Railway applications — Noise emission — Rail roughness measurement related to rolling noise generation

ICS 17.140.30; 93.100

National foreword

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Foreword

This document (EN 15610:2009) has been prepared by Technical Committee CEN/TC 256 “Railway applications”, the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by November 2009, and conflicting national standards shall be withdrawn at the latest by November 2009.

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For relationship with EC Directive(s), see informative Annex ZA, which is an integral part of this document.

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1 Scope

1.1 This European Standard specifies a direct method for characterizing the surface roughness of the rail associated with rolling noise ("acoustic roughness"), in the form of a one-third octave band spectrum.

This standard describes a method for:

a) selecting measuring positions;

b) data acquisition;

c) measurement data processing in order to estimate a set of one-third octave band roughness spectra;

d) presentation of this estimate for comparison with limits of acoustic roughness;

e) comparison with a given upper limit in terms of a one-third octave band wavelength spectrum.

1.2 It is applicable to the:

a) performance testing of reference track sections for the measurement, within a period of three months before or after roughness characterization, of noise emitted by railway vehicles for acceptance testing purposes;

b) acceptance of the rail surface condition only in the case where the result of the direct measurement of the acoustic roughness is regarded as an established acceptance criterion.

1.3 It is not applicable to the:

a) measurement of rail roughness using an indirect method;

b) measurement of combined wheel-rail roughness;

c) analysis of the effect of wheel-rail interaction, such as a “contact filter”;

d) approval of rail reprofiling, including rail grinding operations, except for those where the acoustic roughness (and not the level of corrugation) is an established approval criterion;

e) characterization of track geometry.

Testing and approval of measuring apparatus are not part of the scope of this standard.

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.

EN 61260, *Electroacoustics — Octave-band and fractional-octave-band filters (IEC 61260:1995)*

EN ISO 266, *Acoustics — Preferred frequencies (ISO 266:1997)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
acoustic roughness
r(x)
variation in the height of the rail running surface associated with rolling noise excitation expressed as a function of distance x along the rail

3.2
acoustic roughness spectrum
$\tilde{r}(\lambda)$
amplitude of the acoustic roughness expressed as a function of the wavelength λ

3.3
acoustic roughness level
L_r
level expressed in decibels, given by the following equation:

$$L_r = 10 \cdot \log\left(\frac{r_{RMS}^{\ 2}}{r_0^2}\right) \tag{1}$$

where: L_r is the acoustic roughness level in dB,

r_{RMS} is the root mean square roughness in µm,

r_0 is the reference roughness; r_0 = 1 µm.

NOTE This definition applies to values measured either in the form of a wavelength spectrum, or for a specific wavelength band.

3.4
corrugation
periodic wear pattern of the rail running surface

3.5
direct roughness measurement method
refers to an acoustic roughness measurement method for which the transducer has to be applied directly to the rail surface so that the rail roughness is measured independently of the wheel running surface roughness and independently of any effect of wheel-rail interaction

3.6
indirect roughness measurement method
refers to an acoustic roughness measurement method that measures a quantity that is the result of wheel-rail interaction, such as noise, rail or axle box vibration, whereby the original excitation by the combined wheel and rail roughness is inferred

3.7
test section
specific section of track associated with a particular set of measurements

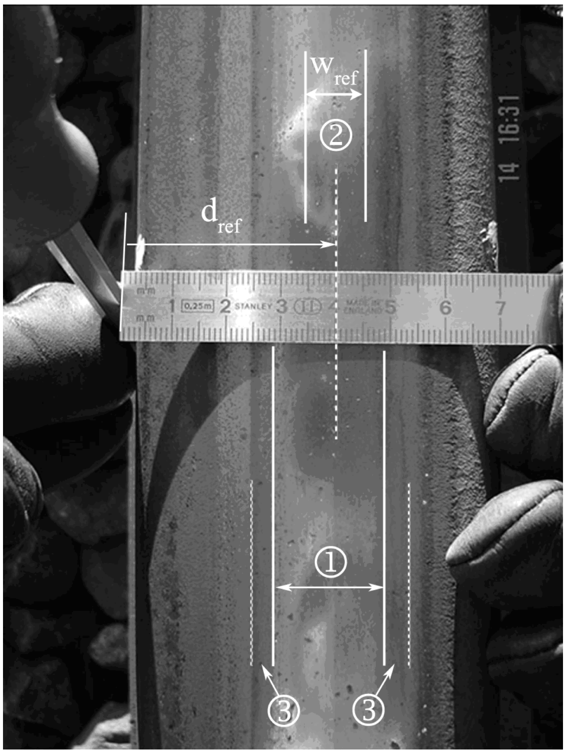
3.8
running band
bright surface of the rail head that contains all the running positions of the wheel-rail contact, associated with current traffic

3.9
reference surface
surface of the rail head, within the running band, that is chosen for the acoustic roughness assessment

3.10
reference length
dimension of the reference surface in the longitudinal rail direction

3.11
reference width
w_{ref}
dimension of the reference surface across the rail

Figure 1 shows an example of some of the defined terms:



Key

① running band
② reference surface
③ partially conditioned surface

Figure 1 — Example showing defined parameters

4 Symbols

C(x): circular curve of radius 0.375 m used for the acoustic roughness processing;

d_{ref}: position, relative to the outer surface of the rail head, of the longitudinal axis of symmetry of the reference surface;

h: height of a spike;

L_r: acoustic roughness level;

r(x): acoustic roughness function;

r'(x): acoustic roughness function processed with the spike removal and curvature algorithm;

w: width of a spike;

w_{ref}: width of the reference surface;

x: variable of the distance along the rail;

x_i: particular position along the rail;

z: mean value of height over a given interval;

$\tilde{r}(\lambda)$: discrete Fourier Transform of r(x);

λ: wavelength.

5 Measuring system requirements

5.1 General

Regardless of the fact that this European Standard does not specify any measuring system evaluation or approval, the requirements of the measuring system are defined. This is done solely in terms of output data and parameters relevant to the output data.

The following measuring system requirements apply.

5.2 Accuracy of the output signal

The measuring system shall be capable of making valid measurements in the wavelength range and at the relevant acoustic roughness levels for the test site being characterized.

However, where it is required simply to show that the estimated acoustic roughness does not exceed a given upper limit, the measuring system shall effect valid measurements for one-third octave band acoustic roughness levels equal to or greater than this limit. This case applies particularly for test section approval.

5.3 Dimensions of the probe

If a contact probe is used, the probe tip shall be spherical and its radius shall not exceed 7 mm.

In the case of a non-contacting sensor, its effective width shall be less than the sampling interval.

5.4 Tracking of the probe

The measuring system probe shall follow a line on the rail head parallel to the field (outer) face of the rail head, with a tolerance of ± 1 mm.

5.5 Sampling interval

The measuring system shall provide data with a sampling interval less than or equal to 1 mm.

5.6 Record length

The system shall provide records of length ≥ 1 m.

6 Data acquisition

6.1 General

The aim of the data acquisition procedure is to obtain digitized records of the acoustic roughness of the two rails in the test section measured at a sufficiently high sampling rate per unit of length of rail, and with a record length sufficient to derive from it the acoustic roughness spectrum. Record lengths of at least 1 m are required to estimate the acoustic roughness spectrum covering the wavelength range up to the 0,25 m one-third octave band.

NOTE To attain wavelengths greater than 0,25 m, records longer than those specified in this subclause should be obtained.

