DRAFT FOR DEVELOPMENT

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13473-4:2008

Characterization of pavement texture by use of surface profiles —

Part 4: Spectral analysis of surface profiles

ICS 17.140.30; 93.080.20

British Standards

National foreword

This Draft for Development is the UK implementation of ISO/TS 13473-4:2008.

This publication is not to be regarded as a British Standard.

It is being issued in the Draft for Development series of publications and is of a provisional nature. It should be applied on this provisional basis, so that information and experience of its practical application can be obtained.

Comments arising from the use of this Draft for Development are requested so that UK experience can be reported to the international organization responsible for its conversion to an international standard. A review of this publication will be initiated not later than three years after its publication by the international organization so that a decision can be taken on its status. Notification of the start of the review period will be made in an announcement in the appropriate issue of *Update Standards*.

According to the replies received by the end of the review period, the responsible BSI Committee will decide whether to support the conversion into an international Standard, to extend the life of the Technical Specification or to withdraw it. Comments should be sent to the Secretary of the responsible BSI Technical Committee at British Standards House, 389 Chiswick High Road, London W4 4AL.

The UK participation in its preparation was entrusted by Technical Committee EH/1, Acoustics, to Subcommittee EH/1/2, Transport noise.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Characterization of pavement texture by use of surface profiles —

Part 4:
Spectral analysis of surface profiles

Caractérisation de la texture d'un revêtement de chaussée à partir de relevés de profils de la surface —

Partie 4: Analyse spectrale des profils de la surface

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In other circumstances, particularly when there is an urgent market requirement for such documents, a technical committee may decide to publish other types of document:

— an ISO Publicly Available Specification (ISO/PAS) represents an agreement between technical experts in an ISO working group and is accepted for publication if it is approved by more than 50 % of the members of the parent committee casting a vote;

— an ISO Technical Specification (ISO/TS) represents an agreement between the members of a technical committee and is accepted for publication if it is approved by 2/3 of the members of the committee casting a vote.

An ISO/PAS or ISO/TS is reviewed after three years in order to decide whether it will be confirmed for a further three years, revised to become an International Standard, or withdrawn. If the ISO/PAS or ISO/TS is confirmed, it is reviewed again after a further three years, at which time it must either be transformed into an International Standard or be withdrawn.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TS 13473-4 was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

ISO 13473 consists of the following parts, under the general title *Characterization of pavement texture by use of surface profiles*:

— *Part 1: Determination of Mean Profile Depth*

— *Part 2: Terminology and basic requirements related to pavement texture profile analysis*

— *Part 3: Specification and classification of profilometers*

— *Part 4: Spectral analysis of surface profiles* [Technical Specification]

— *Part 5: Determination of megatexture*

Introduction

Pavement texture is one of the basic road surface characteristics and as such is related to many functional characteristics, such as noise emission from tyre-road interaction, friction between tyre and road, rolling resistance and tyre wear.

Spectral analysis of measured surface profiles is frequently used as a method of pavement characterization. However, recent practice has shown that the methodology of spectral analysis is not sufficiently well known in the field of pavement measurements to assure reproducible results. Improvement of the reproducibility by offering guidance in the form of a standardization document seems therefore advisable.

Although the principles of frequency analysis are used in various fields of signal processing, it seems that a tailored elaboration of these principles for the application in the field of pavement texture measurements is appropriate and will enhance the use of these methods and the quality of the results achieved.

This elaboration, in the form of an ISO Technical Specification, is intended to stimulate the international exchange of knowledge and data concerning pavement characteristics.

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Characterization of pavement texture by use of surface profiles —

Part 4:
Spectral analysis of surface profiles

1 Scope

This Technical Specification describes the methods that are available to perform a spectral analysis of pavement surface profile signals. It specifies three possible methods for spatial frequency analysis (or texture wavelength analysis) of two-dimensional surface profiles that describe the pavement roughness amplitude as a function of the distance along a straight or curved trajectory over the pavement.

The result of the frequency analysis will be a spatial frequency (or texture wavelength) spectrum in constant-percentage bandwidth bands of octave or one-third-octave bandwidth.

This Technical Specification offers three alternative methods to obtain these spectra:

1) analogue constant-percentage bandwidth filtering;

2) digital constant-percentage bandwidth filtering;

3) constant narrow bandwidth frequency analysis by means of Discrete Fourier Transform, followed by a transformation of the narrow-band spectrum to an octave- or one-third-octave-band spectrum.

The objective of this Technical Specification is to standardize the spectral characterization of pavement surface profiles. This objective is pursued by providing a detailed description of the analysis methods and related requirements for those who are involved in pavement characterization, but are not familiar with general principles of frequency analysis of random signals. These methods and requirements are generally applicable to all types of random signals, but are elaborated in this Technical Specification in a specific description aimed at their use for pavement surface profile signals.

NOTE The user of this Technical Specification should be aware that spectral analysis as specified in this document cannot express all characteristics of the surface profile under study. In particular, the effects of asymmetry of the profile, e.g. the difference of certain functional qualities for “positive” and “negative” profiles cannot be expressed by the power spectral density, as it disregards any asymmetry of the signal. (See Annex F.)

2 Normative references

The following referenced documents are indispensable for the application 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.

ISO 13473-2:2002, *Characterization of pavement texture by use of surface profiles — Part 2: Terminology and basic requirements related to pavement texture profile analysis*

ISO 13473-3, *Characterization of pavement texture by use of surface profiles — Part 3: Specification and classification of profilometers*

IEC 61260, *Electroacoustics — Octave-band and fractional-octave-band filters*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in ISO 13473-2:2002 and the following apply. To assist the users, the most relevant terms and definitions from ISO 13473-2:2002 have been copied into this Technical Specification.

3.1
(texture) wavelength

λ

quantity describing the horizontal dimension of the amplitude variations of a surface profile

NOTE 1 (Texture) wavelength is normally expressed in metres (m) or millimetres (mm).

NOTE 2 Wavelength is a quantity commonly used and accepted in electrotechnical and signal processing vocabularies. Since many users of this Technical Specification may not be accustomed to using the term wavelength in pavement applications, and because electrical signals are often used in the analyses of road surface profiles, there is a possibility of confusion. Hence, the expression “texture wavelength” is preferred here to make a clear distinction in relation to other applications

NOTE 3 The profile may be considered as a stationary, random function of the distance along the surface. By means of a Fourier analysis, such a function may be mathematically represented as an infinite series of sinusoidal components of various frequencies (and wavelengths), each having a given amplitude and initial phase. For typical and continuous surface profiles, a profile analysed by its Fourier components contains a continuous distribution of wavelengths. The texture wavelength in ISO 13473 is the reciprocal of the spatial frequency, the unit of which is reciprocal metre (equivalent to cycles per metre). See also 3.14.

NOTE 4 The wavelengths may be represented physically as the various lengths of periodically repeated parts of the profile.

3.2
profile sampling

selection of representative parts of a road surface of which the profile will be measured

3.3
profilometer

device used for measuring the profile of a pavement surface

NOTE Current designs of profilometers used in pavement engineering include, but are not limited to, sensors based on laser, light sectioning, needle tracer and ultrasonic technologies.

3.4
measurement speed

v

speed at which the profilometer sensor traverses the surface to be measured

NOTE Measurement speed is normally expressed in kilometres per hour (km/h) or metres per second (m/s).

3.5
digital signal sampling

determination of discrete measurement values of a signal at regularly spaced data points (and the subsequent conversion of these values into digital code)

NOTE In this generic definition of digital signal sampling, the regular spacing of the data points may be applied either in the time or in the spatial domain, depending on the domain (time or space) in which the signal is captured.

3.6
sampling interval

distance between two adjacent data points on the surface, which is equal to the measurement speed divided by the sampling frequency of the sensor

NOTE Sampling interval is normally expressed in millimetres (mm).

3.7
profile measurement length

l_p

length of an uninterrupted profile measurement

NOTE Profile measurement length is normally expressed in metres (m) or millimetres (mm).

3.8
repetition interval

r

distance between the beginning of two consecutive profile measurement lengths, the latter as defined in 3.7

NOTE Repetition interval is normally expressed in metres (m).

3.9
evaluation length

l

length of a sample from a profile which has been or is to be analysed

NOTE 1 The evaluation length may or may not be equal to the profile measurement length (but never greater).

NOTE 2 Evaluation length is normally expressed in metres (m) or millimetres (mm).

3.10
drop-out

measured point (sample) on the profile which is recognized as invalid, and which is usually discarded in the subsequent data processing

3.11
drop-out rate

percentage (%) of measured points within the evaluation length which are recognized as being invalid

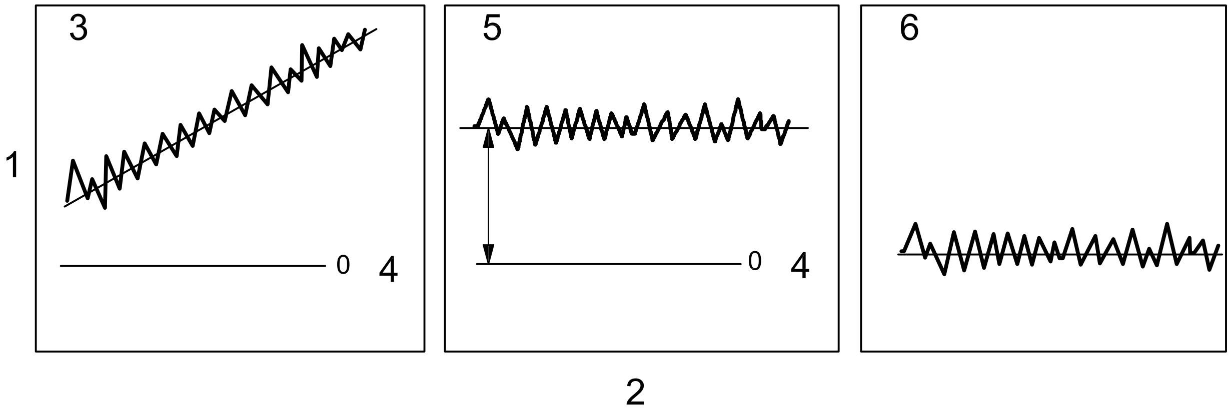
3.12
zero-mean, slope-suppressed profile curve

$Z(x)$

profile curve, $Z(x)$, for which the mean level of the profile over the evaluation length has been brought to zero and for which long-wavelength trends have been removed

NOTE 1 To obtain a profile curve useful for mathematical calculations, it is necessary to remove any slope or long-wavelength component (slope suppression), as well as to bring the mean level of the profile over the evaluation length to zero (offset suppression). This can be accomplished by subtracting a least-squares fit from the profile, see 9.2. The resulting mean line of the profile is then at zero level. See illustration in Figure 1.

NOTE 2 The features in Figure 1 are exaggerated in order to make the illustration clearer. If subtracting a least-squares fit from the profile, the two steps from left to right in the figure are performed in one operation (which can be performed also by high-pass filtering).



Key

1	vertical distance
2	horizontal distance
3	original profile
4	0 level
5	slope suppression applied
6	offset suppression applied

Figure 1 — Illustration of slope and offset suppressions

3.13
surface profile spectrum
texture spectrum
unevenness spectrum

spectrum obtained when a profile curve has been analysed by either digital or analogue filtering techniques in order to determine the magnitude of its spectral components at different wavelengths (3.1) or spatial frequencies (3.14)

NOTE A texture spectrum presents the magnitude of each spectral component as a function of either texture wavelength or spatial frequency.

3.14
spatial frequency

inverse of (texture) wavelength

NOTE 1 Spatial frequency is normally expressed in reciprocal metres (m^{-1}); see also 3.1, Note 3.

NOTE 2 The term “frequency” used in the time domain, more precisely “temporal frequency”, corresponds to “spatial frequency” in the space domain.

