−1,35	0,277 7	0,392 7	0,555 4	16
−0,35	0,555 4	0,785 4	1,110 7	8
0,65	1,110 7	1,570 8	2,221 4	4
1,65	2,221 4	3,141 6	4,442 9	2
2,65	4,442 9	6,283 2	8,885 8	1
3,65	8,885 8	12,566 4	17,771 6	0,5
4,65	17,771 6	25,132 8	35,543 1	0,25
5,65	35,543 1	50,265 6	71,086 3	0,125

[a] Centre frequency = 2^{EXP}.

Annex C

(informative)

General guidance for use of the statistical road profile description

C.1 General

This annex provides general guidance for the use of road profile statistical data for simulation studies and for related studies such as evaluation of comfort, suspensions and road profiles. It is assumed that the exponent of the fitted PSD is $w = 2$ so that the velocity PSD is constant.

C.2 Symbols

The symbols used in this annex are given in Table C.1.

Table C.1 — Symbols

Symbol	Description	Unit
f	Time frequency	Hz
$G_d(.)$	Displacement PSD	m^3
$G_v(.)$	Velocity PSD	m
$G_a(.)$	Acceleration PSD	m^{-1}
l	Wheelbase	m
n	Spatial frequency	cycles/m
n_c	Centre spatial frequency of a frequency band	cycles/m
n_0	Reference spatial frequency (= 0,1 cycles/m)	cycles/m
R	Tyre radius	m
T	Time constant of a filter	s
Δt	Time delay for four-track (two-axle) simulation	s
v	Vehicle speed	m/s
w	Exponent of the fitted PSD calculated on $G_d(.)$	—
ω	Angular frequency (= $2\pi f$)	rad/s
Ω	Angular spatial frequency (= $2\pi n$)	rad/m
Ω_c	Centre angular spatial frequency of a frequency band	rad/m
Ω_0	Reference angular spatial frequency (= 1 rad/m)	rad/m

NOTE The indication (.) means that the parameter of the function can be spatial frequency (n) or angular spatial frequency (Ω).

C.3 Relationship between time frequency and spatial frequency

Figure C.1 gives the relationship between the vehicle speed, the spatial frequency and the time frequency. Knowledge of the resonance frequencies and the speed range for a given class of vehicle makes it possible to choose the useful limits for that class of vehicle.

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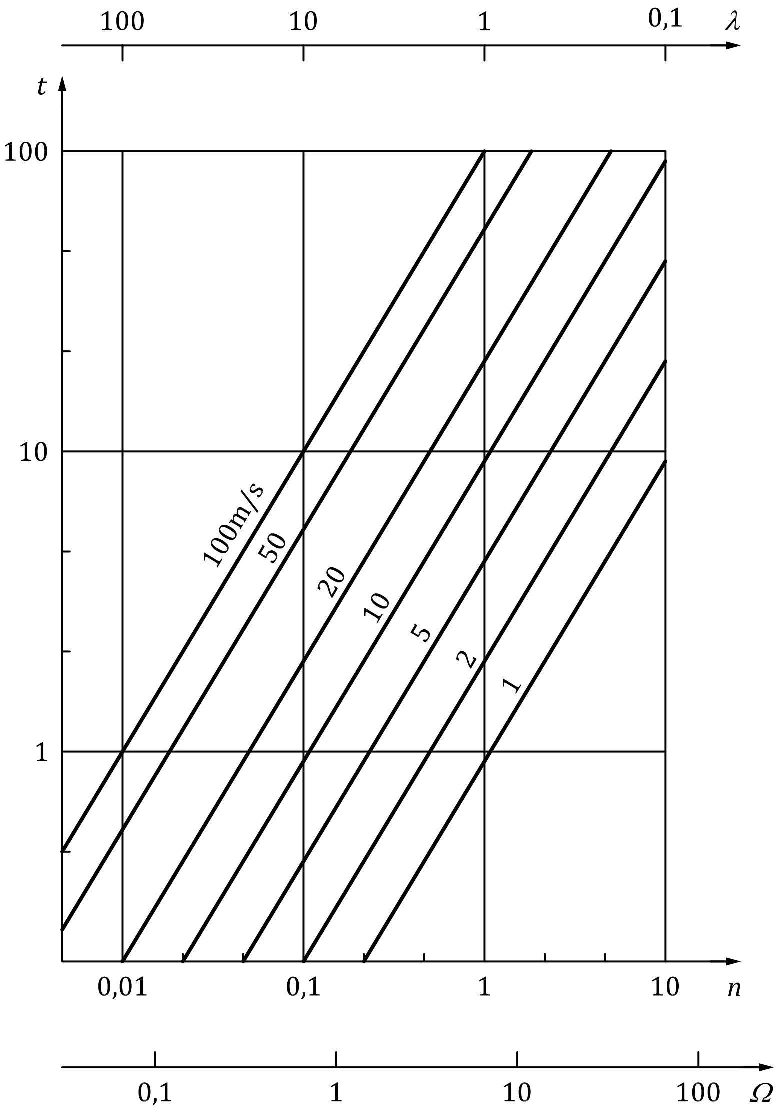
The general expression for this relationship is given by Formula (C.1):

$$f = n \cdot v \tag{C.1}$$

or by Formula (C.2):

$$\omega = \Omega \cdot v \tag{C.2}$$



Key

λ	wavelength, m	n	spatial frequency, cycles/m
t	time frequency, Hz	Ω	angular spatial frequency, rad/m