6.2 Test section requirements

6.2.1 Track structure

The track structure shall be constant along the test section, at least in terms of the following parameters: rail cross-section, rail inclination and rail supporting structure. In the case of a ballasted track, the rail supporting structure parameters are: the rail pad type, the rail fasteners, the sleeper type, the sleeper spacing and the ballast.

NOTE If the track structure changes, separate test sections should be defined and the acoustic roughness of each should be assessed and presented.

6.2.2 Localized geometric features

From the strict point of view of acoustic roughness data acquisition, there is no specific requirement for the test section. However, the rail along the test section may contain localized geometrical features (e.g.: rail defects, wheel burns, etc.), that should not be included in the assessment of the acoustic roughness related to the generation of rolling noise.

NOTE The localized rail defects are not significant in the assessment of the acoustic roughness related to the rolling noise component.

6.3 Reference surface choice

6.3.1 General

The acoustic roughness of the test section shall be assessed over a reference surface. The reference surface is specified, inside the running band, as follows:

a) length along the rail;

b) transverse width w_{ref},

c) relative distance d_{ref} to the field face of the rail.

6.3.2 Cases

It is the responsibility of the measurement team to define the length, width and position of the reference surface of the two rails and to justify its decision.

Where the acoustic rail roughness measurement is required for rolling stock type acceptance testing, any of the three following cases for that justification shall be used:

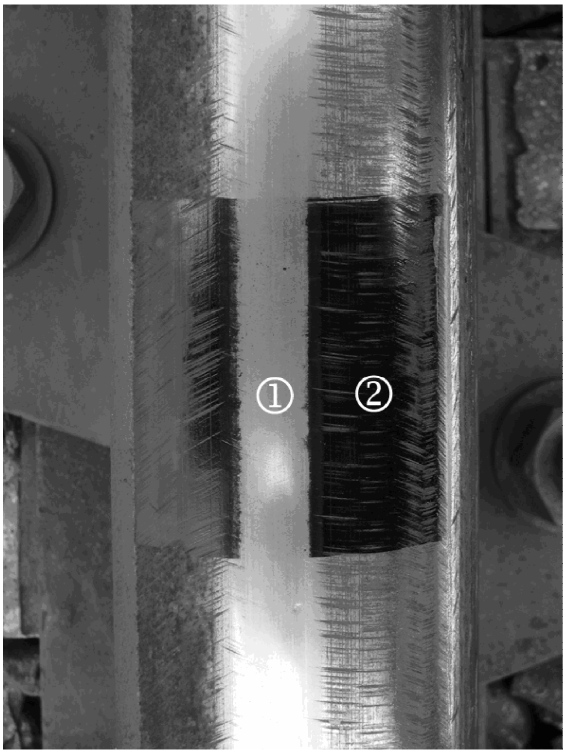
a) Case 1: the running band on the rail head is clear visually and it is known that this running band is produced by the rolling stock to be measured.

Considering that the wheel-rail contact zone is approximately 10 mm wide, any partially conditioned area at the edges of the running band that are less than half this width shall not be considered to be part of the running band.

b) Case 2: the wheel-rail contact zone can be measured for the specific train under test at the time of the acceptance test.

NOTE 1 It is recommended that a line be drawn across the rail head with a permanent marker to identify the wheel-rail contact position satisfactorily. It is advisable to check the position at both ends of the test section.

Figure 2 shows a sample application of this method:



Key

① effective running band of the trainset wheels
② marker ink outside the rolling band

Figure 2 — Example of using a permanent marker on the rail surface

NOTE 2 In judging the width of the reference surface, the minimum width should be taken that is consistent along the test section.

c) Case 3: the wheel-rail contact position can be predicted from the geometry of rail and wheel transverse profiles using simulation tools.

NOTE 3 There are specific situations (such as hollow worn wheels or worn rail head profiles) in which the contact position on the rail head is erratic. Such situations should be avoided for acceptance tests as they would lead to uncertainties in the test conditions.

6.4 Data sampling

6.4.1 General

If the conditions of 6.2.1 are met, a reduced sample representative of the acoustic roughness on the reference surface of the two rails may be produced. Considering that the existing measuring systems record the acoustic roughness in lines along the rail, the variation in the acoustic roughness across the rail head shall be assessed at a limited number of discrete positions.

The following data sampling techniques of the rail reference surface shall be applied both in the longitudinal and transverse directions.

6.4.2 Longitudinal sampling

The acoustic roughness of the reference section shall be assessed using a number of measured samples distributed over the whole reference length. To obtain a reliable assessment of the roughness up to a given wavelength, a minimum record length is required.

If the acoustic roughness is sampled in such a way that it forms less than 80 % of the overall length of the test section, the following criteria shall apply so that the samples are representative of the whole length of the test section:

a) the samples shall be assessed over at least 5 measuring positions for each rail, each at least 1 m long, distributed over the test section;

b) depending on the bandwidth range of interest, the samples shall total a length of at least:

   1) 15 m for each rail, if the bandwidth range involved does not exceed the 0,25 m one-third octave band;

   2) 7,2 m for each rail, if the bandwidth range involved does not exceed the 0,1 m one-third octave band.

6.4.3 Lateral sampling

The acoustic roughness shall be assessed equally on each rail for a given width of rail head surface, irrespective of the actual range of wheel-rail contact positions for a given category of rolling stock and shall only be considered to be valid for the part of the rail head that is conditioned by running wear. Therefore, an important aspect of the acquisition process is to define the lateral position of the valid reference surface of the rail.

The acoustic roughness shall be measured on the reference surface centre line. If the reference surface is wide enough, two supplementary, parallel, equidistant lines at either side of the centre line shall be measured. The distance between the centre line and the supplementary lines depends on the width of the valid rail reference surface:

a) $w_{ref} \leq 20$ mm: measurement of one line;

b) 20 mm $< w_{ref} \leq$ 30 mm: measurement of three lines, each 5 mm apart;

c) $w_{ref} >$ 30 mm: measurement of three lines, each 10 mm apart.

NOTE Regardless of the above, a greater number of lines of acoustic roughness may be measured. In this case the lines selected from a greater data set for comparison with acceptance criteria should conform to these rules.

6.5 Preparation of the rail head surface

Moisture and other contamination shall be removed from the rail head surface before measuring the acoustic roughness.

6.6 Acoustic roughness acquisition

Following the above operations, all the measurements shall be taken and all the data saved before being processed.

7 Data processing

7.1 Principle

The following algorithm shall be applied:

a) the data shall be processed in three stages before calculating the wavelength spectrum:

   1) edit out the data relating to any rail joints, rail head defects and welds. No discontinuities shall be included in the data that would affect the final spectrum analysis (see Annex A).

   2) process the data so as to remove narrow upward spikes that are regarded as being linked with the presence of small particles of foreign matter on the rail surface. This is called the "spike removal" process (see 7.2).

   3) process the data to take account of the effect of the small radius of the probe tip compared to that of the wheel (see 7.3), as the roughness function depends on the radius of the acoustic roughness sensor.

   NOTE This processing takes into account the effects of the wheel-rail contact that cause a change in the spectrum content affecting the excitation mechanism of the rolling noise. It cannot be done after the acoustic roughness spectrum has been produced. Other effects, such as that of the "contact filter", are not within the scope of this standard.

b) calculate the one-third octave band spectrum for each acoustic roughness record (see 7.4);

c) estimate the mean acoustic roughness spectra for the reference section (see 7.6).