3.15
surface (texture) profile level

$L_{\text{tx},\lambda}$

logarithmic transformation of an amplitude representation of a surface profile curve $Z(x)$, the latter expressed as a root mean square value

EXAMPLE $L_{\text{tx},80}$ denotes the texture profile level for the one-third-octave band having a centre wavelength of 80 mm, see Table 1 in ISO 13473-2:2002.

NOTE 1 The texture profile level can be expressed by the following equation:

$$L_{\text{TX},\lambda} \text{ or } L_{\text{tx},\lambda} = 10 \lg \frac{a_{\lambda}^{2}}{a_{\text{ref}}^{2}} = 20 \lg \frac{a_{\lambda}}{a_{\text{ref}}} \text{ dB} \qquad (1)$$

where

$L_{\text{tx},\lambda}$ is the texture profile level in one-third-octave bands (ref. 10^{-6} m), in decibels;

$L_{\text{TX},\lambda}$ is the texture profile level in octave bands (ref. 10^{-6} m), in decibels;

a_λ is the root mean square value of the vertical displacement of the surface profile, in metres;

a_{ref} is the reference value (= 10^{-6} m);

λ is the subscript indicating a value obtained with a one-third-octave-band or octave-band filter having centre wavelength λ.

NOTE 2 Octave-band and one-third-octave-band filters are specified in 4.4 of ISO 13473-2:2002.

NOTE 3 Texture amplitudes expressed as root-mean-square values, whether filtered or not, may have a range of several magnitudes, typically 10^{-5} m to 10^{-2} m. Spectral characterization of signals is used frequently in studies of acoustics, vibrations and electrotechnical engineering. In all those fields, it is most common to use logarithmic amplitude scales. The same approach is preferred in this part of ISO 13473.

NOTE 4 Texture profile levels in practical pavement engineering typically range from 20 dB to 80 dB with these definitions.

3.16
power spectral density
PSD

quantity expressing the power contained in a signal per unit frequency or per unit wavelength as a function of frequency or wavelength

NOTE 1 In the case of a bandwidth filtered signal in the time domain, the PSD may be defined as the limit value of the time averaged squared signal within a certain frequency interval divided by the bandwidth of this frequency interval when the bandwidth approaches zero and the averaging time goes to infinity, resulting in the spectrum being presented in terms of squared amplitude per unit frequency, as expressed by Equation (2).

$$X_{\text{PSD}} = \lim_{\Delta f \to 0,\, T \to \infty} \frac{1}{(\Delta f)T} \int_0^T x^2(f_0, \Delta f, t)\,\mathrm{d}t \tag{2}$$

where

X_{PSD} is the power spectral density of a time signal x;

Δf is the bandwidth of the frequency interval in hertz, Hz;

T is the averaging time in seconds, s.

NOTE 2 In the case of a Discrete Fourier Transform of a sampled signal, the PSD may be defined as the squared magnitude of the components of the Fourier series divided by the effective bandwidth of the (narrow) bands of the Fourier spectrum (see 9.4)

NOTE 3 In the case of spectral analysis of a pavement surface profile, the signal is not a function of time but of evaluation length l. The Power Spectral Density may then be given as a function of the spatial frequency or the (texture) wavelength and will be expressed in the unit $\text{m}^2/\text{m}^{-1} = \text{m}^3$ or in the unit m^2/mm, respectively.

NOTE 4 The word “Power” in this designation originates from electric and acoustic signal terminology where signals incorporate actual power and where the squared amplitude is a measure of this power.

4 Basic outline of methodologies of spatial frequency analysis

Principally, there are three alternative methods to obtain a spatial frequency spectrum in constant-percentage bandwidth bands of octave- or one-third-octave width. These three methods are:

Method 1 – analogue constant-percentage bandwidth filtering;

Method 2 – digital constant-percentage bandwidth filtering;

Method 3 – constant narrow bandwidth frequency analysis by means of Discrete Fourier Transform, followed by a transformation of the narrow band spectrum to an octave- or one-third-octave-band spectrum.

All three methods may be expected to give equivalent results (within the confidence intervals arising from measurement and analysis uncertainty), on condition that the signal quality is high (among other things: free of drop-outs), and that in each of the methods, all signal processing components fulfil the requirements specified in this Technical Specification. If, however, the signal is not free from drop-outs, Method 1 is not recommended because it does not include the possibility for treatment of drop-outs, which may lead to erroneous results.

Method 2 and 3 will produce fully equivalent results. Method 3 includes more steps than Method 2, but may offer greater flexibility in the choice of analysis parameters.

The three alternative methods are shown in the scheme of Figure 2. The left path shows the steps for analogue constant-percentage bandwidth filtering, the middle path shows the steps for digital constant-percentage bandwidth filtering and the right path shows the steps for analysis using the Discrete Fourier Transform.

NOTE 1 In the stepwise approach of Method 2, the steps of “digital sampling” and “digital filtering” may be integrated.

NOTE 2 The different steps of Methods 2 and 3 may be implemented in hardware as well as in software.

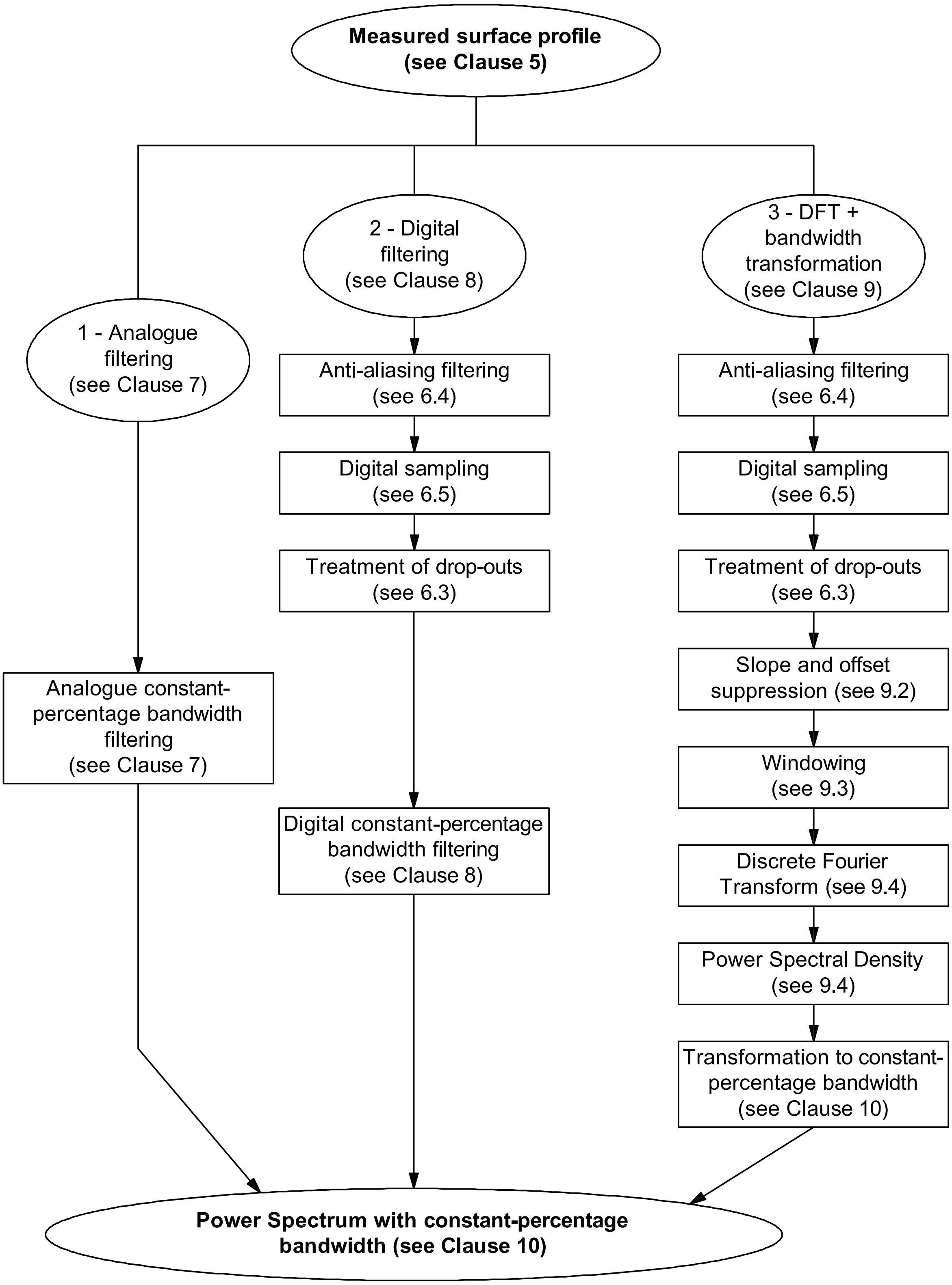


Figure 2 — Scheme for spectral analysis with reference to clauses and subclauses where the subject is discussed

5 Sampling of surface profiles

5.1 Sampling of road sections

The most common and preferred way of sampling the surface profile of a road section is along a straight line in the longitudinal direction of the road. Alternatively, the profilometer may follow other trajectories, adapted to the nature of the survey, e.g. transverse and oblique lines, circles, spirals or sinusoids. Sampling along longitudinal lines may be carried out either in the left or the right wheel track or in between wheel tracks.

In any case, the exact shape and position of the sampling trajectory shall be noted and reported accurately. The spectral analysis shall only be performed on data sets which are derived from a single type of trajectory.

The required evaluation length depends on the frequency analysis to be performed. This leads to the following requirements for the evaluation length l:

$$\begin{array}{ll} l \geqslant 5\,\lambda_{\mathrm{max}} & \text{for octave bands} \\ l \geqslant 15\,\lambda_{\mathrm{max}} & \text{for one-third-octave bands} \end{array} \qquad (3)$$

where λ_{max} is the longest (one-third-) octave-band-centre wavelength used in the spectral analysis.

NOTE These requirements imply that the octave-band levels, respectively one-third-octave band levels, determined over these evaluation lengths will be within a 95%-confidence interval of approximately ± 3 dB around the true band levels (that would result from an infinitely long evaluation length).

For sampling of test sections in the longitudinal direction, the following procedure is recommended.

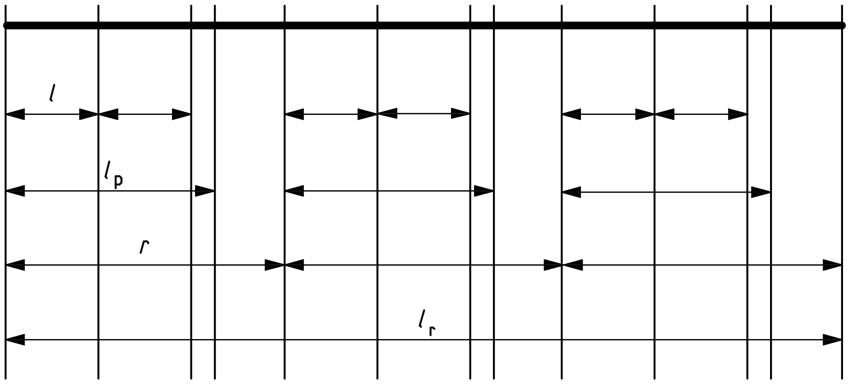
Several profile measurements distributed over the length of the road section shall be carried out. Each profile measurement length and/or evaluation length shall be large enough to meet the requirement for the maximum wavelength of Equation (3). The measured profiles shall be evenly distributed along the test section.

The number of profile measurements shall be such that the surface characteristics are well represented by the measured parts of the test section. The profiles measured shall be analysed separately. When the profiles measured constitute a representative sample from the test section under consideration, the relative standard deviation may be regarded as an estimate of the degree of variation of the surface characteristics along the test section.