Figure C.1 — Relationship between time frequency and spatial frequency as a function of vehicle speed

C.4 Velocity PSD

For simulation studies, it is often convenient to use the velocity PSD, in terms of change of the vertical ordinate of the road surface per unit distance travelled. The relationship between the displacement PSD $G_d(n)$ and the velocity PSD $G_v(n)$ is given by Formulae (C.3) and (C.4):

$$G_v(n) = G_d(n) \cdot (2\pi n)^2 \tag{C.3}$$

$$G_v(\Omega) = G_d(\Omega) \cdot \Omega^2 \tag{C.4}$$

When in Formula (C.5):

$$G_d(n) = G_d(n_0) \cdot (n/n_0)^{-w} \tag{C.5}$$

the exponent of the fitted PSD is $w = 2$ (see Annex B), then the velocity PSD is constant, as given by Formulae (C.6) and (C.7):

$$G_v(n) = G_v(n_0) = \text{constant} \tag{C.6}$$

$$G_v(\Omega) = G_v(\Omega_0) = \text{constant} \tag{C.7}$$

C.5 Classification of roads

An estimate of the degree of roughness of the road can be made by the $G_d(n_0)$ value of the fitted PSD (see B.5). Table C.2 gives the power spectral densities for different classes of roads. In Figure C.2, the class limits are graphed on the displacement PSD. This classification is made by assuming a constant-velocity PSD, which means $w = 2$ (see C.4).

However, due to the fact that the PSD is not always a straight line, more information is given by the power spectral density or the r.m.s. displacement in the different octave bands. This makes it possible to classify the road for every octave band in an appropriate class. It can give some information for the repair need and method. It is also possible to classify the road for an appropriate band of speeds. For example, for highways, when assuming that the velocities are between 70 km/h and 120 km/h, the band between 0,022 1 cycles/m (0,138 8 rad/m) and 1,414 2 cycles/m (8,885 8 rad/m) is the most significant.

Table C.3 gives the mean values and limits of $G_d(n_c)$ and $G_d(\Omega_c)$ for the different classes of road in the different octave bands.

Table C.4 gives the mean values and limits of r.m.s. displacement for the different classes of road in the different octave bands.

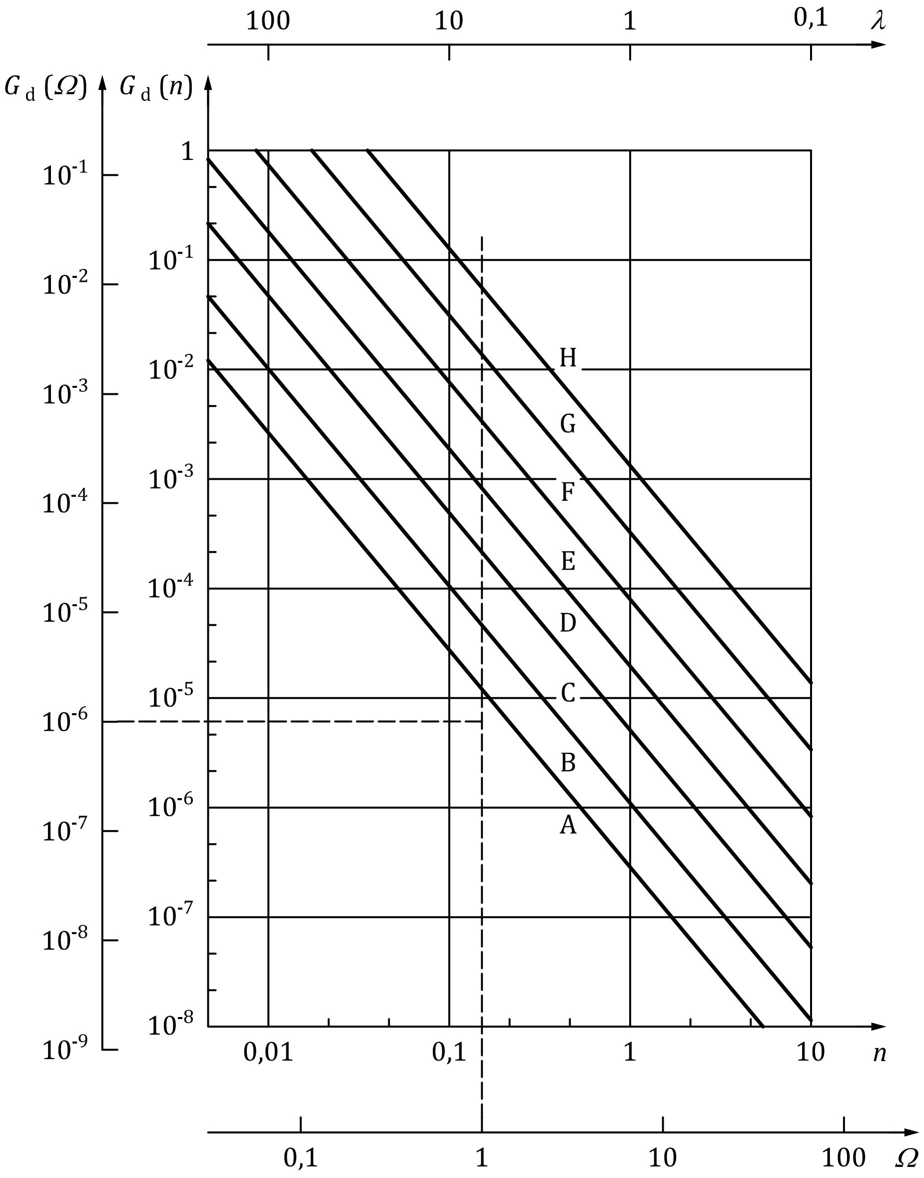
The relationships given in Formulae (C.8), (C.9) and (C.10) are used:

$$G_d(n_0) = 2\pi G_d(\Omega_0) \cdot [\Omega_0/(2\pi n_0)]^2 = 16\ G_d(\Omega_0) \tag{C.8}$$

$$G_v(n) = G_d(n_0) \cdot (2\pi n_0)^2 \tag{C.9}$$

$$G_v(\Omega) = G_d(\Omega_0) \cdot \Omega_0^2 \tag{C.10}$$

NOTE The word “limit” as used in this annex refers to the mathematical meaning of the word in connection with the word “mean”. In other words, a range of values has a mean value and limits which denote the extremes of the range of values. The word “limit”, as used in this annex, is not to be construed to mean the limit of acceptability of a road surface.



Key

λ	wavelength, m	n	spatial frequency, cycles/m
$G_d(n)$, $G_d(\Omega)$	displacement power spectral density, m^3	Ω	angular spatial frequency, rad/m

Figure C.2 — Classification of roads, classes A to H

C.6 General guidance for road simulation

C.6.1 General

The statistical road profile description can be used for computer and laboratory road simulation. However, it may only be used for the determination of output PSDs. Because no information is given about phase shift, there is no guarantee as to the magnitude distribution of the road profile.

C.6.2 One-track (one-axle) simulation

For simulation purposes, it is convenient to describe the road profile as a constant-velocity PSD (w = 2, see C.4).

The advantage of this description is a very easy simulation of the displacement by integrating white noise. The use of any other characteristic can require much effort and, due to the approximation methods to be applied, can result in inaccuracies which cause an unvoidable dispersion in the results of comparison tests. Account should be taken of the influence of the transfer function of the reproducing device.

C.6.3 Two-track (one-axle) simulation

In two-track simulation, the two tracks are simulated as in C.6.2. For the relationship between the two tracks, it is convenient to assume that the road surface possesses the property of isotropy, i.e. that all profiles of a given stretch of road, irrespective of orientation and location, have the same properties, and to accept the coherence function resulting from this assumption.

C.6.4 Two- or multiple-axle track simulation

In two- or multiple-axle track simulation, the front tracks are simulated in accordance with C.6.3. For the following wheels, it could be assumed that each rear wheel travels over the same profile as the corresponding front wheel. Consequently, the rear wheel experiences, after a certain delay, the same imposed displacement as the corresponding front wheel.

The delay Δt, in seconds, is given by Formula (C.11):

$$\Delta t = l/v \tag{C.11}$$

where

l is the corresponding wheelbase, in metres;

v is the speed of the vehicle, in metres per second.

NOTE On unpaved terrain, the passage of the front wheel can modify the track profile such that the profile for the following wheel is not necessarily the same as the profile for the front wheel.

When simulation is to be done by means of a hydraulic simulator, the difference in vertical stiffness between a rolling and a non-rolling tyre should be taken into account. This difference can be reduced by using an adapted tyre pressure and a special profiled plate between the simulator and tyre.

For computer simulation, the stiffness of a rolling tyre should be taken into account.

In order to avoid too large a displacement in the low time frequency range, it is recommended to limit the lowest frequency to a value related to the lowest frequency of interest.

For the study of the reactions from pot-holes or other typical road forms, e.g. concrete joints, these specific forms can be superposed on the normal spectrum or studied separately. However, also in this case, the influence of the enveloping effect of the tyre has to be considered.

For vertical displacement magnitudes which are smaller than $R/10$, a passive low-pass network with a time constant $T = R/(12v)$ can be used. This expresses that in a pot-hole, the vertical displacement of the wheel centre reaches 95 % of its nominal value after the distance of $R/4$, i.e. the time of $R/(4v)$. For displacement magnitudes greater than $R/10$, no correction is needed.

Table C.2 — Road classification

Road class	**Degree of roughness**			
	Lower limit	**Geometric mean**	**Upper limit**	**Geometric mean**
	Spatial frequency units, n			
	$G_d(n_0)$[a] 10^{-6} m^3			$G_v(n)$ 10^{-6} m
A	—	16	32	6,3
B	32	64	128	25,3
C	128	256	512	101,1
D	512	1 024	2 048	404,3
E	2 048	4 094	8 192	1 617
F	8 192	16 384	32 768	6 468
G	32 768	65 536	131 072	25 873
H	131 072	262 144	—	103 490
	Angular spatial frequency units, Ω			
	$G_d(\Omega_0)$ [b] 10^{-6} m^3			$G_v(\Omega)$ 10^{-6} m
A	—	1	2	1
B	2	4	8	4
C	8	16	32	16
D	32	64	128	64
E	128	256	512	256
F	512	1 024	2 048	1 024
G	2 048	4 096	8 192	4 096
H	8 192	16 384	—	16 384

[a] n_0 = 0,1 cycles/m

[b] Ω_0 = 1 rad/m

NOTE 1 The road classification is based on $G_d(n_0)$, $G_d(\Omega_0)$, $G_v(n)$ and $G_v(\Omega)$ values.