7.2 Spike removal technique

The spike removal technique is as follows (see Figure 3):

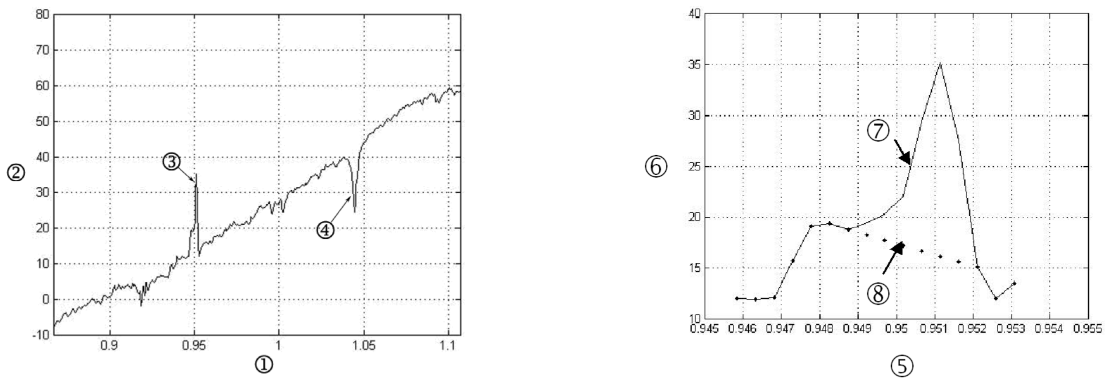
a) on the basis of the roughness r(x), calculate the first derivative dr/dx and the second derivative d^2r/dx^2;

b) locate sign changes of dr/dx, indicating a local data minimum or maximum;

c) identify the spikes by the criteria $d^2r/dx^2 < -10^7$ µm/m^2 and a change of sign for dr/dx;

d) identify the edges of each spike as being the samples (x_1 and x_2) on either side of the maxima or minima, for which abs(dr/dx) becomes less than 5×10^3 µm/m;

e) calculate the width w of the spike with the formula $w = abs(x_2 - x_1)$.



Key

① distance along the rail (metres)
② roughness amplitude (micrometres)
③ spike
④ pit

⑤ distance along the rail (metres)
⑥ roughness amplitude (micrometres)
⑦ measured signal
⑧ signal processed with the spike removal algorithm

Figure 3 — Raw data for roughness (left) and spike removal (right)

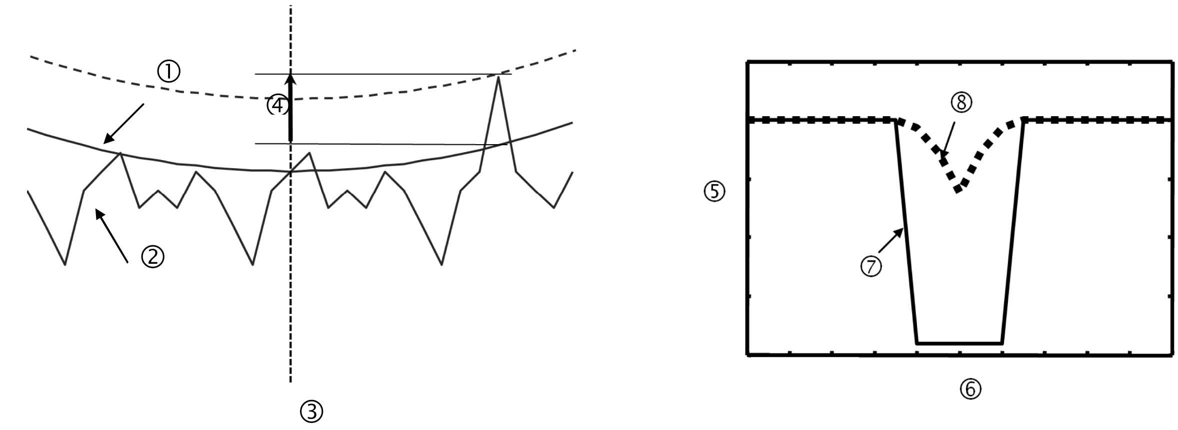
The ratio between height h and width w of each spike shall be tested with the following criterion: $h > w^2/a$, where h and w are expressed in metres and a = 3 m. If this condition is verified, the spike shall be removed by linear interpolation between x_1 and x_2.

The spike removal procedure shall be repeated until no further spike is detected.

7.3 Curvature processing

For each roughness data point x_i from the r(x) roughness function, a circular curve $C_i(x)$ of radius 0,375 m is defined passing through the data point $r(x_i)$, with its centre located at x_i above the r(x) function (see Figure 4).

The correction of the acoustic roughness at the roughness data point x_i is taken as the maximum difference between the roughness function r(x) and this curve $C_i(x)$, so that the resulting height $r'(x_i)$ of the roughness function r(x) is given by the following equation: $r'(x_i) = \max(r(x) - C_i(x)) + r(x_i)$.



Key

① $C_i(x)$

② r(x)

③ xi

④ $r'(x_i)$- $r(x_i)$

⑤ roughness amplitude

⑥ distance along the rail

⑦ r(x)

⑧ r'(x)

Figure 4 — (not to scale) Curvature processing
Left: principle applied to position x_i
Right: effect of the curvature processing on a deep pit

7.4 Spectral analysis

7.4.1 General

The one-third octave band acoustic roughness spectrum $\tilde{r}(\lambda)$ shall be determined on the basis of the roughness data, after removal of the pits and spikes, r'(x), by using one of the two methods described below:

7.4.2 Method A: Fourier analysis

For this, long data records can be divided into segments. In all cases, the length of the data used in a Fourier transform shall correspond to a length of at least 1 m. If a record is divided into successive segments, a 50 % overlap shall be applied. Each segment shall have a zero mean value and the linear trend removed. A Hanning window shall then be applied.

The discrete Fourier transform (DFT) of each segment is used to produce results in terms of wave number. The magnitude squared of the Fourier transforms of each segment shall be averaged to make up a narrow band spectrum which shall be expressed as a function of the wavelength.

The one-third octave band spectrum shall be synthesized on the basis of the narrow band spectrum. Each one-third octave band value shall be calculated as the energy sum of the narrow band values from the discrete Fourier transform. At the one-third octave band boundaries, only the narrow band spectrum values corresponding to the portion of the spectrum included in the one-third octave in question shall be taken into account (see Annex C).

NOTE From a practical point of view, the statistical precision required for band widths of 0,25 m and less is obtained by using records of a minimum length of 1 m and a product of record length and number of records of 15 m or more.

7.4.3 Method B: digital filtering

The one-third octave band values shall be obtained by applying digital one-third octave band filters directly to the roughness data r'(x). The digital filters shall comply with EN 61260.

If the one-third octave digital filtering method is used to analyse the data, 2 m shall be discarded at either end of the record, after filtering, to remove the effects of filter transients.

NOTE 1 This adds extra length to a signal in order to make it suitable for analysis by filtering, requiring the minimum record to be at least 5 m long (i.e. leaving at least 1 m of properly analysed signal).

In total, there shall be a record of at least 15 m available after the 2×2 m have been removed from each record analysed.

NOTE 2 It is expected that in practice the digital filtering technique will only be used for very much longer records.

7.5 Procedure for extending the wavelength range

Fixed-length records produce wavelength data that are inherently limited to a quarter of the length of the record.

If it is required to assess longer wavelengths, the records shall be concatenated by overlapping the measured records. The overlap shall not be used for spectral components of 0,1 m or less. The record concatenation method shall be described in the report, as appropriate.

NOTE Attention should be paid to ensure that the overlap process produces valid data for the required wavelength range.