It is recommended that each evaluation length be at least 1 m; such an evaluation length enables a one-third-octave-band λ_{max} of approximately 0,08 m, which is sufficient to cover the macrotexture range.

EXAMPLE See Figure 3.

length of test section	l_{r}
longest (texture) wavelength	λ_{max}
number of profile measurements	N_{p}
evaluation length	l
profile measurement length	l_{p}
repetition interval	$r = \dfrac{l_{\mathrm{r}}}{N_{\mathrm{p}}}$



The number of profile measurements N_p with profile measurement length l_p can each be divided into parts with evaluation length l.

Figure 3 — Test section of length l_r measured with a repetition interval r

5.2 Measurement of laboratory samples

When testing road surface samples in the laboratory, it is advisable to use the largest samples available and to make maximum use of the dimensions of the sample. Rectangular samples should be scanned by the profilometer along parallel lines. The evaluation length l will be equal to the length of one uninterrupted scanned line.

Round samples may be scanned along the diameter or along a spiral or circular trajectory. The evaluation length l will be equal to the length of the uninterrupted scanned trajectory.

The relationship between the evaluation length l and the longest centre wavelength (λ_{max}) to be used in the spectral analysis according to Equation (3) is also applicable in the case of laboratory sample testing.

NOTE It is advisable to maintain a distance between parallel sampling lines or between the subsequent parts of a spiral trajectory such that the digital samples on one line or part of the trajectory can be considered to be statistically independent from the digital samples on neighbouring lines, in relation to the range of wavelengths included in the spectral analysis.

6 General principles and requirements

6.1 Requirements concerning profilometers

The profilometer used to trace and/or sample the pavement texture irregularities shall comply with all requirements specified in ISO 13473-3 that are applicable to the wavelength range class under observation. If several wavelength range classes are being observed, the strictest requirements of these ranges shall be fulfilled.

6.2 Conversion of spatial frequencies to temporal frequencies

6.2.1 General

When sampling a texture with a measurement speed v (in m/s), the signal obtained will be a function of time. The frequencies within the time signal are defined as temporal frequencies f_{tp} (in Hz or s^{-1}). The temporal frequency is related to the spatial frequency f_{sp} (in m^{-1}) according to:

$$f_{tp} = v f_{sp} \quad (4)$$

A relative change in speed $\Delta v / v$ will cause a relative change in temporal frequency $\Delta f_{\text{tp}} / f_{\text{tp}}$ given by:

$$\frac{\Delta f_{\text{tp}}}{f_{\text{tp}}} = \frac{\Delta v}{v} \tag{5}$$

The resulting variation of the temporal frequency will cause analysis errors. There are two possible ways to control these errors, which are discussed in the following two sub-clauses.

6.2.2 Minimization of speed variations

Variations in speed shall be slow in comparison to the surface amplitude variations to be detected. Therefore, the maximum frequency of the speed variations as a function of time shall be less than 10 % of the minimum temporal frequency (in Hz) to be analysed.

As well for constant-percentage bandwidth filtering (Methods 1 and 2) as for constant narrow bandwidth frequency analysis followed by conversion to a constant-percentage bandwidth spectrum (Method 3) the amplitude of the speed variations shall comply with the following requirements concerning the maximum relative speed variation over one evaluation length:

For octave-band analysis:	Δv / v shall be smaller than or equal to	10 %
For one-third-octave-band analysis:	Δv / v shall be smaller than or equal to	5 %

NOTE The maximum values of $\Delta v / v$ are chosen such that the maximum error in the power per frequency band resulting from the speed variations will normally not exceed 0,4 dB for a continuous texture spectrum. Larger errors may occur, however, for surfaces with irregular frequency spectra, e.g. grooved pavements (see Annex C).

6.2.3 Real time compensation for speed variations during measurement

An alternative for minimization of speed variations is to compensate for the speed variations and the resulting frequency variations during the execution of the measurement. This shall be done in the following way.

In order to acquire a correct digital representation of the surface profile as a function of the measured distance, it is necessary to take samples at constant sampling intervals Δx along the measurement trajectory. When sampling at a measurement speed v, the signal obtained will be a function of time. For a given temporal sampling frequency $f_{\text{tp,s}}$, the temporal sampling intervals $\Delta t = 1/f_{\text{tp,s}}$ will produce spatial sampling intervals Δx according to:

$$\Delta x = \Delta t \cdot v = \frac{v}{f_{\text{tp,s}}} \tag{6}$$

When the speed is constant, the temporal sampling intervals Δt will be converted into constant spatial sampling intervals Δx. If the speed shows variations, the spatial sampling intervals will vary as well.

This can be prevented by applying a speed dependent sampling frequency. Thus, speed variations are compensated by proportional variations in the temporal sampling frequency so that the resulting spatial sampling intervals remain constant. Speed dependent sampling can be achieved by using a speed dependent signal, e.g. derived from the drive mechanism of a measurement vehicle, to control the sampling frequency generator.

If compensation for speed variations during the execution of the measurement is not possible, the compensation may also be carried out during the processing of the measured data according to the method indicated in Annex D.

6.3 Drop-outs

The measurements on a particular pavement shall be considered valid only if the drop-out rate for the evaluation length in question is not more than 10 % and linear interpolation is used to replace the invalid samples.

Several drop-outs in a series may occur, as is illustrated in Figure 4. When a series of invalid samples is preceded and followed by valid samples, each of the invalid samples shall be replaced by an interpolated value z_i according to Equation (7):

$$z_i = \frac{z_n - z_m}{n - m}\left(i - m\right) + z_m \tag{7}$$

where

i is the sample number where the value is invalid;

m is the sample number of the nearest valid value before i;

n is the sample number of the nearest valid value after i;

z_i is the interpolated value for sample i;

z_m is the value of sample m;

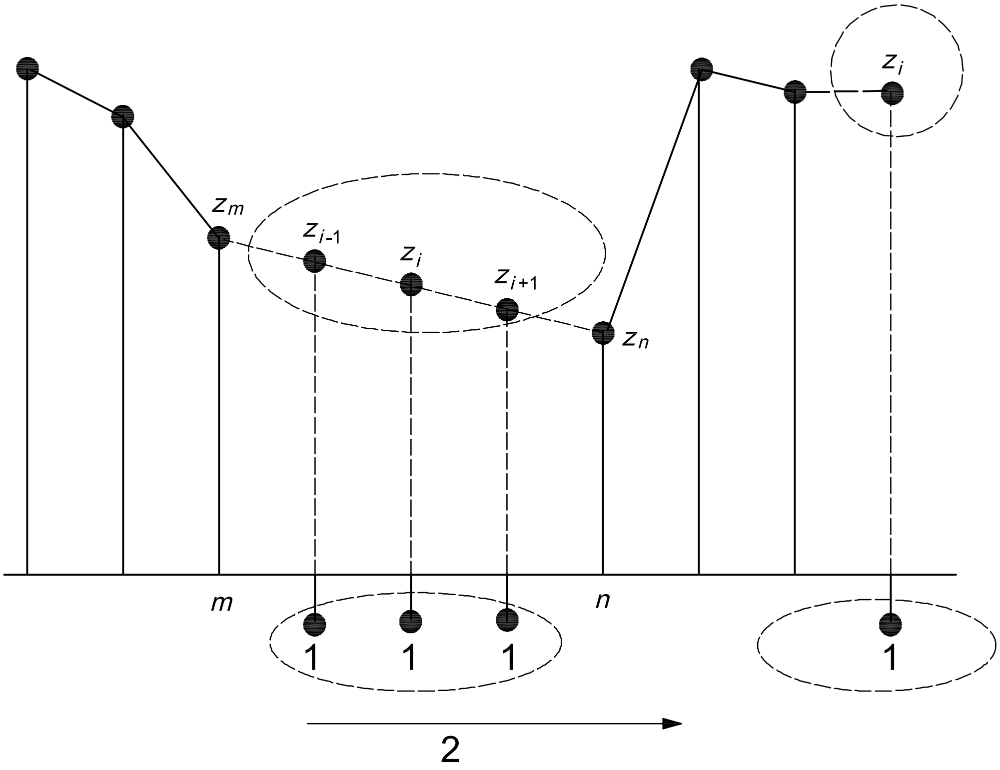
z_n is the value of sample n.

When the invalid sample(s) constitute(s) the beginning or the end of a sampled profile, the invalid samples shall be replaced by the value of the nearest valid sample. This method of extrapolation shall be limited to a maximum length at either side of the sampled profile data series equal to the shortest centre wavelength used in the spectral analysis.

If interpolation or extrapolation is not used, the last reading before the drop-out(s) shall be used as a substitute for the drop-out value(s). In such a case, the drop-out rate shall not exceed 5 %.

Measurements with higher drop-out rates than the allowable values shall be discarded.

NOTE For the evaluation of road surface singularities (such as joints), such singularities may be intentionally included in the analysis, on condition that no invalid readings of the sensor occur.



Key

1 drop-out

2 sample number

NOTE In this case, there are three intermediate consecutive drop-outs, which are linearly interpolated between the samples at position m and n, and one extreme drop-out, which is extrapolated from the preceding sample.

Figure 4 — Illustration of interpolation and extrapolation of drop-outs

6.4 Anti-aliasing filtering

If digital sampling is involved in the spectral analysis method, aliasing errors (see Annex B) may occur. In order to avoid such errors during the spectral analysis, the analogue signal representing the surface profile shall be filtered before digital sampling with a low-pass filter with a cut-off frequency lower than half the sampling frequency.

The filter characteristics shall be such that there is a flat response within 0,4 dB up to the highest frequency to be analysed. The attenuation of the filter at half the sampling frequency shall be 60 dB or more.

If the analogue signal is inherently filtered by the detection process of the profilometer itself (such as the filtering by the spot-size of a laser beam) or by a natural high frequency roll-off, the combined characteristics of this inherent filtering and the anti-aliasing filter shall meet the above mentioned requirements.

The requirements with respect to the filter characteristics may be alleviated if it can be determined from preliminary information that the surface profile spectrum will be continuous and smooth in the frequency range of interest.

6.5 Digital sampling

When the spectral analysis method involves digital sampling, it shall be performed at spatial sampling intervals Δx that are determined according to ISO 13473-3 for the shortest wavelength involved in the spectral analysis.

The required temporal sampling frequency $f_{\text{tp, s}}$ (in Hz) for a moving profilometer can be obtained from the requirement concerning the spatial sampling interval Δx (in m) and the measurement speed of the profilometer v (in m/s) by:

$$f_{\text{tp,s}} = \frac{v}{\Delta x} \tag{8}$$

Sampling shall be performed with constant (spatial) sampling intervals. To maintain a constant sampling interval, it is recommended that the temporal sampling frequency be adjusted continuously to the measurement speed (see Annex D). If this method of compensation is not possible, variations in the measurement speed will cause analysis errors, which shall remain relatively small. If digital sampling is used to derive an octave- or one-third-octave-band spatial frequency spectrum, the requirements for the maximum relative speed variation of 6.1 apply.

If the final result of the narrow band analysis by means of Discrete Fourier Transform is a narrow band spectrum, only the method of compensation for the speed variations shall be used to achieve a constant spatial sampling interval.

7 Spectral analysis in constant-percentage bandwidth bands (octave- or one-third-octave bands) by analogue filtering (Method 1)

The method of spectral analysis by analogue constant-percentage bandwidth filtering shall only be used if it can be verified that the measurement signal from the profilometer is completely free of drop-outs. Such verification may consist of detailed visual inspection of the (analogue) recorded profiles or the use of a drop-out detection system on the profilometer.

The analogue signal obtained by tracing the surface profile may be fed directly into analogue octave- or third-octave-band filters. These filters, used for frequency analysis in constant-percentage bandwidth bands, shall have centre texture wavelengths and centre spatial frequencies according to ISO 13473-2:2002 (4.4 and Table 1), which is established so as to numerically correspond to the bands specified in IEC 61260. The upper and lower cut-off (–3 dB) frequencies of each band, as well as the shape of the filter frequency response shall conform to IEC 61260.