NOTE 2 The fit exponent $w = 2$ is assumed (see B.5 and C.4).

NOTE 3 The mean values for road classes A and H are only for simulation purposes.

Table C.3 — Geometric mean and limits of the displacement PSD for different classes of roads as a function of octave bands

Spatial frequency units, n											
Road class	**Mean and limits** $G_d(n_c)$ 10^{-6} m^3	**Octave centre spatial frequency**, n_c cycles/m									
		0,007 8	0,015 6	0,031 2	0,062 5	0,125	0,25	0,5	1	2	4
A	Mean	2 621	655	164	41,0	10,2	2,56	0,64	0,16	0,04	0,010
	Upper	5 243	1 311	328	81,9	20,5	5,12	1,28	0,32	0,08	0,020
B	Lower	5 243	1 311	328	81,9	20,5	5,12	1,28	0,32	0,08	0,020
	Mean	10 486	2 621	655	163,8	41,0	10,24	2,56	0,64	0,16	0,040
	Upper	20 972	5 243	1 311	327,7	81,9	20,48	5,12	1,28	0,32	0,080
C	Lower	20 972	5 243	1 311	327,7	81,9	20,48	5,12	1,28	0,32	0,080
	Mean	41 943	10 486	2 621	655,4	163,8	40,96	10,24	2,56	0,64	0,160
	Upper	83 886	20 972	5 243	1 310,7	327,7	81,92	20,48	5,12	1,28	0,320
D	Lower	83 886	20 972	5 243	1 310,7	327,7	81,92	20,48	5,12	1,28	0,320
	Mean	167 772	41 943	10 486	2 621,4	655,4	163,84	40,96	10,24	2,56	0,640
	Upper	335 544	83 886	20 972	5 242,9	1 310,7	327,68	81,92	20,48	5,12	1,280
E	Lower	335 544	83 886	20 972	5 242,9	1 310,7	327,68	81,92	20,48	5,12	1,280
	Mean	671 089	167 772	41 943	10 485,8	2 621,4	655,36	163,84	40,96	10,24	2,560
	Upper	1 342 177	335 544	83 886	20 971,5	5 242,9	1 310,72	327,68	81,92	20,48	5,120
F	Lower	1 342 177	335 544	83 886	20 971,5	5 242,9	1 310,72	327,68	81,92	20,48	5,120
	Mean	2 684 354	671 089	167 772	41 943,0	10 485,8	2 621,44	655,36	163,84	40,96	10,240
	Upper	5 368 709	1 342 177	335 544	83 886,1	20 971,5	5 242,88	1 310,72	327,68	81,92	20,480
G	Lower	5 368 709	1 342 177	335 544	83 886,1	20 971,5	5 242,88	1 310,72	327,68	81,92	20,480
	Mean	10 737 417	2 684 354	671 089	167 772,1	41 943,0	10 485,76	2 621,44	655,36	163,84	40,960
	Upper	21 474 834	5 368 709	1 342 177	335 544,3	83 886,1	20 971,52	5 242,88	1 310,72	327,68	81,920
H	Lower	21 474 834	5 368 709	1 342 177	335 544,3	83 886,1	20 971,52	5 242,88	1 310,72	327,68	81,920
	Mean	42 949 668	10 737 417	2 684 354	671 088,6	167 772,1	41 943,04	10 485,76	2 621,44	655,36	163,840

NOTE The mean values for road classes A and H are only for simulation purposes.