7.6 Averaging process

A mean square average shall be calculated for each acoustic roughness line. No weighting of the roughness records shall be applied with regard to their position in the test section. Therefore, either one average spectrum or three average spectra shall be produced for each rail in accordance with 6.4.3, depending on the reference width.

8 Acceptance criteria

Any test track section approval, if requested, shall be considered for a given reference surface.

The process leads to two (one for each rail) or six (three for each rail) acoustic roughness spectra. For approval by comparison with a limit curve, none of the spectra produced shall exceed the limit curve in any of the one-third octave bands for the criteria to be met.

9 Presentation of the data

The data shall be presented in the form of:

a) an acoustic roughness graph, presented as follows :

   1) all the average roughness spectra shall be represented graphically in one-third octave bands, with the roughness level as a function of wavelength, in decreasing order accompanied by the limit spectrum, if necessary;

   2) the range of wavelengths shall contain at least the one-third octave bands for the wavelengths between 0,1 m (or 0,25 m if necessary) and 0,003 m;

3) the ratio of the horizontal and vertical axes shall be 3:4 (1 octave: 10 dB). The numbering of the wavelength labels shall correspond to the preferred frequencies of EN ISO 266.

b) a table of the associated data.

10 Report

The test report shall contain the presentation of the results as specified in clause 9, and a reference to this European Standard.

In addition, the following shall be detailed:

a) description of the measuring site;

b) position of the test section, by track designation and track distance reference;

c) precise position of the reference surfaces within the test section, in particular: the width w_{ref} of the reference surface and its relative distance to the field (outer) face of the rail d_{ref};

d) description of the method used to determine the reference surface of each rail;

e) description of the exact position of the samples of records along the reference length;

f) designation of the rail section;

g) manufacturers, type and serial number or other means of identification of the measuring equipment;

h) photographs of the rail surface with an indication of the position of the reference surface.

Annex A
(informative)

Examples of rail defects

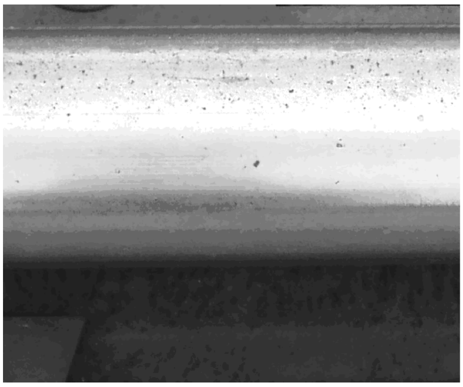
This Annex is a guide helping to identify the localized geometric features of the rail surface that are not suitable for inclusion in the assessment of the acoustic roughness.

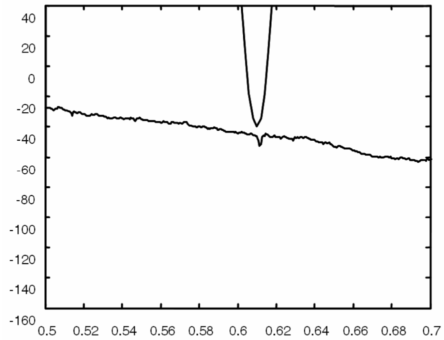
The examples shown below result from measurements using a straight-edge device. Each defect is shown in a photograph and in an adjacent measured profile compared with the curvature of a 920 mm diameter wheel. On the measured profiles, the distance axis is in metres (0,2 m shown) and the height axis is in micrometres (200 µm shown). The scales are all the same.

1 Spot (pit)

small by comparison with wheel radius

- should not be left out of measurement

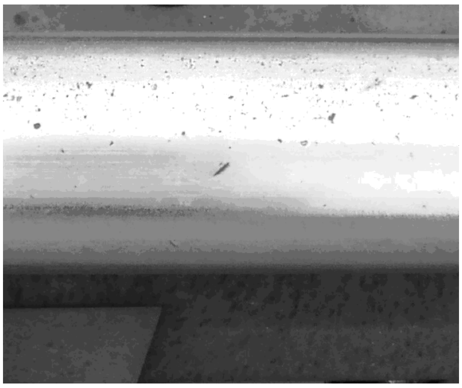


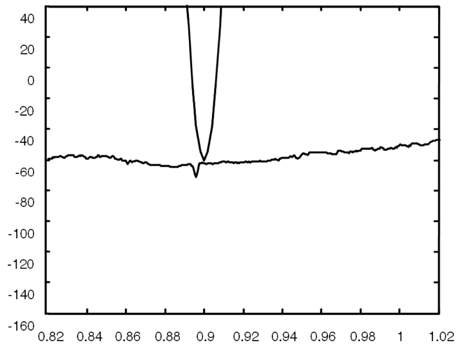


2 Nick

Small by comparison with wheel radius

- should not be left out of measurement

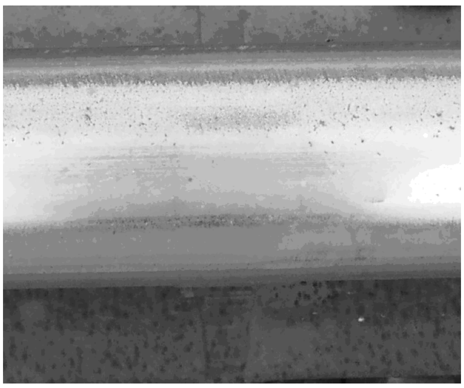


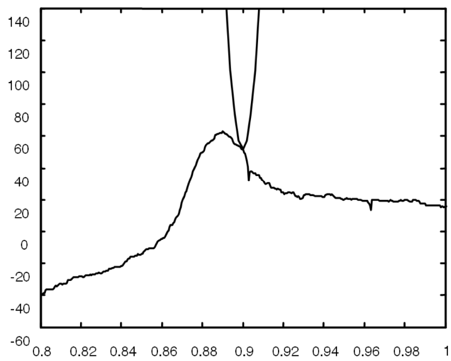


3 Weld

Large by comparison with wheel radius

- should be left out of measurement

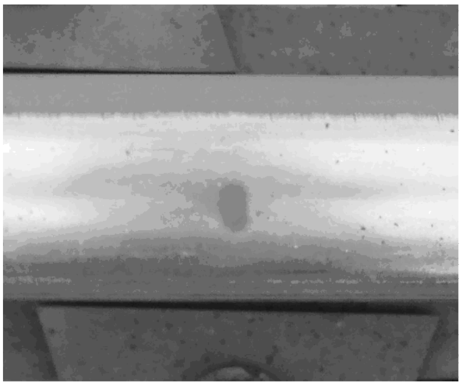


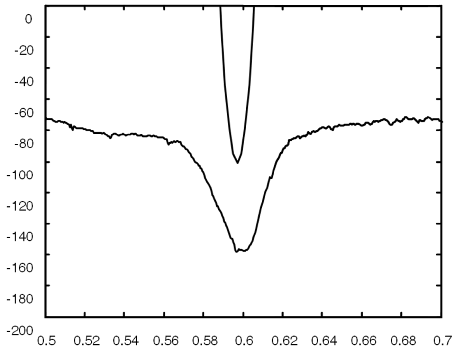


4 Hanging sleeper defect

Large by comparison with wheel radius

- should be left out of measurement



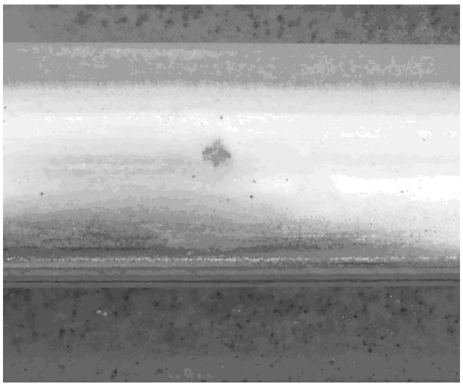


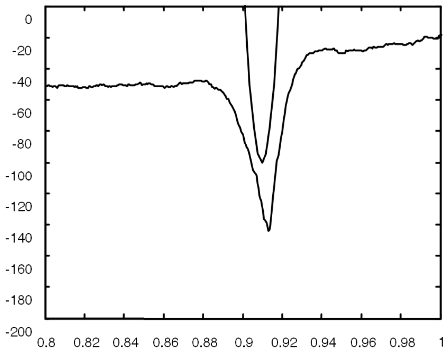
5 Large dip 1

Large by comparison with wheel radius

- should be left out of measurement.