Frequency analysis by analogue filtering may be applied directly to the time signal resulting from the measurement of the surface profile with a profilometer with a measurement speed v. The temporal frequency and the pass band of the filters shall be adapted to the measurement speed. If $f_{\text{sp,m}}$ is the mid-band frequency of the required spatial frequency band, the temporal centre frequency $f_{\text{tp, m}}$ of the filter shall be:

$$f_{\text{tp,m}} = v\, f_{\text{sp,m}} \tag{9}$$

For standardized band pass filters with a fixed series of temporal centre frequencies, the speed of the measurement shall be adjusted such that the filtering corresponds to the preferred spatial frequency bands (compliant with Table 1 of ISO 13472-2:2002). Using the preferred base-ten system, the measurement shall be conducted at one of the speeds determined according to Equation (10):

$$\begin{aligned} v &= 3{,}6 \cdot 10^{\frac{3n}{10}} \quad \text{km/h} \qquad \text{for} \quad \text{one-octave bands} \\ v &= 3{,}6 \cdot 10^{\frac{n}{10}} \quad \text{km/h} \qquad \text{for} \quad \text{one-third-octave bands} \end{aligned} \tag{10}$$

where n is an integer, the value of which can be freely chosen from the series: …, –2, –1, 0, 1, 2, … in order to obtain a desired speed.

In Table 1, the one-third-octave-band spatial frequencies are listed with the required temporal frequencies for three different examples of measurement speeds from the series defined by Equation (10).

Table 1 — List of one-third-octave-band spatial frequencies and the required one-third-octave-band temporal frequencies for three different measurement speeds

Texture wavelength in mm	One-third-octave-band spatial frequency in m^{-1}	One-third-octave-band temporal frequency at speed 18 km/h in Hz	One-third-octave-band temporal frequency at speed 36 km/h in Hz	One-third-octave-band temporal frequency at speed 72 km/h in Hz
500	**2,00**	10,0	20,0	40,0
400	2,50	12,5	25,0	50,0
315	3,15	16,0	31,5	63,0
250	**4,00**	20,0	40,0	80,0
200	5,00	25,0	50,0	100
160	6,30	31,5	63,0	125
125	**8,00**	40,0	80,0	160
100	10,0	50,0	100	200
80,0	12,5	63,0	125	250
63,0	**16,0**	80,0	160	320
50,0	20,0	100	200	400
40,0	25,0	125	250	500
31,5	**31,5**	160	315	630
25,0	40,0	200	400	800
20,0	50,0	250	500	1 000
16,0	**63,0**	315	630	1 250
12,5	80,0	400	800	1 600
10,0	100	500	1 000	2 000
8,00	**125**	630	1 250	2 500
6,30	160	800	1 600	3 200
5,00	200	1 000	2 000	4 000
4,00	**250**	1 250	2 500	5 000
3,15	315	1 600	3 150	6 300
2,50	400	2 000	4 000	8 000
2,00	**500**	2 500	5 000	10 000
1,60	630	3 150	6 300	12 500
1,25	800	4 000	8 000	16 000
1,00	**1 000**	5 000	10 000	20 000
0,80	1 250	6 300	12 500	25 000
0,63	1 600	8 000	16 000	32 000
0,50	**2 000**	10 000	20 000	40 000
0,40	2 500	12 500	25 000	50 000

NOTE Otave-band frequencies are printed in bold.

8 Spectral analysis in constant-percentage bandwidth bands (octave- or one-third-octave bands) by digital filtering (Method 2)

The method of constant-percentage bandwidth filtering by means of digital filters shall be conducted according to the following steps:

a) anti-aliasing filtering according to 6.4;

b) digital sampling according to 6.5;

c) interpolation of drop-outs (if needed) according to 6.3;

d) digital constant-percentage bandwidth filtering.

The last step mentioned above shall be performed with digital octave- or one-third-octave-band filters. These filters shall have centre texture wavelengths and centre spatial frequencies according to ISO 13473-2:2002 (4.4 and Table 1), which are established so as to numerically correspond to the bands specified in IEC 61260. The upper and lower cut-off (–3 dB) frequencies of each band, as well as the shape of the filter frequency response shall conform to IEC 61260.

If digital filtering is applied to the sampled time signal resulting from the measurement of the surface profile, the temporal frequency and the pass-band of the filters shall be adapted to the measurement speed v as specified in Clause 7, Equation (9) and Equation (10) and examples in Table 1.

9 Spectral analysis in narrow constant bandwidth bands by means of Discrete (Fast) Fourier Transform methods (Method 3)

9.1 Overview of methodology

The methodology to derive a constant-percentage bandwidth power spectrum from a road surface profile by Discrete Fourier Transform or Fast Fourier Transform consists of the steps listed in Table 2.

Table 2 — List of steps to be performed for Discrete Fourier Transform analysis

Step	Result	Discussed in clause
Anti-aliasing filtering	Analogue signal	6.4
Digital sampling	Digital signal sampled at intervals Δx ($= v/f_s$)	6.5
Interpolation of drop-outs	Digital signal with interpolated values at drop-outs	6.3
Offset suppression	Digital signal with zero average	9.2
Slope suppression	Digital signal with zero slope	9.2
Windowing	Finite sampled signal with length $l = \Delta x \cdot N$ with N being the number of samples	9.3
Discrete Fourier Transform	Complex spectrum with constant bandwidth $\Delta f_{sp} = 1/l$ at frequencies 0 ... $(N - 1)\ \Delta f_{sp}$	9.4
Transformation to Power Spectral Density	Power density spectrum with constant bandwidth $\Delta f_{sp} = 1/l$ at frequencies 0 ... $(N - 1)\ \Delta f_{sp}$	9.4
Transformation to constant relative bandwidth spectrum	Profile level spectrum with constant-percentage bandwidth	10

NOTE The Discrete Fourier Transform is a Fourier transform of a sampled signal with a finite number of samples. Mostly, it is referred to as Fast Fourier Transform (FFT). The adjective “Fast” refers to the efficient algorithm that is used for the transformation. The algorithm works most efficiently when the number of samples is a power of 2. In many programming languages where the Fourier transform is referred to as FFT, the language simply uses the fastest possible algorithm. Some programming languages might require that the number of samples be a power of 2. A Fourier transform for an arbitrary number of samples could be indicated as DFT (Discrete Fourier Transform). In this document, no distinction will be made between Discrete Fourier Transform and Fast Fourier Transform; both will be indicated as DFT.

9.2 Slope and offset suppression

Let z_i be the measured signal value for sample i at x_i and N be the number of samples within the evaluated signal, then the slope b_1 of the surface profile is given by:

$$b_1 = \frac{12\sum_{i=0}^{N-1} i z_i - 6(N-1)\sum_{i=0}^{N-1} z_i}{N(N+1)(N-1)} \qquad (11)$$

The offset b_0 of the surface profile is given by:

$$b_0 = \frac{1}{N}\sum_{i=0}^{N-1} z_i - b_1 \cdot \tfrac{1}{2}(N-1) \qquad (12)$$

The measured signal value z_i shall be corrected for slope and offset according to Equation (13) resulting in the corrected sampled signal value Z_i:

$$Z_i = z_i - b_1 i - b_0 \qquad \text{for} \quad i = 0,\ldots, N-1 \qquad (13)$$

NOTE For the calculation of the slope and offset correction, the surface profile is treated as a function of the sample number i, and not of the measured distance x (= $i\,\Delta x$).

9.3 Windowing

The Discrete Fourier Transform is based on the assumption that the input signal repeats itself with a period equal to the signal duration. For instance, a signal sampled over a distance l is considered to repeat itself at …, $-2l$, $-l$, 0, l, $2l$, ..., etc. At the edges of the signal, there might be a jump in the composite signal, this effect is known as leakage. Leakage has its effect on the spectrum that is obtained. To prevent leakage, a window, which reduces the signal to zero at the edges, shall be applied.

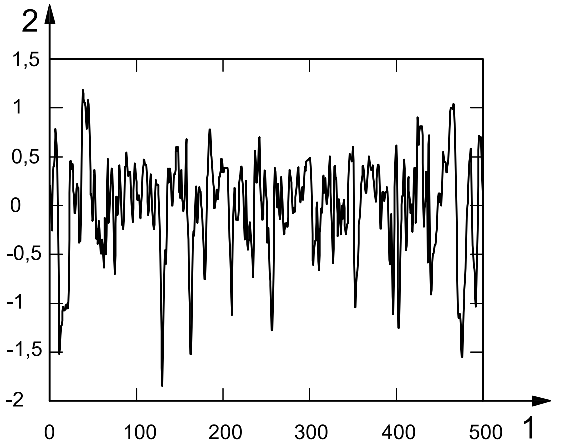
The preferred window type to be used for spectral analysis of surface profiles is the Hanning window. This window has the shape of a squared cosine and is defined as:

$$w_{i,H} := \frac{1-\cos(2\pi\, i/N)}{2} = 1-\cos^2\left(\frac{\pi\, i}{N}\right) \quad \text{for} \qquad i = 0,\ldots,N-1 \qquad (14\text{ a})$$

Because of its shape, the Hanning window reduces the effective length of a signal, which influences the low frequency content of the signal. Therefore, an alternative window, the Split Cosine Bell Window (SCBW; sometimes indicated as Cosine Digital Tapering Window) may be used if the evaluation length of the profile is shorter than 1,0 m. The shape of the SCBW is that of an increasing squared cosine in the first tenth of the window length and a decreasing squared cosine in the last tenth. In the intermediate section of eight tenths of the length, the window is equal to unity, as follows:

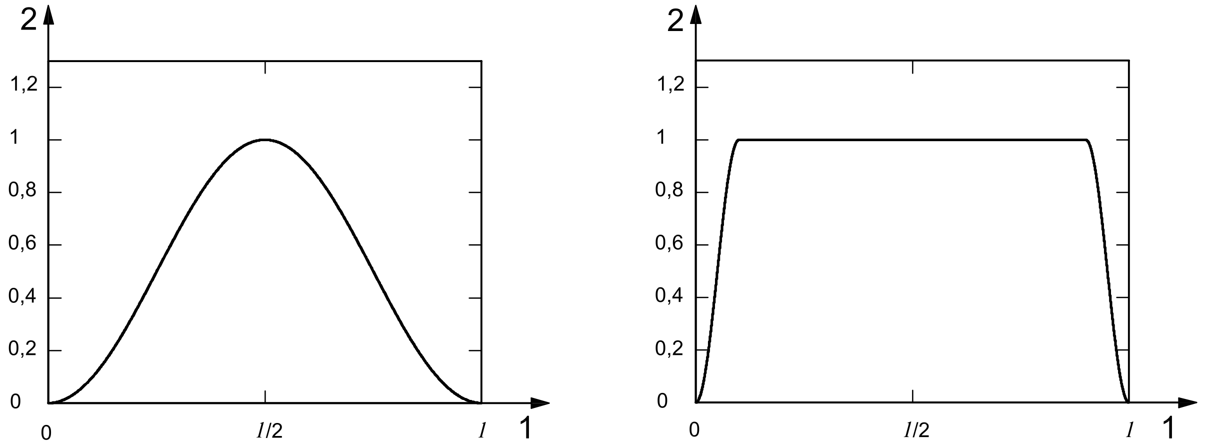
$$w_{i,\mathrm{C}} := \begin{cases} \cos^2\left(\dfrac{5\pi\, i}{N} - \dfrac{\pi}{2}\right) & \text{for } 0 \leqslant i < N/10 \\ 1 & \text{for } N/10 \leqslant i \leqslant 9N/10 \\ \cos^2\left(\dfrac{5\pi\, i}{N} - \dfrac{9\pi}{2}\right) & \text{for } 9N/10 < i < N \end{cases} \qquad (14\text{ b})$$

A disadvantage of the SCBW is a loss of spectral resolution compared to the Hanning window, caused by spectral errors due to side-lobe leakage. Therefore, the use of the SCBW is not generally recommended and, when it is used, this fact shall be stated clearly in the analysis report. However, actual roads do not tend to have such regular deformations that very specific wavelength peaks are normally present in the spectrum. Consequently, the spectral resolution will not always be an important issue.



