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Virtual certification of acoustic performance for freight and passenger trains

D2.4 – Proposed analysis method for wheel roughness

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EXECUTIVE SUMMARY

A procedure for wheel roughness measurement and analysis is proposed. It follows the main ideas of the European Standard EN 15610:2009, used for rail roughness.

After a brief introduction, a description of the scope and of the terms and symbols adopted, attention is focused on the measuring system requirements (Section 2). Details on the data acquisition and post processing are given in Sections 3 and 4. Sections 5 and 6 are devoted to the presentation of the data and to the report to be produced at the end of the measurements campaign. Section 7 lists further work required to refine this procedure.

This measurement and analysis procedure will be reviewed following experience obtained during measurements to be performed in Acoutrain task 2.3 and updated as necessary.

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INTRODUCTION

There is currently no national or international standard for the measurement or analysis of wheel roughness. Indeed, wheel roughness measurements are far less commonly carried out than those for rail roughness. However, within Acoutrain it is envisaged that there may be situations where wheel roughness measurements may be used as part of a virtual certification procedure. Therefore a standard protocol for measurement and analysis is required.

For the rail roughness associated with rolling noise (‘acoustic roughness’) a European Standard EN 15610:2009 has recently been adopted. The procedure for wheel roughness proposed here is based closely on EN 15610:2009. Reference has also been made to the measurement specification for wheel roughness recommended from the NOEMIE project (Fodiman, 2005).

1. SCOPE

As in EN 15610:2009, this document proposes a method for:

(a) selecting measuring positions;

(b) data acquisition;

(c) data processing to estimate a set of one-third octave band spectra;

(d) presentation of the results.

The purpose of such a measurement is to quantify the wheel roughness of a vehicle or a train for comparison with the rail roughness, for comparison with various reference spectra or for use in prediction models.

In contrast to wheel roughness measurements, the main purpose of rail roughness measurements according to EN 15610:2009 is for performance testing of reference tracks that will be used for acceptance testing of rail vehicles. In practice the same measurement method is used to compare a track with another one without consideration of the limits. Nevertheless, it should be remembered that this is the rationale behind the ‘limit’ curves as defined in TSI or ISO 3095:2005. Unlike rail roughness, there is no upper limit for wheel roughness but the limit curves from TSI or ISO 3095:2005 can still be used as a reference point.

2. MEASURING SYSTEM REQUIREMENTS

Testing and approval of measurement apparatus are not part of the scope of the present procedure. The requirements of the measurement system are defined solely in terms of output data and parameters relevant to the output data.

The following arrangement is envisaged (although other possible arrangements may be allowable):

- The wheelset will be jacked clear of the rail by a distance sufficient to allow free rotation.
- One or more probes will be located against the running surface using the rail as a reference.
- The wheel will be rotated either by hand or by a dedicated motor arrangement.

Accuracy: The measuring system shall be capable of making valid measurements in the wavelength range and at the relevant acoustic roughness levels for the wheel being characterised. This means that at least wavelengths in the range 3 to 250 mm shall be measured[1].

Dimension of the probe: If a contact probe is used, the probe tip shall be spherical and its radius shall not exceed 7 mm. For a non-contacting sensor, its effective width shall be less than the sampling distance.

Sampling interval: The measuring system shall provide data with a fixed and known spatial sampling interval less than or equal to 1 mm.

Record length: The system shall be capable of measuring record lengths of at least one complete circumference of the wheel at a time.

[1] Preferably at least the 315 mm band should also be included and longer wavelengths if possible.

3. DATA ACQUISITION

3.1 SELECTION OF WHEELS

If it is not possible to measure all the wheels of a train, measurements shall be made of a representative number of wheels[2]:

1. For measurements of a single vehicle, at least 4 wheels shall be measured, distributed on both sides of the vehicle (they may include wheels at both ends of the same axle);
2. For a whole train, at least 10 wheels, distributed on both sides of the train (or one quarter of all wheels if this is greater);
3. Where both powered and unpowered wheels are present in a train, the measured wheels should include at least 4 powered and 4 unpowered wheels (or at least one quarter of each category of wheel if this is greater than 4);
4. Where different wheels in a train have different braking systems, at least 4 wheels of each type of braking system should be included (or at least one quarter of each category of wheel if this is greater than 4).

For each category of wheel identified in points 3 and 4, the samples should be distributed over the whole train and on both sides. The report should indicate clearly which wheels have been measured.

ADVISORY NOTE:

Due to the large spread in roughness that may occur between different wheels in a train, it may be the case that measuring only ¼ of the wheels is not sufficient to give a reliable estimate of the roughness of the whole train.

3.2 WHEEL DEFECTS

The wheel running surfaces shall be cleaned carefully before making the measurements in order to remove surface contamination.