Clearly visible because wheel does not touch bottom of dip



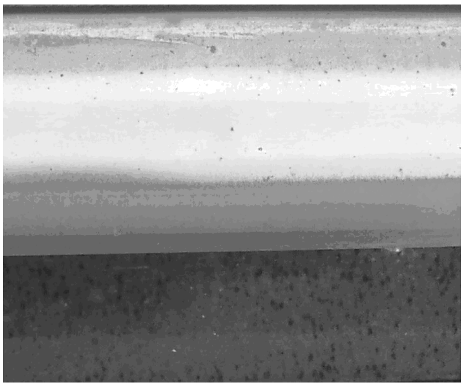


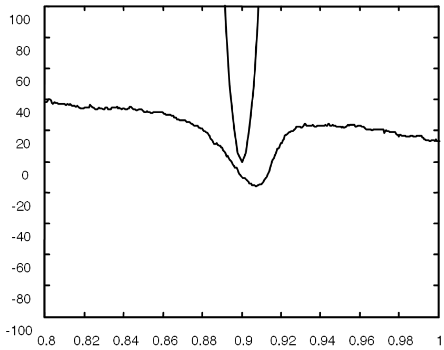
6 Large dip 2

Large by comparison with wheel radius

- should be left out of measurement.

Not easily visible because wheel touches bottom of dip.





Annex B
(informative)

Example of program code to implement acoustic roughness processing

B.1 Purpose

This program processes acoustic roughness according to the method described in this European Standard. It carries out the following processing elements:

a) manual selection of record length;

b) processing to remove spikes;

c) curvature processing to account for the effect of the small radius of the probe tip compared to that of the wheel;

d) one-third octave band filtering to obtain the spectrum if the record is long enough;

e) spectral analysis by DFT with Hanning window.

The program is written in the Matlab™ language and can only be run under the Matlab™ software environment. It is not intended to provide a full facility for roughness analysis, rather it is to show by example the implementation of the standard. Therefore, it is not necessary to run the program, but only to be able to understand the coding language.

B.2 Conditions of use

No restrictions are placed upon the use of the code presented in this Annex; this program can be run and used freely for any purpose. The code can be used as a basis for the development of enhanced or specific software for roughness analysis.

B.3 List of Matlab program files

a) RoughProcess.m (Main Program)

b) ruwcurve_rp.m

c) noct_rp.m

Copies of the program and sample data can be downloaded from:

http://www.isvr.soton.ac.uk/DG/RailwayandVibrationResearch.htm.

B.4 Input data file requirements

This version of the program will accept only a single record of raw roughness data. No averaging is carried out of multiple segments of input data. If long enough, the input record is divided into overlapping segments of just over 1 m long for the spectral analysis. These are then averaged.

The user selects the input data file in .mat format. The input file should contain two variables, a distance vector 'dist' and a roughness vector 'rough', of equal length. The distance should be in units of metres, the roughness in units of micrometres. Incorrectly scaled inputs usually result in failure of the curvature analysis. The points shall be equidistant, but they do not need to start at the origin point location...

This program does not make any assessment of the wavelength range for which the results are statistically accurate. This will depend on the length of data available. The user shall ensure that sufficient raw data are available to give valid results for the wavelength range of interest, as described in the standard. The 1 m segments used in the spectral analysis will give results valid for wavelengths up to 0,25 m, if the original input data comprise records of sufficient length. The user shall carry out any necessary averaging of the results from a number of short input records as described in the standard.

B.5 Processing options

The program allows the user to select or omit spike removal or curvature processing. The spectral analysis is carried out by default using method A (discrete Fourier transform), described in the standard. Spectral analysis using digital filtering (method B) can also be used but is optional.

B.6 Spectral analysis

The default spectral analysis divides the data available into segments containing a number of points, actually an integer power of two points, corresponding to at least 1 m of data. This data is used with 50 % overlapping and a Hanning window. Zero padding of data is not used.

The data may also be analyzed by 1/3 octave band filtering. Since a record length of 4 m is removed from the data to avoid the effects of transients, the shortest record that can be analyzed this way is 5 m, i.e. for an analyzed record length of only 1 m. Users are advised only to analyze much longer records by this technique in practice.

B.7 1/3 octave reporting

The results are averaged into 1/3rd octave bands using the subroutine noct_rp.m. This is currently set to require only one line in a 1/3rd octave band in order to output a result for that band. The code can be changed to set this to 3 lines per band. The user needs to ensure that they have enough record data length to comply with the standard in terms of statistical accuracy.

B.8 Output

The results are output to Matlab figures and compared to the limit spectrum. The results are left in the Matlab workspace and given in the following variables.

a) wavelength: wavelength values from the DFT;

b) a: acoustic roughness values (dB ref. 1 µm) from the DFT;

c) wl_d: wavelength values from the one-third octave filtering method;

d) specdf: roughness values (dB ref. 1 µm) from the one-third octave filtering method.