Key
1 distance (mm)
2 amplitude (mm)

a) **Measured road surface**

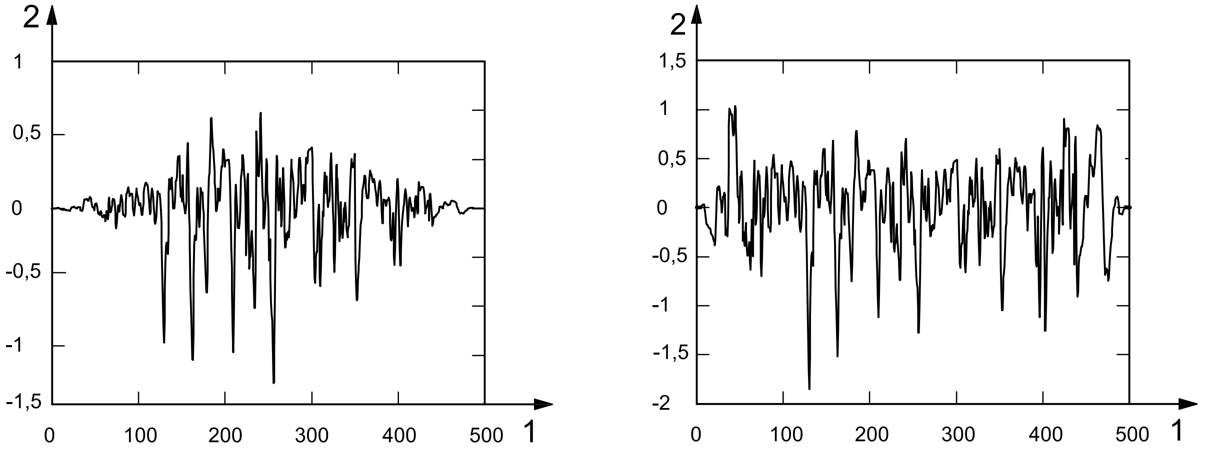


Key
1 length
2 amplitude

Key
1 length
2 amplitude

b) **Hanning window**

c) **Split Cosine Bell Window (SCBW)**



Key
1 distance (mm)
2 amplitude (mm)

Key
1 distance (mm)
2 amplitude (mm)

d) **Measured road surface after windowing (Hanning)**

e) **Measured road surface after windowing (SCBW)**

Figure 5 — An illustration of the application of a Hanning window and a Split Cosine Bell Window (SCBW)

The window shall be applied by simply multiplying the signal with the filter function (see Figure 5). Because the signal will be attenuated by this operation, it shall be normalized by dividing the product by the integral of the window. Therefore, the window shall be applied as follows:

For the Hanning window:

$$Z_{i,\text{ win}} = \frac{w_{i,\text{H}}\, Z_i}{0{,}612\,4} \qquad \text{for } i = 0, \ldots, N-1 \tag{15 a}$$

For the Split Cosine Bell Window:

$$Z_{i,\text{ win}} = \frac{w_{i,\text{C}}\, Z_i}{0{,}935\,4} \qquad \text{for } i = 0, \ldots, N-1 \tag{15 b}$$

The general equation for determining the windowed profile is given in Equation (15 c):

$$Z_{i,\text{win}} = \frac{w_i\, Z_i}{\sqrt{\frac{1}{N}\sum_{i=0}^{N-1} w_i^2}} \qquad \text{for} \qquad i = 0, \ldots, N-1 \tag{15 c}$$

9.4 Discrete Fourier Transform and Power Spectral Density

The Discrete Fourier Transform (DFT) Z_k of the windowed profile is defined by:

$$Z_k = \frac{1}{N}\sum_{i=0}^{N-1} Z_{i,\text{win}}\, \mathrm{e}^{-j\left(\frac{2\pi k}{N}\right)i} \qquad \text{for} \qquad k = 0, \ldots, N-1 \tag{16}$$

in which j is the imaginary unit ($j^2 = -1$).

NOTE 1 Z_k is a function of the spatial frequency, while $Z_{i,\text{ win}}$ is a function of the measured distance. Thus, the DFT comprises a transformation from the distance domain to the spatial frequency domain.

In some software packages that provide a DFT or FFT, this definition may be different, where the factor $1/N$ is sometimes disregarded or replaced by $1/\sqrt{N}$. This can be checked by applying Parseval's theorem defined by:

$$\sum_{i=0}^{N-1} \left|Z_{i,\text{win}}\right|^2 = N\sum_{k=0}^{N-1} \left|Z_k\right|^2 \tag{17}$$

If Equation (17) proves to be true, the DFT is in accordance with Equation (16); if not, the documentation of the software should be checked for the definition used.

NOTE 2 Equation (17) compares the total power of the signal in the distance domain with the total power of the signal in the spatial frequency domain and thus checks whether the law of the conservation of energy is satisfied.

The result of the DFT is a constant bandwidth narrow band spectrum with complex values. The bandwidth depends on the evaluation length l and is equal to:

$$\Delta f_{\text{sp}} = \frac{1}{l} \tag{18}$$

The frequency scale starts at 0 with steps equal to Δf_{sp} until $(N-1)\Delta f_{\text{sp}}$ (note: $N\Delta f_{\text{sp}} = 1/\Delta x$). Only the frequencies up to $(½N-1)\Delta f_{\text{sp}}$ shall be used for further evaluation.

To obtain the power spectral density (PSD) from the results of a DFT the amplitude of each narrow band shall be squared and divided by the spectral bandwidth according to Equation (19):

$$Z_{\mathrm{PSD},k} = \frac{2\left|Z_k\right|^2}{\Delta f_{\mathrm{sp}}} \quad \text{for} \quad k = 0,\ \ldots,\ (\tfrac{1}{2}N - 1) \tag{19}$$

The narrow band spectral value of the profile level $L_{\mathrm{tx},k}$ is calculated with:

$$L_{\mathrm{tx},k} = 10\lg\left(2\left|\frac{Z_k}{a_{\mathrm{ref}}}\right|^2\right) \quad \text{for} \quad k = 0,\ \ldots,\ (\tfrac{1}{2}N - 1) \tag{20}$$

where

a_{ref} is the reference value of the surface profile amplitude ($= 10^{-6}$ m);

$L_{\mathrm{tx},k}$ is the profile level within frequency band f_k with bandwidth Δf_{sp} (dB).

9.5 Wavelength resolution

For a constant narrow bandwidth spectrum, the spatial frequency resolution is constant for all spatial frequencies. The spatial wavelength resolution $\Delta\lambda_{\mathrm{sp}}$, on the other hand, is not constant but depends on the centre spatial wavelength λ_{sp} ($= 1/f_{\mathrm{sp}}$) itself, and can be described according to Equation (21) (see Annex E):

$$\Delta\lambda_{\mathrm{sp}} = \frac{l\ \lambda_{\mathrm{sp}}^2}{l^2 - \frac{1}{4}\lambda_{\mathrm{sp}}^2} \tag{21}$$

10 Transformation of constant bandwidth spectral data to constant-percentage bandwidth spectral data

The transformation of a constant bandwidth spectrum to a constant-percentage bandwidth spectrum can be performed according to the procedure specified below, which is valid only for a transformation on the spatial frequency scale. A procedure for a transformation on the wavelength scale would require other, more complex equations.

For the derivation of a constant-percentage bandwidth spectrum from a constant bandwidth spectrum, the band pass (fractional-octave-band) filters may be assumed to be “ideal”, i.e. the pass-band is a square window in the frequency domain. The total power within this window is obtained by summation of all narrow band power contributions falling within this square window (see Figure 6). The power of a narrow band that coincides with the boundary between two consecutive fractional-octave bands is divided proportionally over these fractional-octave bands.

The power $Z_{\mathrm{p},m}$ within the fractional-octave band m is thus calculated from the narrow band power spectral density according to Equation (22).

$$\begin{aligned} Z_{\mathrm{p},m} \ = \ & Z_{\mathrm{PSD,\,lo}} \cdot \left(f_{\mathrm{sp,lo}} + \tfrac{1}{2} \cdot \Delta f_{\mathrm{sp}} - 10^{\frac{-1{,}5}{10n}} f_{\mathrm{sp},\,m} \right) + \\ & \sum_{k=\mathrm{lo}+1}^{\mathrm{up}-1} Z_{\mathrm{PSD},\,k} \cdot \Delta f_{\mathrm{sp}} + \\ & Z_{\mathrm{PSD,\,up}} \cdot \left(10^{\frac{1{,}5}{10n}} f_{\mathrm{sp},\,m} - f_{\mathrm{sp,\,up}} + \tfrac{1}{2} \cdot \Delta f_{\mathrm{sp}} \right) \end{aligned} \tag{22}$$

where

$f_{\mathrm{sp},m}$ is the centre frequency of the fractional-octave band m;

$f_{\mathrm{sp,lo}}$ is the centre frequency of the narrow band that coincides with the lower boundary of the fractional-octave band;

$Z_{\mathrm{PSD,lo}}$ is the Power Spectral Density of the narrow band that coincides with the lower boundary of the fractional-octave band;

$f_{\mathrm{sp,up}}$ is the centre frequency of the narrow band that coincides with the upper boundary of the fractional-octave band;

$Z_{\mathrm{PSD,up}}$ is the Power Spectral Density of the narrow band that coincides with the upper boundary of the fractional-octave band.

NOTE Equation (22) consists of three parts: 1) the proportional part of the power of the narrow band coinciding with the lower boundary of the fractional octave; 2) the summation of all narrow bands falling within the fractional-octave; and 3) the proportional part of the power of the narrow band coinciding with the upper boundary of the fractional octave.