Unless it is the purpose of the measurements to quantify them, specific wheel defects such as wheel flats should be omitted from the measurement. If possible this should be done by avoiding wheels containing such defects; otherwise they should be removed from the data (see Section 5).

ADVISORY NOTE:

If the purpose of the wheel roughness measurements is to make comparisons with noise measurements made in parallel then wheels with flats are not suitable for the investigation.

[2] Note: the numbers of wheels in points 2 to 4 are taken from (Fodiman, 2005).

3.3 MEASUREMENT ZONE

A **measurement zone** shall be defined as a region of constant width on the running surface of the wheel. Unlike rails, the running band on wheels is usually wide and its limits may not be clear. Where a clear running band is visible on the wheel tread, the measurement zone shall be located within this visible band. It is the responsibility of the measurement team to define the lateral position and width of the measurement zone on the wheel and to justify its decision.

At least three lines of measurement shall be made 10 mm apart across the wheel tread within the measurement zone[3]. If relevant, positions at 60, 70 and 80 mm from the flange-back shall be used out of preference for a standard main line tyre width of 135 mm (provided that they are within the running band). Additional lateral positions between or beyond these positions may also be used in order to cover the running band. Where possible the measurements at all lateral positions should be synchronised relative to each other.

At each position at least two full circumferences of the wheel shall be measured.

ADVISORY NOTE:

Due to the width of the running band a large spread in roughness that may occur between lines within the visible running band. It is recommended to select the relevant lines using a geometrical wheel/rail contact prediction for any further comparison with pass-by noise or rail roughness. This may require the measurement of wheel (and rail) transverse profiles.

4. DATA PROCESSING

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

1. Edit out the data relating to any wheel defects.
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 wheel surface (‘spike removal’ process).
3. Process the data to take account of the effect of the small radius of the probe tip compared with that of the wheel (‘curvature processing’).

Stages 2. and 3. shall always be carried out in this order. The removal of defects (stage 1) may be carried out either before or after stages 2. and 3.

EN 15610:2009 contains advice and example measurements of features that should, and should not be, regarded as defects on the rail head. Corresponding criteria should apply for the wheel roughness measurements[4].

[3] Note: according to (Fodiman, 2005) six lines spaced at 5 mm apart should be used. Here it is considered more appropriate to measure three lines on more wheels but this can be a matter for further investigation.

[4] It has been pointed out that the spikes algorithm in EN 15610:2009 may require adaptation for use with wheel roughness as it may remove too much data (the pits algorithm appears to be acceptable). This requires further investigation. See also (UIC DT405) for classification of defects and (UIC B169 RP28) for acoustic influence typical wheel defects.

Other effects such as the 'contact filter' are not within the scope of this procedure.

(b) Calculate the one-third octave band spectrum for each acoustic roughness record using the Fourier analysis method specified in EN 15610:2009. The 1/3 octave filtering method should not be used.

(c) Estimate the mean acoustic roughness spectrum for the vehicle or train using an energy average[5]. An indication of the statistical distribution should also be given.

For the above steps, identical processing shall be used as specified for the rail in EN 15610:2009 (not repeated here) except for the following differences.

I. In step (b) windows and multiple data segments shall **not** be used: the data segment shall have a length equal to one revolution of the wheel and shall be analysed using a single Discrete Fourier Transform (DFT) without zero padding. The number of samples corresponding to the circumference of the wheel shall be determined by a suitable method. For example:

- Difference methods, where the estimated circumference is varied and the sum of squared differences is minimised over points one test circumference apart;
- Using an auto correlation method.
- Mechanically by the measurement device or using a trigger.

II. In step (c) allowance should be made for the number of powered and unpowered wheelsets and a weighted average used as appropriate. Similarly, if there are different braking mechanisms on different vehicles of the train, allowance should be made for the number of each within each noise measurement section of the train. Thus, if there are N_1 wheels in one category and N_2 in another, the average for the train should be calculated as

$$L_r = 10\log_{10}\left(\frac{N_1 \times 10^{(L_{r,N1}/10)} + N_2 \times 10^{(L_{r,N2}/10)}}{N_1 + N_2}\right)$$

where $L_{r,N1}$ is the average roughness level of the first category, etc.

III. A decision needs to be made about how many parallel lines to include in the average. It is suggested that the average roughness over a wide running band is less appropriate than a suitable selection of one or two lines corresponding to the expected contact point.

The repeatability of the measurement shall be checked by comparing the profile measurement records from successive rotations of the wheel.

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[5] According to (Fodiman, 2005), for each wheel the roughness spectra on each parallel line should be averaged using an energetic mean; subsequently for each wheel type the arithmetic mean should be determined of the mean spectra for each wheel. Only those lines within the running band should be used. The use here of an energy average over wheels differs from (Fodiman, 2005) but corresponds to the procedure in EN 15610:2009 and should correspond more closely to radiated noise.