Table C.3 — *(continued)*

Angular spatial frequency units, Ω											
Road class	**Mean and limits** $G_d(\Omega_c)$ 10^{-6} m^3	**Octave centre angular spatial frequency, Ω_c** rad/m									
		0,049 1	0,098 2	0,196 3	0,392 7	0,785 4	1,570 8	3,141 6	6,283 2	12,566 4	25,132 7
A	Mean	415	104	25,94	6,48	1,621	0,405	0,101 3	0,025 3	0,006 33	0,001 58
	Upper	830	208	51,88	12,97	3,242	0,811	0,202 6	0,050 7	0,012 67	0,003 17
B	Lower	830	208	51,88	12,97	3,242	0,811	0,202 6	0,050 7	0,012 67	0,003 17
	Mean	1 660	415	103,75	25,94	6,485	1,621	0,405 3	0,101 3	0,025 33	0,006 33
	Upper	3 320	830	207,51	51,88	12,969	3,242	0,810 6	0,202 6	0,050 66	0,012 67
C	Lower	3 320	830	207,51	51,88	12,969	3,242	0,810 6	0,202 6	0,050 66	0,012 67
	Mean	6 640	1 660	415,01	103,75	25,938	6,485	1,621 1	0,405 3	0,101 32	0,025 33
	Upper	13 280	3 320	830,02	207,51	51,876	12,969	3,242 3	0,810 6	0,202 64	0,050 66
D	Lower	13 280	3 320	830,02	207,51	51,876	12,969	3,242 3	0,810 6	0,202 64	0,050 66
	Mean	26 561	6 640	1 660,05	415,01	103,753	25,938	6,484 6	1,621 1	0,405 28	0,101 32
	Upper	53 121	13 280	3 320,09	830,02	207,506	51,876	12,969 1	3,242 3	0,810 57	0,202 64
E	Lower	53 121	13 280	3 320,09	830,02	207,506	51,876	12,969 1	3,242 3	0,810 57	0,202 64
	Mean	106 243	26 561	6 640,18	1 660,05	415,012	103,753	25,938 2	6,484 6	1,621 14	0,405 28
	Upper	212 486	53 121	13 280,37	3 320,09	830,023	207,506	51,876 4	12,969 1	3,242 28	0,810 57
F	Lower	212 486	53 121	13 280,37	3 320,09	830,023	207,506	51,876 4	12,969 1	3,242 28	0,810 57
	Mean	424 972	106 243	26 560,74	6 640,19	1 660,046	415,012	103,752 9	25,938 2	6,484 56	1,621 14
	Upper	849 944	212 486	53 121,48	13 280,37	3 320,093	830,023	207,505 8	51,876 4	12,969 11	3,242 28
G	Lower	849 944	212 486	53 121,48	13 280,37	3 320,093	830,023	207,505 8	51,876 4	12,969 11	3,242 28
	Mean	1 699 888	424 972	106 242,95	26 560,74	6 640,186	1 660,046	415,011 5	103,752 9	25,938 22	6,484 56
	Upper	3 399 775	849 944	212 485,91	53 121,48	13 280,371	3 320,092	830,023 0	207,505 8	51,876 45	12,969 11
H	Lower	3 399 775	849 944	212 485,91	53 121,48	13 280,371	3 320,092	830,023 0	207,505 8	51,876 45	12,969 11
	Mean	6 799 550	1 699 888	424 971,81	106 242,97	26 560,742	6 640,184	1 660,046 0	415,011 6	103,752 90	25,938 22
NOTE The mean values for road classes A and H are only for simulation purposes.											

Table C.4 — Geometric mean and limits of the r.m.s. displacement for the roughness for different classes of roads as a function of octave bands

Spatial frequency units, n											
Road class	**Mean and limits in r.m.s. displacement** 10^{-3} m	**Octave centre spatial frequency**, n_c cycles/m									
		0,007 8	0,016	0,031	0,062	0,125	0,25	0,5	1	2	4
A	Mean	4	3	2	1,3	1,0	0,7	0,48	0,34	0,24	0,17
	Upper	5	4	3	1,9	1,3	1,0	0,67	0,48	0,34	0,24
B	Lower	5	4	3	1,9	1,3	1,0	0,67	0,48	0,34	0,24
	Mean	8	5	4	2,7	1,9	1,3	0,95	0,67	0,48	0,34
	Upper	11	8	5	3,8	2,7	1,9	1,35	0,95	0,67	0,48
C	Lower	11	8	5	3,8	2,7	1,9	1,35	0,95	0,67	0,48
	Mean	15	11	8	5,4	3,8	2,7	1,90	1,35	0,95	0,67
	Upper	22	15	11	7,6	5,4	3,8	2,69	1,90	1,35	0,95
D	Lower	22	15	11	7,6	5,4	3,8	2,69	1,90	1,35	0,95
	Mean	30	22	15	10,8	7,6	5,4	3,81	2,69	1,90	1,35
	Upper	43	30	22	15,2	10,8	7,6	5,38	3,81	2,69	1,90
E	Lower	43	30	22	15,2	10,8	7,6	5,38	3,81	2,69	1,90
	Mean	61	43	30	21,5	15,2	10,8	7,61	5,38	3,81	2,69
	Upper	86	61	43	30,4	21,5	15,2	10,76	7,61	5,38	3,81
F	Lower	86	61	43	30,4	21,5	15,2	10,76	7,61	5,38	3,81
	Mean	122	86	61	43,1	30,4	21,5	15,22	10,76	7,61	5,38
	Upper	172	122	86	60,9	43,1	30,4	21,53	15,22	10,76	7,61
G	Lower	172	122	86	60,9	43,1	30,4	21,53	15,22	10,76	7,61
	Mean	244	172	122	86,1	60,9	43,1	30,44	21,53	15,22	10,76
	Upper	344	244	172	121,8	86,1	60,9	43,05	30,44	21,53	15,22
H	Lower	344	244	172	121,8	86,1	60,9	43,05	30,44	21,53	15,22
	Mean	487	344	244	172,2	121,8	86,1	60,89	43,05	30,44	21,53

NOTE The mean values for road classes A and H are only for simulation purposes.