The lower boundary frequency of the fractional-octave band m is: $10^{\frac{-1,5}{10n}}\, f_{\mathrm{sp},m}$;

and has the following relationship to $f_{\mathrm{sp,\,lo}}$:

$$f_{\mathrm{sp,\,lo}} - \tfrac{1}{2}\Delta f_{\mathrm{sp}} \;<\; 10^{\frac{-1,5}{10n}}\, f_{\mathrm{sp},m} \;<\; f_{\mathrm{sp,\,lo}} + \tfrac{1}{2}\Delta f_{\mathrm{sp}}$$

The upper boundary frequency of the fractional-octave band m is: $10^{\frac{1,5}{10n}}\, f_{\mathrm{sp,m}}$;

and has the following relationship to $f_{\mathrm{sp,\,up}}$:

$$f_{\mathrm{sp,\,up}} - \tfrac{1}{2}\Delta f_{\mathrm{sp}} \;<\; 10^{\frac{1,5}{10n}}\, f_{\mathrm{sp},\,m} \;<\; f_{\mathrm{sp,\,up}} + \tfrac{1}{2}\Delta f_{\mathrm{sp}}$$

The fractional-octave-band (texture) profile level is calculated with:

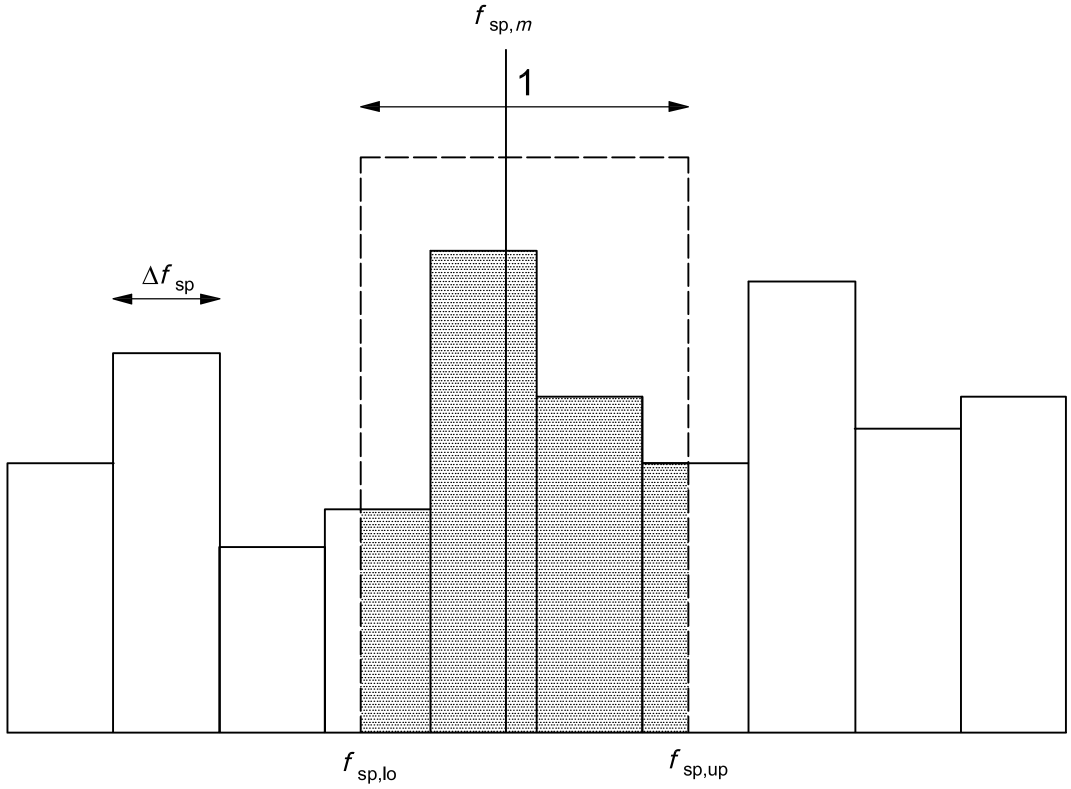
$$L_{\mathrm{tx},m} = 10\,\lg\left(\frac{Z_{\mathrm{p},m}}{a_{\mathrm{ref}}^{2}}\right)\ \mathrm{dB} \tag{23}$$

where

a_{ref} is the reference value of the surface profile amplitude ($= 10^{-6}$ m);

$L_{\mathrm{tx},m}$ is the (texture) profile level within fractional-octave band m (ref. 10^{-6} m), in decibels.

In the case of octave-band filtering, the profile level shall be indicated as $L_{\mathrm{TX},m}$ (TX written as capitals).



Key

1 passband of 1/*n*-octave band

The power contained within the narrow bands coinciding with the upper and lower fractional-octave-band boundaries is allocated proportionally to the adjacent fractional-octave bands.

Figure 6 — Illustration of the allocation of the power contained within the narrow bands to a specific fractional-octave band

11 Uncertainty of analysis results

The uncertainty of results obtained from spectral analysis of pavement surface profiles according to this Technical Specification shall be evaluated, preferably in compliance with the ISO/IEC Guide 98-3. If reported, the expanded uncertainty together with the corresponding coverage factor for a stated coverage probability of 95 % as defined in the ISO/IEC Guide 98-3 shall be given. Guidance on the determination of the expanded uncertainty is given in Annex A.

The uncertainty of the results of spectral analysis of pavement surface profiles will be determined by contributions from two main origins:

- the uncertainty of the measured surface profile signal, which constitutes the data input for the spectral analysis process;
- the added uncertainty caused by the spectral analysis process itself.

For the evaluation of the combined standard uncertainty and the expanded uncertainty of the octave-, one-third-octave- or fractional-octave-band levels resulting from the spectral analysis methods, the contributions from both origins shall be taken into account. In this Technical Specification, the emphasis is on the contribution of the spectral analysis process.

12 Reporting of analysis results

When reporting analysis results, the following information shall be included:

1) date of measurement;
2) location and identification of the road section or laboratory test samples measured;
3) description of the type of road surface measured;
4) description of the surface condition, (contamination, moisture, deterioration, cracks, joints, etc.);
5) shape, position and orientation of the sampling trajectory;
6) total length of the measured road section or dimensions of laboratory test samples;
7) repetition interval;
8) evaluation length;
9) number of evaluations within one profile measurement;
10) measurement speed and variation;
11) horizontal and vertical resolution of the sensor;
12) list of equipment used (manufacturer, type and serial number);
13) description of the characteristics of the analysis: analysis method, interpolation or not, type of window, octave, one-third-octave or fractional-octave band;
14) drop-out rate;
15) octave-, one-third-octave- or fractional-octave-band levels presented as an arithmetic average over all evaluation lengths of a test section, presented in tabular and in graphic form;
16) optional: standard deviations of the individual octave-, one-third-octave- or fractional-octave-band levels over all evaluation lengths of a test section, presented as numerical values in tabular form and as uncertainty areas on either side of the average values in the graphic form;
17) optional: the octave-, one-third-octave- or fractional-octave-band levels for each evaluation length of the test section, presented in tabular form or in graphic form;
18) optional: expanded uncertainty of the results specified under 15), 16) and 17), determined according to the method given in Annex A.

NOTE The items “interpolation” and “type of window” as mentioned under 13) do not apply when analogue filtering (Method 1) is used.

Annex A
(normative)

Uncertainty of spectral analysis results

A.1 General

The final results of the spectral analysis methods treated in this Technical Specification consist of octave-, third-octave or fractional-octave-band levels, which together constitute a spectral representation of a road surface profile. The method does not constitute a complete measurement method, but only a method of processing of data that are acquired according to measurement methods that are not treated in this document.

Therefore, the uncertainty of the final result can only partially be attributed to factors discussed in this document. Other contributions to this uncertainty will be determined by factors related to the measurement process. The uncertainty contributions from the first group of factors will be analysed and discussed in this annex. The uncertainty contributions from the second group must be derived from standards describing the measurement methods. The measured surface profiles will be considered as input data and the propagation of the uncertainty of the input data to the output of the spectral analysis process will be discussed in this annex too.

The format for expression of uncertainties in this annex is in conformity to ISO/IEC Guide 98-3. This format incorporates an uncertainty budget, in which all the various sources of uncertainty are identified and quantified, from which the combined standard uncertainty can be obtained. The (quantitative) data necessary to calculate the combined standard uncertainty are only partially available at the moment. In so far as the uncertainty contributions cannot be quantified, indications are given of possible assessment methods for such quantification.

Finally, in accordance with ISO/IEC Guide 98-3, the combined standard uncertainty must be multiplied with a coverage factor in order to achieve an expanded uncertainty with a coverage probability of 95 %.

A.2 Expression for the calculation of the fractional-octave-band levels

The general expression for the calculation of the fractional-octave-band level, $L_{\mathrm{tx},m}$, is given by the following equation:

$$L_{\mathrm{tx},m} = \overline{L_{\mathrm{tx},m}} + \varDelta_{\mathrm{meas}} + \delta_{\mathrm{length}} + \delta_{\mathrm{speed}} + \delta_{\mathrm{drop}} + \delta_{\mathrm{alias}} + \delta_{\mathrm{slope}} + \delta_{\mathrm{window}} + \delta_{\mathrm{filter}} \tag{A.1}$$

where

$\overline{L_{\mathrm{tx},m}}$	is the expectation (mean value) of the result of the spectral analysis, expressed as the fractional-octave-band level derived from Equation (23);
$\varDelta_{\mathrm{meas}}$	is the Fourier Transform of an input quantity to account for any deviation caused by the measurement process of the surface profile [which is transformed into a deviation of the spectral values by propagation through the spectral analysis process (see A.3.2)];
δ_{length}	is an input quantity to account for any deviation caused during the spectral analysis process by possible limitations of the evaluation length;
δ_{speed}	is an input quantity to account for any deviation caused during the spectral analysis process by variations of the measurement speed;
δ_{drop}	is an input quantity to account for any deviation caused during the spectral analysis process by the occurrence of drop-outs;

δ_{alias}	is an input quantity to account for any deviation caused during the spectral analysis process by imperfections of the anti aliasing-filter;
δ_{slope}	is an input quantity to account for any deviation caused during the spectral analysis process by imperfections in the slope and offset suppression;
δ_{window}	is an input quantity to account for any deviation caused during the spectral analysis process by a reduction of the effective signal length due to windowing;
δ_{filter}	is an input quantity to account for any deviation caused during the spectral analysis process by imperfections of the pass band characteristics of the octave-, one-third-octave- or fractional-octave filters (analogue or digital).

NOTE The input quantities included in Equation (A.1) to account for uncertainty contributions are those thought to be applicable in the state of knowledge at the time of preparing this Technical Specification, but further research could reveal other types of uncertainty contributions.

A.3 Contributions to the spectral analysis uncertainty

A.3.1 General

As expressed in Equation (23), the expectation (mean value) of the fractional-octave-band level $\overline{L_{\text{tx},m}}$ is a logarithmic function of the power $Z_{\text{p},m}$ contained within the fractional-octave band m, which in turn is obtained from the measured quantity z_i in a series of conversion steps, expressed by the Equations (13), (15c), (16), (19) and (22).

Consequently, the input quantity Δ_{meas} to account for the combined deviations resulting from the measurement process must be derived from the measurement uncertainty of the measured quantity z_i. This uncertainty will be specified in the International Standard describing the specifications for profilometers (ISO 13473-3). The way the measurement uncertainty of z_i is propagated through the spectral analysis process into a (partial) uncertainty associated with $L_{\text{tx},m}$ is described in A.3.2.

The uncertainties associated with the input quantities Δ and δ are assumed to be of a stochastic nature and a probability distribution (normal, rectangular, etc.) is associated with each of these quantities. Its expectation (mean value) is the best estimate for the value of the quantity and its standard deviation is a measure of the dispersion of values, termed standard uncertainty. It is presumed that the mean values of all of the input quantities given in Equation (A.1) are equal to zero. However, in any particular determination of a fractional-octave-band level during the spectral analysis of a road surface profile, the uncertainties do not vanish and they contribute to the combined standard uncertainty associated with the values of the fractional-octave-band levels.

The estimation of the uncertainties associated with the input quantities should preferably be carried out for the actual parameter values and conditions that apply to a specific spectral analysis case. In A.3.3, there is a discussion of how the uncertainties can be evaluated and indications are given of typical values of the standard uncertainties that may be expected for the three spectral analysis methods discussed in Clause 4.

A.3.2 Propagation of measurement uncertainty through the spectral analysis process

If the measurement uncertainty of the measured profile signal z_i has the character of a stochastic non-correlated deviation, this may be written as:

$$z_i = \overline{z_i} + \delta_{\text{meas},i} \qquad \text{(A.2)}$$

where

$\overline{z_i}$	is the expectation (“true” value) of the sampled displacement value of the profile z_i;
$\delta_{\text{meas},i}$	is the random deviation added to each sample i due to inaccuracies of the measurement process.

The Fourier transform of such a simple sum of two variables is equal to the sum of the Fourier transforms. If, according to 9.3, the profile z_i is multiplied with a window function w_i in the spatial domain, this will result in a convolution and a summation in the frequency domain as follows:

$$Z_k = W_k * \overline{Z_k} + W_k * \Delta_{\text{meas},k} \tag{A.3}$$

where

Z_k is the Fourier transform of the sampled displacement values of the profile z_i;

W_k is the Fourier transform of the windowing function w_i;

$\overline{Z_k}$ is the Fourier transform of the expectation of the sampled displacement values of the profile z_i;

$\Delta_{\text{meas},k}$ is the Fourier transform of the random deviation due to inaccuracies of the measurement process $\delta_{\text{meas},i}$.