B.9 Listing

B.9.1 file RoughProcess.m

B.9.2

```
% This program takes roughness data in mat file format and processes it in
% accordance with EN 15610
%
% It carries out the various processing elements of:
% 1. 1/3 octave band filtering to limit data to wavelengths of interest
% 2. Processing to remove spikes
% 3. Processing to account for the effect of the small radius of the probe
%    tip compared to that of the wheel
% 4. Spectral analysis and averaging
%
% Calls subprograms ruwcurve_rp.m, noct_rp.m
% tested on Matlab version 7.4 (2007)
%
% This code is provided on an as-is basis by members of CEN TC256 WG3 with
% no implied warranty or obligation of software maintenance.
% It is intended to help the reader of the standard
% implement their own software for the processing defined in the version of
% EN 15610 to which it is attached as an advisory appendix. It may be used
% freely by all users of the standard.
%
% November 2007

clear all
close all

% --------------------------------------------------------------------------
% Ask series of questions about which processing options to include
% --------------------------------------------------------------------------

% Which input data file to use? Must be a .mat file in the current
% directory
[File,Path]=uigetfile('*.mat');
load (File);

% Spikes processing or not
button1 = questdlg('Do you want to include spikes removal processing?');
if button1(1,1) == 'C';
    return
end

% Use Ruwcurve or not
button2 = questdlg('Do you want to include curvature processing?');
if button2(1,1) == 'C';
    return
end

% Manually select which data to use or not
button3 = questdlg('Do you want to view raw data and select a segment to
process?');
if button3(1,1) == 'C';
    return
end
```

```
% Spectral analysis via digital filtering of spatial data
button4 = questdlg('Do you want to carry out spectral analysis via digital
filtering of spatial data?');
if button4(1,1) == 'C';
    return
end

%-------------------------------------------------------------------------
% calculate sample spacing from data

rows=numel(dist);
sampdist=abs((dist(rows)-dist(1)))/(rows-1);
totallength=dist(rows)-dist(1);

% Manually select data without major discontinuities
%--------------------------------------------------------------------------
% If this option was selected:
% Depending on length of original sample and if the major defects have been
% included in the data or not, cut out section of sufficient length between
% defects and process that...
%-------------------------------------------------------------------------

figure
plot(dist,rough);
ylabel('Roughness (um)');
xlabel('Distance (m)');
hold on

if button3(1,1)=='Y'

    % Select distance range
    uiwait(msgbox('Choose start and end position of good data'));
    [dist1,rough1]=ginput(1);
    Start=find(abs(dist-dist1)==min(abs(dist-dist1)));
    plot(dist(Start),(rough(Start)),'xr');  % Plot chosen point on plot
    [dist2,rough2]=ginput(1);
    Finish=find(abs(dist-dist2)==min(abs(dist-dist2)));
    plot(dist(Finish),(rough(Finish)),'xr');
    % If user picks end point before start point, switch around so no errors
    % come up later.
    if Finish<Start
        temp=Finish;
        Finish=Start;
        Start=temp;
    end

    % Truncate data
    rough=rough(Start:Finish);
    dist=dist(Start:Finish);
    % Mark selected data points on graph
    subplot(1,1,1);
    plot(dist,rough,'r');
    refresh(gcf);
    pause(0.25);

    rows=numel(dist);
    disp(['Length of chosen record = ' num2str((Finish-Start)*sampdist) ' m']);
    disp(['Length of chosen record = ' int2str(Finish-Start+1) ' data points']);
```

```
    totallength=dist(rows)-dist(1);

end

%---------------------------------------------------------------------------
% Spike removal - if this option was selected
%--------------------------------------------------------------------------
% note differentiation depends on constant sample
% distance

if button1(1,1)=='Y'
    % approximate differation using central difference method
    % assume constant gradient values for first and last points
    drdx=zeros(rows,1);
    d2rdx2=zeros(rows,1);
    for m=2:rows-1;
        drdx(m)=(rough(m+1)-rough(m-1))./(2*sampdist);
        d2rdx2(m)=(rough(m-1)-2*rough(m)+rough(m+1))./(sampdist.^2);
    end
    drdx(1)=drdx(2);
    drdx(rows)=drdx(rows-1);

    % Detect spikes criteria
    while min(d2rdx2) <-10^7
        for n = 2:rows-1
            y = d2rdx2(n);
            d1=sign(drdx(n-1));
            d2=sign(drdx(n+1));
            % if d2rdx2 is big enough and drdx changes sign
            if (y < -10^7) && (d1 ~= d2)

                % find location of first edge of spike
                p=1;
                while (p<n-1 && (abs(drdx(n-p))>= 5.0e3))
                    p=p+1;
                end
                x1=dist(n-p);

                % find location of second edge of spike
                q=1 ;
                while (q<(rows-n) && (abs(drdx(n+q))>=5.0e3))
                    q=q+1;
                end
                x2=dist(n+q);

                % number of points to change
                num=p+q-1;

                % change per point in microns
                change=(rough(n+q)-rough(n-p))./(num+1);

                % Evaluate average height and width of spike in metres
                % This is height from peak of pit/spike vertically to the
                % interpolation line that will replace the pit/spike
                height=(rough(n)-(rough(n-p)+change*p))*1e-6;
                w=abs(x2-x1);
```

```
                % Test ratio of height to width then interpolate if required
                if height > w^2/3
                    for a=1:num
                        rough(n-p+a)=rough(n-p)+change.*a;
                    end
                end
            end
            % recalculate differentials with spike removed before continuing
            for m=2:rows-1;
                drdx(m)=(rough(m+1)-rough(m-1))./(2*sampdist);
                d2rdx2(m)=(rough(m-1)-2*rough(m)+rough(m+1))./(sampdist.^2);
            end
            drdx(1)=drdx(2);
            drdx(rows)=drdx(rows-1);
        end
    end
end

% Next apply curvature processing, i.e. modified existing function ruwcurve
% If this option was selected
%------------------------------------------------------------------

if button2(1,1)=='Y'
    ruw=rough;
    x=dist; %leave distance in m as that is what ruwcurve_rp needs
    diam=0.375*2; % standard specifies radius of 0.375m
    [rfilt,x1]=Ruwcurve_rp(ruw,x,diam);

else rfilt=rough;
    x1=dist;
end
%---------------------------------------------------------------------------
% Detrend data before carrying out processing
%--------------------------------------------------------------------------
% detrend removes the best straight-line fit from vector x and returns it
% in y. If x is a matrix, detrend removes the trend from each column.
% result has a mean of zero for all records
rfilt=detrend(rfilt); % detrend is a Matlab function

%---------------------------------------------------------------------------
% Spectral analysis via digital filtering of data
%--------------------------------------------------------------------------

if button4(1,1)=='Y'

    if (totallength>5) % only do digital filtering if record
        %is 1 m long + 2 metres at each end

        % check for correct orientation of data and transpose if necessary
        test=size(rfilt);
        if test(1)>test(2)
            y=rfilt;
        else
            y=rfilt.';
        end
        test=size(x1);
        if test(1)>test(2)
            x=x1;
        else
```

```
            x=x1.';
        end

        fs_samp=1/sampdist; % sampling spatial freq [fs_samp]=m^(-1)

        % specify max and min wavenumbers and hence frequencies for filtering;
        % This should be modified by the user if wavelengths outside the range
        % specified are required.
        wl_min=0.0025;
        wl_max=0.5;

        % wavelengths of interest, centre of 1/3rd octave bands
        wl_d=[0.5 0.4 0.315 0.25 0.2 0.16 0.125 0.1 0.08 ...
            0.063 0.05 0.04 0.0315 0.025 0.02 0.016 0.0125 0.01 0.008 ...
            0.0063 0.005 0.004 0.00315 0.0025];
        fsc=1./wl_d; % [fsc]=m^(-1)
        nfreq=length(fsc);
        fsmin=fsc/(2^(1/6));
        fsmax=fsc*(2^(1/6));
        specdf=zeros(nfreq,1);

        rraw=y; % raw roughness data
        rrawd=decimate(rraw,10); % resamples data to give less points total
        % used later for fsc(q)<50 ie lambda >0.02
        % longer wavelengths can be identified from
        % fewer samples

        for q=1:nfreq    % to calculate for all frequency bands (ascending)
            order=3;      % filter order.
            if fsc(q)>=20 % undecimated data for wavelengths <= 0.05m
                Wn=[fsmin(q) fsmax(q)]/(fs_samp/2);
                [b,a]=butter(order,Wn);
                rf=filtfilt(b,a,rraw);
                % chop off end transients
                % find x values further than 2 m from ends
                indxrng=find(x>min(x)+2 & x < max(x)-2);
                rf=rf(indxrng);
            elseif fsc(q)<20; % decimated data (longer wavelengths)
                Wn=[fsmin(q) fsmax(q)]/(fs_samp/20);
                [b,a]=butter(order,Wn);
                rf=filtfilt(b,a,rrawd);
                xd=x(1:10:length(x)); % decimated distance to match
                % chop off end transients
                % find x values further than 2 m from ends
                indxrng=find(xd>min(xd)+2.0 & xd < max(xd)-2.0);
                rf=rf(indxrng);
            end
            specdf(q)=std(rf);
        end
        specdf=20.*log10(specdf./1);
    else
        disp('Record not long enough to do digital filtering');
    end
end

% -----------------------------------------------------------------------
% Spectral analysis of data using Welch's averaged, modified periodogram
% spectral estimation method and Hanning Window
% -----------------------------------------------------------------------
```

```
number=1/sampdist;   % Number of samples required to make up 1m

% set segment length depending on length of original data
if totallength<2    % if records are short, use all available data
    seglength=length(dist); %segment length is equal to total number of samples
else    %if record is long, restrict seglength to just over 2m
    power=1;             % Start value for power of two to calculate seglength
    while 2^power<2*number;
        power=power+1;   % Increase until at least 2m of data is in the segment
    end
    seglength=2^power;
end

%check that there are enough points in the data to support this
%seglength. A record with just over 2m of data may cause this
if seglength>rows
    seglength=seglength/2;
    disp('Warning: Segment length of less than 1m used')
end

Fs=number;           % Sampling frequency samples/m

Hs=spectrum.welch('Hann');
Hopts = dspopts.spectrum;
set(Hs,'SegmentLength',seglength);
set(Hs,'OverlapPercent',50);
set(Hopts,'NFFT','NextPow2');
set(Hopts,'Fs',Fs);
hpsd=psd(Hs,rfilt,Hopts);
f=get(hpsd,'Frequencies');
data=get(hpsd,'data');
% use noct to convert to 1/3 octave bands
[a,centfreq]=noct_rp(data,f);

% convert from wavenumbers to wavelength
wavelength=1./centfreq;

% Enter TSI roughness spectrum for comparison
wl_tsi=[0.400 0.315 0.250 0.200 0.160 0.125 0.100 0.080 0.063 0.050 ...
    0.040 0.032 0.025 0.020 0.016 0.013 0.010 0.008 0.006 0.005 0.004 ...
    0.003];
tsi_rough=[17.1 15.0 13.0 11.0 9.0 7.0 4.9 2.9 0.9 -1.1 -3.2 -5.0 -5.6 ...
    -6.2 -6.8 -7.4 -8.0 -8.6 -9.2 -9.8 -10.4 -11.0];

figure
semilogx(wavelength,a,'r',wl_tsi,tsi_rough,'b');
hold on
title('1/3 Octave Roughness Spectrum')
ylabel('Roughness (dB re 1um)');
xlabel('1/3 octave band centre wavelength (m)')
legend('Roughness (DFT + Hanning)','2007 TSI limit')
set(gca,'XDir','reverse');
set(gca,'XTick',[0.001 0.002 0.004 0.008 0.016 0.0315 0.063 0.125 0.25 0.5 1]);
set(gca,'YTick',[-30 -20 -10 0 10 20 30 40]);
axis([0.00315  0.25  -25  15]);  %  see  PlotBoxAspectRatio  below  for  scaling  axes
correctly
```

```
set(gca,'PlotBoxAspectRatio',[19/3  4*4/3  1]);  %    19x1/3  oct  bands  &  4x10dB
divisions

if (button4(1,1)=='Y') & (totallength >5)
    semilogx(wl_d,specdf,'g',wl_tsi,tsi_rough,'b');
    legend('Roughness (DFT + Hanning)','2007 TSI limit','via digital filtering')
end
```