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Table C.4 *(continued)*

Angular spatial frequency units, Ω											
Road class	**Mean and limits in r.m.s. displacement** 10^{-3} m	**Octave centre angular spatial frequency**, Ω_c rad/m									
		0,049 1	0,098	0,196	0,393	0,785	1,571	3,14	6,28	12,57	25,13
A	Mean	3,8	2,7	1,9	1,34	0,95	0,67	0,47	0,34	0,24	0,17
	Upper	5,4	3,8	2,7	1,90	1,34	0,95	0,67	0,47	0,34	0,24
B	Lower	5,4	3,8	2,7	1,90	1,34	0,95	0,67	0,47	0,34	0,24
	Mean	7,6	5,4	3,8	2,68	1,90	1,34	0,95	0,67	0,47	0,34
	Upper	10,7	7,6	5,4	3,80	2,68	1,90	1,34	0,95	0,67	0,47
C	Lower	10,7	7,6	5,4	3,80	2,68	1,90	1,34	0,95	0,67	0,47
	Mean	15,2	10,7	7,6	5,37	3,80	2,68	1,90	1,34	0,95	0,67
	Upper	21,5	15,2	10,7	7,59	5,37	3,80	2,68	1,90	1,34	0,95
D	Lower	21,5	15,2	10,7	7,59	5,37	3,80	2,68	1,90	1,34	0,95
	Mean	30,4	21,5	15,2	10,74	7,59	5,37	3,80	2,68	1,90	1,34
	Upper	42,9	30,4	21,5	15,18	10,74	7,59	5,37	3,80	2,68	1,90
E	Lower	42,9	30,4	21,5	15,18	10,74	7,59	5,37	3,80	2,68	1,90
	Mean	60,7	42,9	30,4	21,47	15,18	10,74	7,59	5,37	3,80	2,68
	Upper	85,9	60,7	42,9	30,36	21,47	15,18	10,74	7,59	5,37	3,80
F	Lower	85,9	60,7	42,9	30,36	21,47	15,18	10,74	7,59	5,37	3,80
	Mean	121,5	85,9	60,7	42,94	30,36	21,47	15,18	10,74	7,59	5,37
	Upper	171,8	121,5	85,9	60,73	42,94	30,36	21,47	15,18	10,74	7,59
G	Lower	171,8	121,5	85,9	60,73	42,94	30,36	21,47	15,18	10,74	7,59
	Mean	242,9	171,8	121,5	85,88	60,73	42,94	30,36	21,47	15,18	10,74
	Upper	343,5	242,9	171,8	121,45	85,88	60,73	42,94	30,36	21,47	15,18
H	Lower	343,5	242,9	171,8	121,45	85,88	60,73	42,94	30,36	21,47	15,18
	Mean	485,8	343,5	242,9	171,76	121,45	85,88	60,73	42,94	30,36	21,47
NOTE The mean values for road classes A and H are only for simulation purposes.											

Annex D
(informative)

Considerations for PSD processing and precision

D.1 General

The most common technique for PSD evaluation is the use of the fast Fourier transform (FFT) of digital profile data. Other techniques, however, can also be used.

D.2 Symbols

The symbols used in this annex are given in Table D.1.

Table D.1 — Symbols

Symbol	Description	Unit
B'_e	Frequency resolution, resorting from FFT	cycles/m
B_e	Reported frequency resolution	cycles/m
B_r	Actual half-power point bandwidth of the peak	cycles/m
$E[.]$	Expected value of [.]	
G	True value of the PSD	
$\hat{G}$	Estimated value of the PSD	
G''	Second derivative of the PSD	
L	Total sampling distance or total record	m
L'	Record length of one block for FFT	m
L''	Calculated block size for FFT	m
ΔL	Sampling interval	m
n	Spatial frequency	cycles/m
n_h	Highest spectral frequency to be analysed	cycles/m
n_l	Lowest spectral frequency to be analysed	cycles/m
n_s	Sampling frequency	cycles/m
N	Block size for FFT; normally to be rounded up to the nearest power of two	—
q	Number of blocks in time averaging	—
r	Number of averaged components in frequency smoothing	—
ε	Total normalized mean-square error	—
ε_b	Bias error	—
ε_r	Normalized standard error (equals the random error)	—

D.3 Digitizing of data

Digitizing requires two settings, n_s and N.

In this case, the following relevant parameters are fixed:

$n_h = n_s/2$ is the minimum required; as an approximation, to avoid aliasing, $n_h = n_s/3$ can be used

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$\Delta L = 1/n_\mathrm{s}$

$L' = N/n_\mathrm{s}$

$B'_\mathrm{e} = n_\mathrm{s}/N = 1/L'$

D.4 Signal conditioning prior to digitizing

A signal to be digitized and subsequently Fourier transformed shall not contain spectral components above one-half the sampling frequency to avoid aliasing. The application of anti-aliasing filters is necessary in most cases.

Prior to digitizing, frequency components, the period of which is longer than the record length of one block, may be reduced or eliminated with a high-pass filter with an appropriate low cut-off frequency (this manipulation is called de-trending).

De-trending may also be accomplished after digitizing by digital methods of regression analysis with low-order polynomials.

D.5 Sampling window

Some form of sampling window is usually necessary to avoid the distortion of the spectrum known as leakage. Numerous weighting curves are available and a correction factor is used.