From this very generally formulated result, it may be inferred that if the uncertainty in the spatial domain has a stochastic nature there will not be a frequency dependency of the uncertainty in the frequency domain.

If the uncertainty has the character of a white noise-like contribution to the profile signal, the spectrum of the uncertainty will be a constant in the frequency domain. This means that the uncertainty will cause a frequency independent increase of the Power Spectral Density of the “true” profile. If this influence is visualized on a logarithmic amplitude scale, the influence will seem larger for those parts of the spectrum with a low value of the PSD.

If presented in octave, third-octave or fractional-octave-band levels on a logarithmic frequency scale, the spectrum of a white noise increases with 3 dB per octave with increasing mid-band frequency. This means that for octave, third-octave or fractional-octave-band representations of the spectrum the influence of this type of uncertainty will increase with frequency.

A.3.3 Uncertainty associated with the input quantities δ

A.3.3.1 Spectral analysis uncertainty originating from evaluation length limitations

As indicated in 5.1, the minimum evaluation length should be 5 times the longest centre wavelength for octave-band analysis and 15 times the longest centre wavelength for one-third-octave-band analysis. If this requirement is observed, the standard uncertainty will be approximately 1,5 dB. When longer evaluation lengths can be applied, the corresponding standard uncertainty will be reduced considerably as indicated in Table A.1.

Table A.1 — Standard uncertainties as a function of evaluation length

Evaluation length expressed in number of wavelengths		**Standard uncertainty**
Octave bands	**One-third-octave bands**	
5 λ_{max}	15 λ_{max}	1,5 dB
15 λ_{max}	45 λ_{max}	1,0 dB
80 λ_{max}	240 λ_{max}	0,5 dB
360 λ_{max}	1 080 λ_{max}	0,25 dB
10 000 λ_{max}	30 000 λ_{max}	0,05 dB

A.3.3.2 Spectral analysis uncertainty originating from speed variations

The values of the standard uncertainty originating from speed variations as given in Table A.2 will be valid if the requirements of 6.2.2 are fulfilled and if the spectrum is continuous and sufficiently flat. For conditions deviating from these assumptions, the standard measurement uncertainties may be assessed according to Annex C.

A.3.3.3 Spectral analysis uncertainty originating from the occurrence of drop-outs

The values of the standard uncertainty originating from drop-out occurrence may be assessed with the aid of results of a study, see Reference [9] in the Bibliography.

If the drop-outs are linearly interpolated and the drop-out percentage does not exceed 10 %, the standard uncertainty may be estimated at 0,5 dB.

If the drop-outs are not interpolated but substituted by the last valid reading and the drop-out percentage does not exceed 5 %, the standard uncertainty may be estimated at 0,5 dB for wavelengths below 0,5 m and at 1,0 dB for wavelengths equal to or larger than 0,5 m.

A.3.3.4 Spectral analysis uncertainty originating from imperfections of anti-aliasing filters

The values of the standard uncertainty originating from imperfections of anti-aliasing filters as given in Table A.2 are estimated in view of the requirements of 6.3. The use of more appropriate values taken from actual specifications or test results of applied anti-aliasing filters is advisable.

A.3.3.5 Spectral analysis uncertainty originating from imperfections in the slope and off-set suppression

Relevant values for the standard uncertainty resulting from this origin have not yet been determined.

A.3.3.6 Spectral analysis uncertainty due to influence of signal windowing

Relevant values for the standard uncertainty resulting from this origin have not yet been determined.

A.3.3.7 Spectral analysis uncertainty originating from imperfections of the octave, one-third octave or fractional-octave-band filters

Relevant values for the standard uncertainty resulting from this origin have not yet been determined.

A.3.4 Assessment of uncertainty contributions

The contributions to the combined uncertainty associated with the value of the fractional-octave-band levels depend on each of the input quantities, their respective probability distributions and sensitivity coefficients, c_i. The sensitivity coefficients are a measure of how the values of the fractional-octave-band level are affected by changes in the values of the respective input quantities. In the model used in Equation (A.1), all sensitivity coefficients have the value 1. The contributions of the respective input quantities to the overall uncertainty are then given by the products of the standard uncertainties and their associated sensitivity coefficients. Thus, the information needed to derive the overall uncertainty is given in Table A.2.

Table A.2 — Uncertainty budget for the determinations of the fractional-octave-band level

Quantity	Estimate in dB	Standard Uncertainty u_i in dB	Further information	Probability Distribution	Sensitivity Coefficient c_i	Uncertainty Contribution $c_i u_i$ in dB
Δ_{meas}	0	*)	See A.3.2	Normal	1	*)
δ_{length}	0	*)	See A.3.3.1	Normal	1	*)
δ_{speed}	0	0,2	See A.3.3.2	Normal	1	0,2
δ_{drop}	0	*)	See A.3.3.3	Normal	1	*)
δ_{alias}	0	0,1	See A.3.3.4	Normal	1	0,1
δ_{slope}	0	*)	See A.3.3.5	Normal	1	*)
δ_{window}	0	*)	See A.3.3.6	Normal	1	*)
δ_{filter}	0	*)	See A.3.3.7	Normal	1	*)

*) To be determined according to specific conditions.

NOTE As explained in A.1, the uncertainty budget given above only contains uncertainty contributions due to spectral analysis. For uncertainty contributions related to the profile measurement process, reference is given to the relevant measurement standard.

A.4 Expanded uncertainty of the spectral analysis

The combined standard uncertainty of the determination of the fractional-octave-band level $u(L_{\text{tx},m})$ is given by the following equation:

$$u(L_{\text{tx},m}) = \sqrt{\sum_{i=1}^{8}(c_i u_i)^2} \qquad \text{(A.4)}$$

ISO/IEC Guide 98-3 requires an expanded uncertainty, U, to be specified, such that the interval $[L_{\text{tx},m} - U, L_{\text{tx},m} + U]$ covers 95 % of the values of $L_{\text{tx},m}$ that might reasonably be attributed to $L_{\text{tx},m}$. To that purpose, a coverage factor, k, is used that depends on the probability distribution associated with the quantity. The expanded uncertainty U shall be calculated according to Equation (A.5):

$$U(L_{\text{tx},m}) = k \cdot u(L_{\text{tx},m}) \qquad \text{(A.5)}$$

If the uncertainties may be assumed to have a normal distribution, the coverage factor k will have an approximate value of 2, which means that the expanded uncertainty is twice the standard uncertainty.

Annex B
(informative)

Aliasing

When sampling a surface profile, the samples represent the texture depth at a discrete place. The distance (or time interval) between two samples defines the minimum wavelength that can be measured properly. In other words, the sampling frequency (f_s) determines the highest frequency to be measured properly.

Figure B.1 shows the result of a specific sampling frequency for different signals:

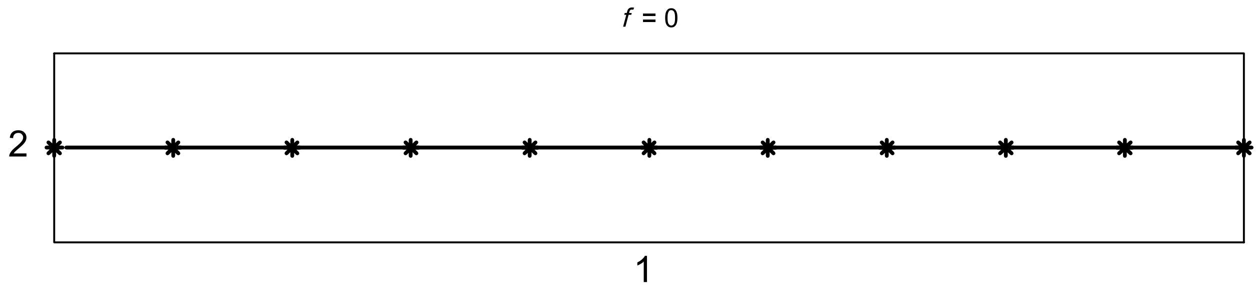
The maximum frequency that can be represented correctly by a sampled signal is half the sampling frequency (the Nyquist frequency). If the signal contains frequency components above the Nyquist frequency, these will be misinterpreted as lower frequencies in the spectrum of the sampled signal. This phenomenon is called "aliasing".

Two classic examples of aliasing are:

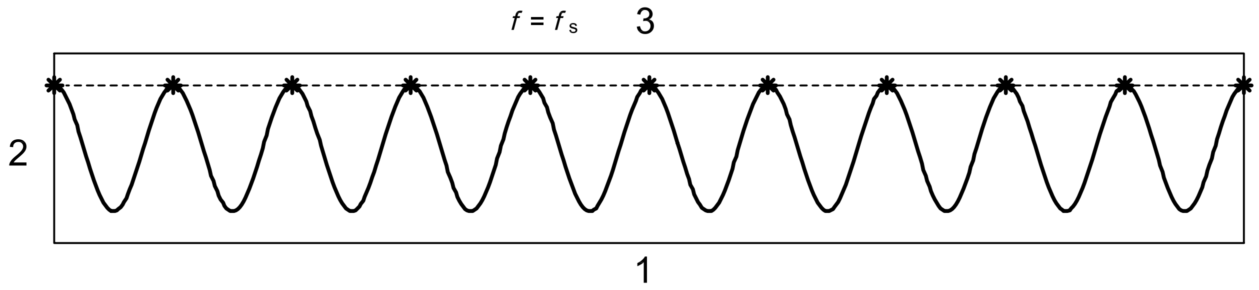
1) the cartwheels in western films often appear to run backwards (i.e. negative frequency) or too slowly forwards because of the sampling involved in filming;

2) the stroboscope is in fact an aliasing device which is designed to represent high frequencies as low ones (even zero frequency when the picture is frozen).

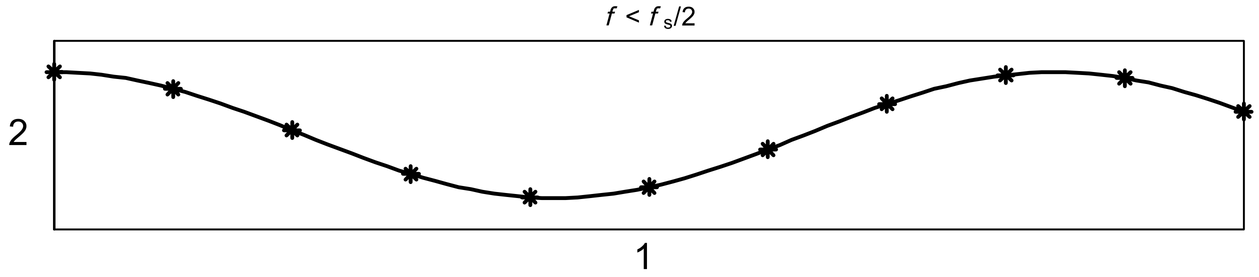
To prevent aliasing, the higher frequency components of the signal should be removed by applying low-pass filtering before sampling, with a cut-off frequency less then half the sampling frequency (in practice, the cut-off frequency will be even lower).