B.9.3 file ruw_curve_rp.m

```
%function [rfilt,x1]=Ruwcurve_rp(ruw,x,diam,npts)
%
%------------------------------------------------------------------------
% apply curvature analysis to roughness
% ruw   is input roughness vector in microns (outwards positive)
% x     is vector of same length giving distance along wheel/rail in mm
% diam  is wheel diameter in m
% npts  is number of data points to be taken within the filter (-npts:npts)
%   (take this large enough so that the 'contact' is never right at the
%   edge of the data but not too large as the speed of the program would
%   become too slow, default is 20)
% rfilt is output  in microns (shorter than ruw by 2*npts)
% x1    is vector of same length giving distance along wheel/rail in mm
% -----------------------------------------------------------------------
%
function [rfilt,x1]=ruwcurve(ruw,x,diam,npts);
%
if nargin<4; npts=20; end;
if nargin<3; diam=0.92; end;
%
[r,k]=size(ruw);
if k>r;
  ruw=ruw';
% pad data with minimum value in sample at each end so final output is not
abbreviated
  ruw=[ones(npts,r).*min(ruw);ruw;ones(npts,r).*min(ruw)];
  [r,k]=size(ruw);
else
  ruw=[ones(npts,k).*min(ruw);ruw;ones(npts,k).*min(ruw)];
  [r,k]=size(ruw);
end
rad=diam/2;
%
dx=(x(2)-x(1));
xcirc=[-npts:npts]'.*dx;
wcirc=rad-sqrt(rad.^2-xcirc.^2);

if length(k)>1;
 [dum,k]=size(k);
end;
if rem(k,1);
 error('n must be a integer number');
end;
[rn,s]=size(wcirc);
if s>1;
 c=[wcirc];
 [rn,afm]=size(c);
 while afm<s*k;
    if afm<=s*k/2;
```

```
     c=[c c];
    else;
     c=[c c(:,1:(s*k-afm))];
    end;
    [rn,afm]=size(c);
 end;
else
 c=wcirc*ones(1,k);
end;
wcirc=c.*1e6;
%
nn=r-npts-npts;
rfilt=zeros(nn,k);
for ii=1:nn
  imax=ii+npts*2;
  ruw1=ruw(ii:imax,:)-wcirc;
  [maxruw1,jmax]=max(ruw1);
  if jmax==1 | jmax==npts*2+1
     error('in ruwcurve: npts not big enough...')
  end
  rfilt(ii,:)=maxruw1;
end;

x1=x(:,:);
```