D.6 Statistical precision

D.6.1 General

The precision of PSD may be thought of in terms of two component sources of error. The total normalized mean-square error ε is given by Formula (D.1):

$$\varepsilon = \left[\frac{E\left[\left(\hat{G}(n) - G(n) \right)^2 \right]}{G^2(n)} \right]^{1/2} = \left[\frac{1}{B_\mathrm{e} \cdot L''} + \frac{B_\mathrm{e}^4}{576} \left(\frac{G''(n)}{G(n)} \right)^2 \right]^{1/2} = \left(\varepsilon_\mathrm{r}^2 + \varepsilon_\mathrm{b}^2 \right)^{1/2} \tag{D.1}$$

The first term represents the normalized random error component ε_r and the second the normalized bias error ε_b. From Formula (D.1), conflicting error requirements on the frequency resolution B_e can be seen. The bias error increases with B_e, while the random error decreases with B_e but also with the block size L'' (record length). Thus the strategy is to select B_e based upon bias error considerations and then proceed to reduce the random error by taking advantage of its additional dependence on record length.

NOTE A more complete explanation of statistical errors can be found in Reference [10].

D.6.2 Random error

D.6.2.1 General

The normalized standard error is defined as the random error, as given by Formula (D.2):

$$\varepsilon_\mathrm{r} = (B_\mathrm{e} \cdot L)^{-1/2} \tag{D.2}$$

This means that the normalized standard error is equal to

$\varepsilon_r = (1/q)^{1/2}$ for time averaging (see D.6.2.2)

$\varepsilon_r = (1/r)^{1/2}$ for frequency smoothing (see D.6.2.3)

$\varepsilon_r = [1/(r \cdot q)]^{1/2}$ for combined procedures

D.6.2.2 Time averaging

Time averaging involves cutting the total signal length into equal blocks, computing the spectrum of each individual block, and then averaging these spectra to the resulting spectrum:

$q = L/L'$ number of blocks

$B_e = B'_e = 1/L'$ frequency resolution

D.6.2.3 Frequency smoothing

Frequency smoothing involves computing the spectrum of the entire record and then averaging the spectra at adjacent frequencies:

r = number of frequency components of the original spectrum which are averaged together

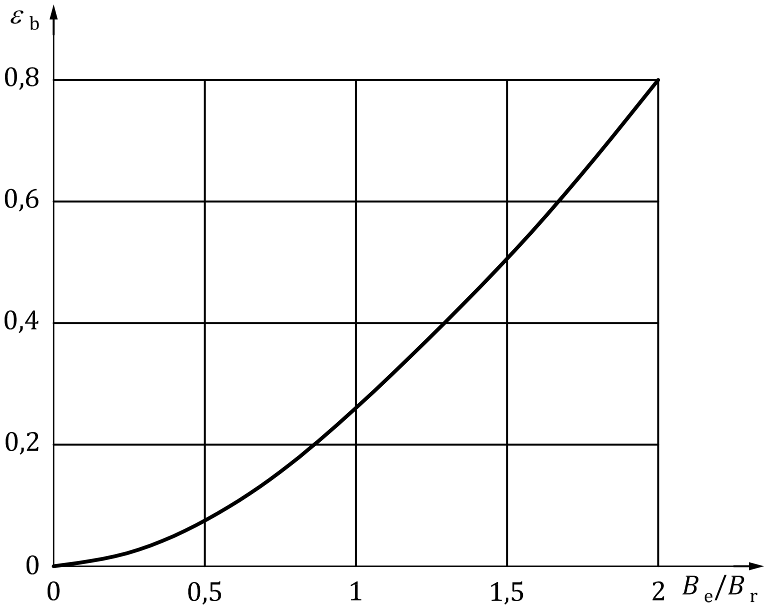
$B_e = r \cdot B'_e = r/L'$ frequency resolution

NOTE Time averaging requires less computer memory than frequency smoothing for the same normalized standard error.

The equations given for the normalized standard error apply only in the case where all of the time averages are from independent time series (blocks) of data, e.g. where the averages are from consecutive time series (blocks). For the case where the averages are from overlapping segments of a longer time history, or when in doubt, the normalized standard error should be calculated from Formula (D.2).

D.6.3 Bias error

Though it is of more importance for rail tracks, in road profile data, the bias error is also of importance in the consideration of PSDs used to represent road profile geometry data thought to contain periodic components. Because the bias error term in Formula (D.1) is a function of the second derivative of the PSD, it plays a crucial role in the estimation of spectral peaks. When bias error exists, sharp peaks in the PSD tend to be underestimated. Although there is no proof that spectral peaks in profile data behave like resonant peaks of a second-order system, an idea of this underestimation is given in Reference [10]. Figure D.1 gives the bias error for a second-order system. B_r is the actual half-power point bandwidth of the actual peak.



Key

ε_b bias error

B_e/B_r bandwith ratio

Figure D.1 — Bias error for second-order system response

Figure D.1 has been calculated using Formula (D.3):

$$D = \hat{G}(n)/G(n) = B_r/B_e \cdot \arctan(B_e/B_r) \tag{D.3}$$

The bias error is given by Formula (D.4):

$$\varepsilon_b = \frac{1 - D}{D} \tag{D.4}$$

In road profiles, the probability of high periodic peaks is small and normally the influence of the bias error can be neglected.

D.7 Selection of parameters

D.7.1 In general, the precision problem can be characterized in terms of three sets of constraints which enter into the selection of parameters.

a) Application constraints: desired frequency range and desired statistical precision.

b) Measurement constraints: longest allowable record length and shortest allowable sampling interval.

c) Computational costs: number of points input to FFT routine, amount of computer memory required, additional computational routines.