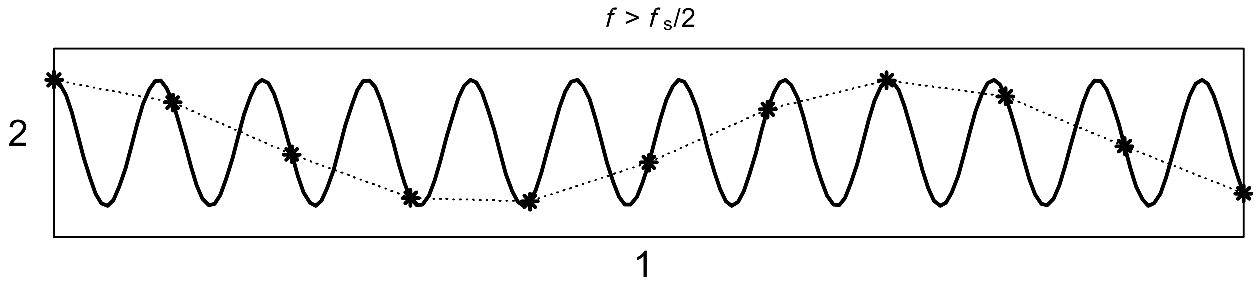
a) **Zero frequency (no amplitude variations)**



b) **Component at sampling frequency** f_s **interpreted as zero frequency**



c) **Frequency component at** $(1/N)\,f_s$;



d) **Frequency component at** $[(N + 1)/N]\,f_s$ **interpreted as** $(1/N)\,f_s$

Key

1 time

2 amplitude

3 (f_s = sampling frequency)

Figure B.1 — Illustration of “aliasing”

Annex C
(informative)

Estimation of the deviation in energy within a frequency band caused by variations in speed

Speed variations will cause a shift in temporal frequency leading to deviations in the value obtained for the energy within a frequency band. To estimate this error, the following approach is used.

As a conservative approach to estimate the deviation, a spectrum is assumed with all its energy within one fractional-octave band and a flat frequency characteristic within this band. If the temporal frequency is shifted, a part of the energy will not remain within this band. The fractional loss of energy can be calculated with the following procedure:

Let $f_{\text{sp},1}$ and $f_{\text{sp},2}$ be the lower and upper boundary respectively of the spatial frequency band in question. The temporal frequencies can be calculated using the measurement speed v:

$$\begin{aligned} f_{\text{tp},1} &= v \cdot f_{\text{sp},1} \\ f_{\text{tp},2} &= v \cdot f_{\text{sp},2} \end{aligned} \tag{C.1}$$

When the speed changes (Δv), the temporal frequencies are:

$$\begin{aligned} f'_{\text{tp},1} &= \left(v + \Delta v\right) f_{\text{sp},1} \\ f'_{\text{tp},2} &= \left(v + \Delta v\right) f_{\text{sp},2} \end{aligned} \tag{C.2}$$

If Δv is positive, the fractional energy loss will be:

$$\Delta P_{\text{fr, pos}} = \frac{f'_{\text{tp},2} - f_{\text{tp},2}}{f_{\text{tp},2} - f_{\text{tp},1}} = \frac{\text{abs}\left(\Delta v\right) f_{\text{sp},2}}{v\left(f_{\text{sp},2} - f_{\text{sp},1}\right)} \tag{C.3}$$

If Δv is negative, the fractional energy loss will be:

$$\Delta P_{\text{fr, neg}} = \frac{f_{\text{tp},1} - f'_{\text{tp},1}}{f_{\text{tp},2} - f_{\text{tp},1}} = \frac{\text{abs}\left(\Delta v\right) f_{\text{sp},1}}{v\left(f_{\text{sp},2} - f_{\text{sp},1}\right)} \tag{C.4}$$

On average, this is:

$$\Delta P_{\text{fr, avg}} = \frac{\text{abs}\left(\Delta v\right)}{2v} \cdot \frac{f_{\text{sp},2} + f_{\text{sp},1}}{f_{\text{sp},2} - f_{\text{sp},1}} \tag{C.5}$$

This equation shows that the deviation increases with frequency and decreases with bandwidth. For constant-percentage bandwidth bands, these effects cancel each other leading to an equation which is only dependent on the relative bandwidth:

$$\Delta P_{\text{fr, avg}} = \frac{\text{abs}\left(\Delta v\right)}{2v} \cdot \frac{10^{\frac{3}{20n}} + 10^{-\frac{3}{20n}}}{10^{\frac{3}{20n}} - 10^{-\frac{3}{20n}}} \tag{C.6}$$

with $n = 1$ for octave bands and $n = 3$ for one-third-octave bands.

Annex D
(informative)

Compensation for speed variations during processing of the measured data

If the speed variations during the measurement of a surface profile are too large to comply with the requirements of 6.2.2, they should be compensated for by using a speed dependent sampling of the surface according to 6.2.3. If the measurement has already been carried out without speed compensation, it is possible to correct for the speed variations during the data processing.

This method requires that the measurement speed be measured at the same sampling rate as the surface profile. From the actual speed values at each sampling point, the actual length of each spatial sampling interval may be determined. The lengths of the intervals in combination with the corresponding surface profile values yield a series of non-uniformly spaced surface profile values.

By using an appropriate interpolation method from a data processing software package, this may be transformed into a series of uniformly spaced surface profile values, that can be processed according to the methods 2 (Clause 8) or 3 (Clause 9) for spectral analysis.

Annex E
(informative)

Explanation of the relation between the wavelength resolution and the spatial frequency resolution

The frequency resolution of the narrow band spectrum resulting from the Discrete Fourier Transform is defined by Equation (E.1):

$$\Delta f_{\mathrm{sp}} = \frac{1}{l} \tag{E.1}$$

where l is the the evaluation length.

The frequency band around the centre spatial frequency f_{sp} has a lower boundary defined by:

$$f_{\mathrm{sp,\,low}} = f_{\mathrm{sp}} - \tfrac{1}{2}\Delta f_{\mathrm{sp}} \tag{E.2}$$

and an upper boundary defined by:

$$f_{\mathrm{sp,\,up}} = f_{\mathrm{sp}} + \tfrac{1}{2}\Delta f_{\mathrm{sp}} \tag{E.3}$$

The wavelength resolution is now dependent on the centre wavelength λ_{sp} itself, as follows:

$$\begin{aligned}
\Delta\lambda_{\mathrm{sp}} &= \frac{1}{f_{\mathrm{sp,\,low}}} - \frac{1}{f_{\mathrm{sp,\,up}}} \\
&= \frac{1}{f_{\mathrm{sp}} - \tfrac{1}{2}\Delta f_{\mathrm{sp}}} - \frac{1}{f_{\mathrm{sp}} + \tfrac{1}{2}\Delta f_{\mathrm{sp}}} \\
&= \frac{\Delta f_{\mathrm{sp}}}{f_{\mathrm{sp}}^2 - \tfrac{1}{4}\Delta f_{\mathrm{sp}}^2} \\
&= \frac{\frac{1}{l}}{\frac{1}{\lambda_{\mathrm{sp}}^2} - \frac{1}{4}\frac{1}{l^2}} \\
&= \frac{l \cdot \lambda_{\mathrm{sp}}^2}{l^2 - \tfrac{1}{4}\lambda_{\mathrm{sp}}^2}
\end{aligned} \tag{E.4}$$

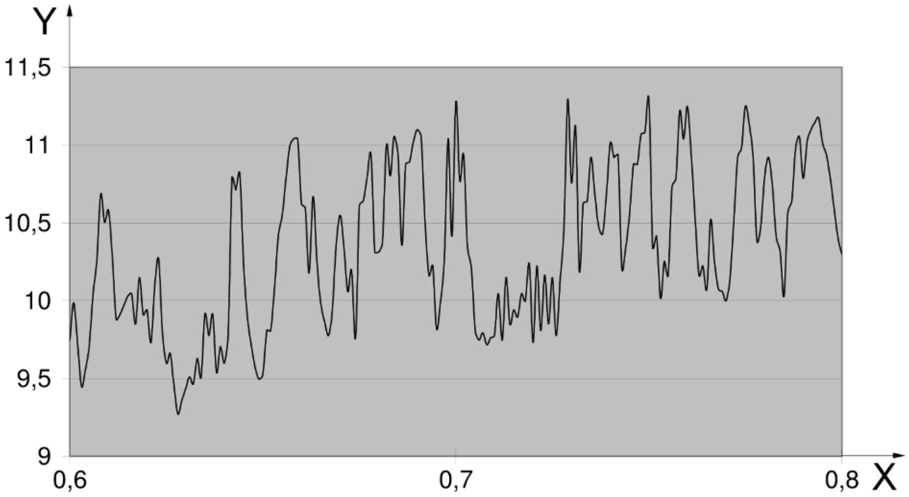
Annex F
(informative)

Spectral analysis and profile asymmetry

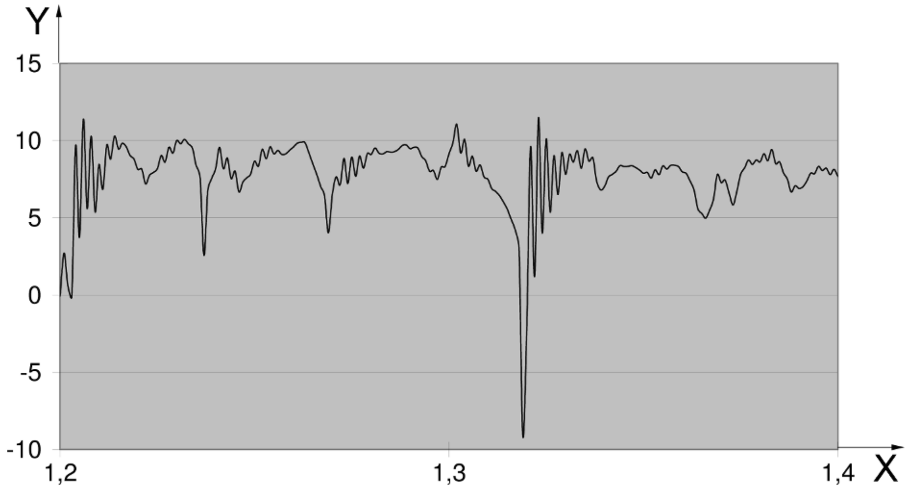
The method of spectral analysis given in this Technical Specification, in a statistical sense a second moment analysis, cannot reveal all relevant characterizations of the pavement surface profile. The mathematical operations involved in the Discrete Fourier Transform and the determination of the power spectral density disregard any asymmetry of the signal under analysis.

Therefore, the user of this method should be aware that some relevant information contained in the profile may be lost during the process of spectral analysis. In particular, a possible asymmetry of the profile, resulting in a “positive” or “negative” texture will not be expressed in the results of the analysis. It would require an analysis of the skewness, i.e. the third statistical moment of the quantity, to reveal this aspect of the profile.

Nevertheless, a “positive” texture (exhibiting protrusions) may show a significantly different behaviour in functional qualities, like skid resistance or noise generation, than a negative texture (exhibiting depressions).



a) Surface profile of positive macrotexture



b) Surface profile of negative macrotexture

Key

X profile height (mm)

Y distance (m)

Figure F.1 — Examples of surface profiles

Although the method of spectral analysis does have these shortcomings, it is considered to be sufficiently relevant as a method of characterization of road surfaces and is therefore elaborated in this Technical Specification with the aim to standardize the method and to improve the uniformity of the determination of road surface characteristics.

During the lifetime of the Technical Specification, possible methods to deal with the asymmetry problem will be considered and, if possible, investigated. Such methods may be:

- applying a weighting factor to the spectral values that is proportional to the quotient MPD/rms of the profile; the value of this quotient should be reasonably well correlated with the skewness or asymmetry of the profile;
- elaborating a method of spectral analysis on the third moment of the profile (skew) instead of on the unprocessed profile;
- applying a tyre enveloping function to the profile before spectral analysis is applied. A consequence of this approach would be that the enveloping behaviour of a tyre would have to be defined and standardized.

For the moment, the conclusion must be that no solution for a more comprehensive spectral description of road surface profiles is ready for standardization. If a method will become available during its lifetime, this Technical Specification may be the appropriate document to incorporate such a method.

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1) ISO/IEC Guide 98-3 will be published as a reissue of the *Guide to the expression of uncertainty in measurement (GUM)*, 1995.

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