ADVISORY NOTE:

Attention should be paid to avoid the following sources of error.

- Movement of the wheel can occur due to the effort of turning it during the measurement.
- The tachometer tracking of the measurement may slip on the wheel tread during measurement.
- The height of the jack used to lift the wheel may change slightly during the measurement, leading to differences in the raw data from one revolution to the next. If possible this should be avoided by comparing successive revolutions.
- If the rotational speed of the wheel is too great the measurement quality may be adversely affected by vibration, high tangential forces, slip, etc.

5. PRESENTATION OF THE DATA

Similar to EN 15610:2009, the data shall be presented in the form of:

(a) An acoustic roughness graph in one-third octave bands with the roughness level plotted as a function of wavelength, in decreasing order. This may be accompanied by a reference spectrum if necessary (not mandatory). The range of wavelengths shall contain at least one-third octave bands for the wavelengths between 250 mm and 3 mm. The ratio of horizontal and vertical axes shall be 3:4 (1 octave : 10 dB)[6]. The numbering of the wavelength labels shall correspond to the preferred frequencies of ISO 266.

- Average spectra shall be presented for each category of wheel for the most relevant lateral positions on the tread. These shall be given together with an indication of the statistical dispersion (e.g. plus/minus one standard deviation).
- The weighted average spectrum for the whole train shall also be presented (see Section 4).
- If required, spectra of individual wheels and for different lateral positions shall be included in annexes.

(b) A table of the associated one-third octave spectrum data shall be included for the first two items listed above.

(c) In addition, the peak amplitude of the first 10 out-of-round harmonics shall be tabulated[7]. These can be obtained from the DFT of the roughness signal. Thus if $R(1/\lambda_n)$ is the (complex) DFT of the roughness signal $r(x)$, the relevant harmonics are:

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[6] Although this requirement is present in EN 15610:2009 it is noted that it is seldom adhered to.

[7] The number of harmonics to be included can be reduced to the extent that the one-third octave spectra cover longer wavelengths. The choice of the number of harmonics should ensure that no wavelengths are omitted between them and the one-third octave spectra.

$|R(1/\lambda_n)|$, for $n=1, 2, 3, \ldots, 10$.

This shall be presented for central line of roughness only.

The wheel diameters shall also be determined and stated.

Polar plots of the circumferential profile data may also be included.

6. REPORT

The test report shall contain the presentation of the results as specified in Section 5. In addition the following shall be included:

(a) Description of the train including the position in the train of each wheel that has been measured and an indication of which wheels are driven / trailer and the type of braking system for each wheelset.

(b) Distance or time since reprofiling where this is known.

(c) Wheel diameters (and state of wear).

(d) Precise lateral position of the measurement in terms of the distance of each measurement line to the flange-back.

(e) Manufacturer, type and serial number or other means of identification of the measuring equipment.

(f) Photographs of the wheel surface with an indication of the position of the measurement zone and measurement lines.

7. FURTHER WORK

From analysis of measurements to be made in Acoutrain task 2.3 (and other data) it will be further determined:

- whether it is necessary to distinguish between powered and unpowered axles (if these have identical braking systems);
- the number of wheels required to characterise a train;
- whether energy or arithmetic averages should be used;
- the number of parallel lines used for the measurements and how many of these are required to form the average to characterise a wheel;
- whether the ‘spikes’ algorithm in EN 15610:2009 requires adaptation for use with wheel roughness and if so how it should be modified.

The procedure described in this report will be reviewed in the light of experience obtained during measurements to be performed in Acoutrain task 2.3 and updated as necessary.

REFERENCES

EN 15610, Railway applications – Noise emission – Rail roughness measurement related to rolling noise generation (EN 15610:2009)

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

EN ISO 266, Acoustics – Preferred frequencies (ISO 266:1997)

EN ISO 3095, Railway applications – Acoustics – Measurement of noise emitted by railbound vehicles (ISO 3095:2005)

EC Commission Decision of 23 December 2005 concerning the technical specification for interoperability relating to the subsystem 'rolling stock – noise' of the trans-European conventional rail system, 2006/66/EC.

EC Commission Decision of 21 February 2008 concerning the technical specification for interoperability relating to the 'rolling-stock' subsystem of the trans-European high-speed rail system, 2008/232/CE.

Fodiman, P., NOEMIE Project Final report (Project 2002/EU/1663), AEIF, July 2005, see Appendix D.

UIC report B169 DT405, Catalogue of defects on wheels / axles / wheelsets. Part 1: introductions, terminology, classification of defects, types of defects on wheelsets, 2006.

UIC report B169 RP28, Optimisation of wheels. Effect of defects in wheel running surfaces on noise emitted into the environment, 2007.