B.9.4 file noct_rp.m

```
function [A,centfreq]=noct_rp(spect,fspec)
% Derive 1/n-octave spectra from narrow band spectra
% Output: A        = matrix of 1/n octave spectra (in dB)
%         centfreq = array of centre frequencies
%                    (minimum is band 1 => 1.25 Hz)

n=3; % To use 1/3rd octaves
incode=22; % for spectral densities (amp^2/Hz)
nperband=1;

% for 1/3 octaves use 10^(1/10)
ratio=10^(0.3/n);

[npts,nspec]=size(spect);
minband=1;                            % arbitrary choice (must be >0)
maxband=fix(15*n);                    % arbitrary choice
A=zeros(maxband,nspec);
nint=zeros(maxband,1);                % number of lines included per band

% set first band limits
fcmin=ratio^minband;
fgrens1=fcmin/sqrt(ratio);
fgrens2=fcmin*sqrt(ratio);
iband=1;

f=fspec;
fmax=fspec(npts);
fstart=fspec(1);

% lower and upper boundary frequency arrays for n.b. data
fgrnb1=[f(1); (f(2:npts)+f(1:npts-1))./2];
fgrnb2=[(f(2:npts)+f(1:npts-1))./2; f(npts)];
```

```
bwnb=fgrnb2-fgrnb1; % bandwidth array for n.b. data

% find first band with data in it
ifreq=1;
while (fgrnb1(ifreq)>fgrens1);
  fgrens1=fgrens2;
  fgrens2=fgrens2*ratio;
  iband=iband+1;
end;

% find first line wholly or partly in this first band
while (fgrnb2(ifreq)<fgrens1);
  ifreq=ifreq+1;
end;

% add "lines" within each band
while (fgrens2<=fmax);
  if (fgrnb2(ifreq)< fgrens2);
    % first "line" overlaps 1/n-octave boundary
    A(iband,:) = A(iband,:) + ...
       spect(ifreq,:).*(fgrnb2(ifreq)-fgrens1);
    nint(iband)=nint(iband)+1;
    ifreq=ifreq+1;
  else;
    % "line" overlaps start and end of 1/n-octave band!
    A(iband,:) = A(iband,:) + ...
       spect(ifreq,:).*(fgrens2-fgrens1);
    nint(iband)=nint(iband)+1;
    % NOT  ifreq=ifreq+1  ....reuse this "line" in next band.
  end;
  while (fgrnb2(ifreq)< fgrens2);
    A(iband,:) = A(iband,:) + spect(ifreq,:).*bwnb(ifreq);
    nint(iband)=nint(iband)+1;
    ifreq=ifreq+1;
  end;

  if (fgrnb1(ifreq)> fgrens1);
    % last "line" overlaps 1/n-octave boundary
    A(iband,:) = A(iband,:) + ...
       spect(ifreq,:).*(fgrens2-fgrnb1(ifreq));
    nint(iband)=nint(iband)+1;
    % NOT  ifreq=ifreq+1  ....reuse this "line" in next band.
  end;

  % move to next 1/n-octave band
  fgrens1=fgrens2;
  fgrens2=fgrens2*ratio;
  iband=iband+1;
  if (iband>maxband);
    break;
  end;
end;
%
iband=iband-1;
icount=[1:maxband]';
manyratio=ones(maxband,1)*ratio;
centfreq=manyratio.^icount;
bw0=sqrt(ratio)-1/sqrt(ratio);
bw=centfreq*bw0;
```

```
nint=nint-1;                % allow for "half" included lines
%
% shorten arrays
%   iband = band no of last band with valid data
%   jband = band no of first band with valid data
%
jband=iband;
while (nint(jband)>=nperband);
 jband=jband-1;
 if (jband==0);
   break;
  end;
end;
jband=jband+1;

A=A(jband:iband,:);
centfreq=centfreq(jband:iband);

% convert to dB's
A=10.*log10(A);
```

Annex C
(normative)

Algorithm used to synthesize a one-third octave band spectrum from a corresponding narrow band spectrum

The following symbols are used (see also Figure A.1):

— k is the index of the one-third octave band of interest;

— n_k is the number of the narrow frequency bands having an energy contribution within the one-third octave band of index k;

— S_j is the value of the autospectrum in the narrow band of index j ($j = 1, \cdots, n_k$);

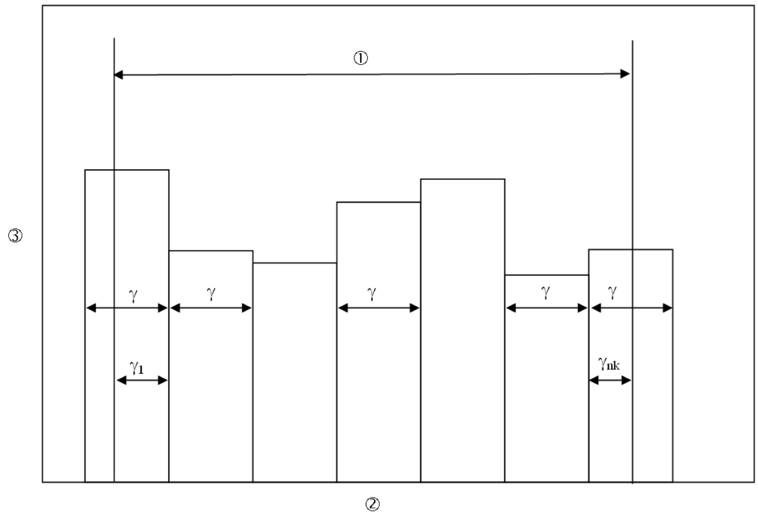
— γ is the narrow bandwidth resulting from the DFT analysis, in Hertz.

The level in one-third octave band k shall be calculated using the following equation:

$$L_k = 10 \log \left[\frac{\gamma_1}{\gamma} S_1 + \sum_{j=2}^{n_k - 1} S_j + \frac{\gamma_{n_k}}{\gamma} S_{n_k} \right] \quad \text{(C.1)}$$

where

γ_1 and γ_{n_k} are the portions of the narrow bands to be taken into account at the one-third octave band boundaries:



Key

① one-third octave bandwidth
② wavelength
③ acoustic roughness amplitude

Figure C.1 — Spectral Fourier analysis — averaging into one-third octave bands

Annex ZA
(informative)

Relationship between this European Standard and the Essential Requirements of EU Directive EU 2008/57/EC

This European Standard has been prepared under mandates given to CEN/CENELEC/ETSI by the European Commission and the European Free Trade Association to provide a means of conforming to Essential Requirements of Directive 96/48/EC.

Once this standard is cited in the Official Journal of the European Communities under that Directive and has been implemented as a national standard in at least one Member State, compliance with the clauses of this standard given in Table ZA.1 for the Conventional Rail Noise TSI (published 23 December 2005) and Table ZA.2 for the High-Speed Rolling Stock TSI (revised, published on 21 February 2008) confers, within the limits of the scope of this standard, a presumption of conformity with the corresponding Essential Requirements of that Directive and associated EFTA regulations.

Table ZA.1— Correspondence between this European Standard, the Conventional Rail Noise TSI, (published on 23 December 2005) and Directive 2008/57/EC

Clause/sub-clauses of this European Standard	Chapter/ § of TSIs	Corresponding text, annexes/§ of Directive 2008/57/EC	Comments
The whole standard is applicable.	4.2. Functional and technical specifications of the subsystem 4.2.1. Noise emitted by freight wagons 4.2.1.1. Limits for pass-by noise 4.2.2. Noise emitted by locomotives, multiple units and coaches 4.2.2.1. Introduction 4.2.2.4. Limits for pass-by noise ANNEX A: Measuring conditions A.1.4. Reference track for pass-by noise	Annex III Essential Requirements 1. General requirements 1.4. Environmental protection 1.4.1 The environmental impact of establishment and operation of the rail system must be assessed and taken into account at the design stage of the system in accordance with the Community provisions in force. 1.4.4. Operation of the rail system must respect existing regulations on noise pollution.	

Table ZA.2 — Correspondence between this European Standard, the High-Speed Rolling Stock TSI (published on 21 February 2008) and Directive 2008/57/EC

Clause/ sub-clauses of this European Standard	Chapter/ § of TSIs	Corresponding text, annexes / § of Directive 2008/57/EC	Comments
The whole standard is applicable.	4.2. Functional and technical specification of the subsystem 4.2.6. Environmental conditions 4.2.6.5. Exterior noise 4.2.6.5.1 Introduction 4.2.6.5.4. Limits for pass-by noise ANNEX N Measuring conditions for noise N.1.4. Reference track for pass-by noise	Annex III Essential Requirements 1. General requirements 1.4. Environmental protection 1.4.1 The environmental impact of establishment and operation of the rail system must be assessed and taken into account at the design stage of the system in accordance with the Community provisions in force. 1.4.4. Operation of the rail system must respect existing regulations on noise pollution.	

WARNING — Other requirements and other EU Directives may be applicable to the product(s) falling within the scope of this standard.

Bibliography

[1] EN 13231-3:2006, *Railway applications — Track — Acceptance of works — Part 3: Acceptance of rail grinding, milling and planing work in track*

[2] EN 13848-1:2003, *Railway applications — Track — Track geometry quality — Part 1: Characterization of track geometry*

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