Normally, the value of resolution, B_e, is chosen to be equal to the lowest spatial frequency in the spectrum of interest. This value is the minimum required to pick out the longest wavelength of interest in the data, and thus is the least expensive choice in terms of trade-off costs.

In this case, the distance between the first two spectral lines is one octave. The lowest spectral line also could contain a lot of leakage from components at almost 0 Hz. For this reason, it is recommended to use a much smaller frequency resolution and then disregard the data of the first two or three spectral lines. When the first spectral line above 0 Hz is used, the data shall be carefully de-trended.

D.7.2 In the example given in Table D.2 the use of time averaging is assumed.

The following expressions are useful:

$n_s = 2n_h$ minimum sampling frequency allowed

$N = 2n_s/n_l$ minimum blocksize for FFT, normally rounded up to the nearest power of two

Figure D.2 shows the relationship between the normalized standard error (random error), the bias error and the resolution for the example given in Table D.2.

Table D.2 — Example of the relationship between the different parameters, the bias error and the random error for different measuring situations

Case		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total signal length, L (m)		1 000	1 000	1 000	1 000	2 000	2 000	2 000	2 000
Length of block, L' (m)		1 000	1 000	200	100	2 000	2 000	200	100
Resolution, B_e (cycles/m)		0,005	0,01	0,005	0,01	0,005	0,01	0,005	0,01
Highest wavelength, $1/B_e$ (m)		200	100	200	100	200	100	200	100
Number of blocks, q		1	1	5	10	1	1	10	20
Random error, ε_r		0,2	0,1	0,45	0,32	0,1	0,05	0,32	0,22
Bias error, ε_b		0,078	0,27	0,078	0,27	0,078	0,27	0,078	0,27
Lowest wavelength, $1/n_h$ (m)	A	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2
	B	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
Sampling frequency, $3n_h$ (cycles/m)	A	15	15	15	15	15	15	15	15
	B	6	6	6	6	6	6	6	6
Number of samples per block, $L' \cdot 3n_h$	A	15 000	15 000	3 000	1 500	30 000	30 000	3 000	1 500
	B	6 000	6 000	1 200	600	12 000	12 000	1 200	600
Number of samples rounded up to the nearest power of 2	A	16 384	16 384	4 096	2 048	32 768	32 768	4 096	2 048
	B	8 192	8 192	2 048	1 024	16 384	16 384	2 048	1 024

NOTE 1 Case A gives as highest spatial frequency 5 cycles/m.

Case B gives as highest spatial frequency 2 cycles/m.

NOTE 2 For the cases 1 to 8, random error and bias error are shown in Figure D.2.

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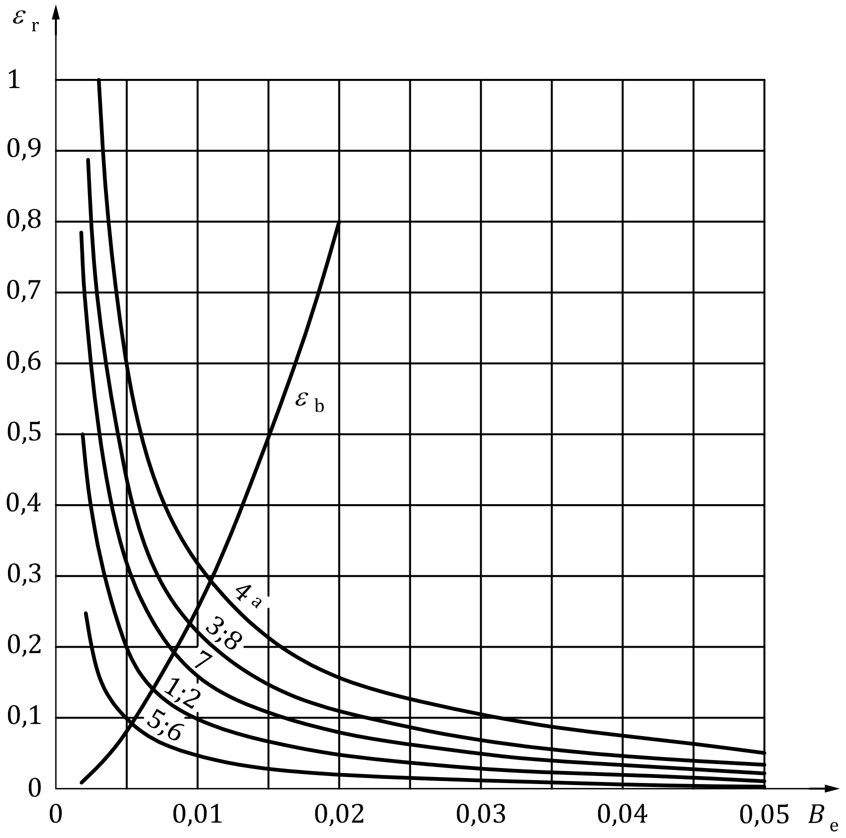

Key

ε_r random error

ε_b bias error

B_e resolution, cycles/m

[a] For the cases 1 to 8, see Table D.2.

Figure D.2 — Random error and bias error for peaks with 0,01 cycles/m half-power bandwidth

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