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Multiple sensors and partial calibration for on-board measurement of rail acoustic roughness: results of rolling tests

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Abstract. The indirect measurement of roughness using vibro-acoustic sensors on board rolling stock is promising, as shown by recent research on this topic. However, a number of improvements can be made to the existing methods to extend their range of validity. In this paper, the performance of the multi-sensor method developed in the framework of the French research project MEEQUAI is presented. The estimation of the effective roughness is performed for different sensor families using a least squares method in the frequency domain, from the signal spectra in third octave and modelled transfer functions corresponding to the detected track layout. A partial calibration method is also proposed. The calibration gain is relative and allows the variability of the transfers with the track support to be retained, thanks to the models. The method was tested in France with sensors installed on a test train running at several speeds on a track section of a railway test center as well as on two track sections of the national railway network with different supports.

Keywords: Rolling noise, Rail roughness, On-board measurement, Calibration.

1 Introduction

The evolution of models for the prediction of railway noise emitted in the environment implies an increasingly detailed knowledge of the characteristics of the vehicles and the tracks at the origin of the noise. The knowledge of the rail acoustic roughness and its evolution in time on a whole railway network becomes useful nowadays. The indirect measurement of roughness using vibro-acoustic sensors on board rolling stock is promising, as shown by recent research on this topic [1-8]. However, a number of improvements can be made to the existing methods to extend their range of validity. In particular, it is necessary to guarantee a correct accuracy over a wide range of wavelengths, independently of the measurement conditions such as the vehicle speed or the track support.

To achieve these objectives, research has been carried out within the framework of the French research project MEEQUAI [5,7]. Several advances are proposed. On the one hand, the combination of several families of sensors for indirect measurement allows a wider wavelength band to be covered. On the other hand, the use of models for estimating the transfer functions between sensors and roughness allows some parametrisation of the transfer functions, particularly with regard to speed and track support. Finally, a partial calibration principle improves the accuracy of the method while keeping the interest of the modelling. In this paper, the results obtained during rolling on different types of tracks and at several speeds are presented. Prior to this, the characteristics of the proposed method are reviewed. The paper aims to assess the performance of the indirect measurement method, independently of a roughness separation stage. Conclusions are therefore drawn on the basis of comparisons between direct and indirect measurements of wheel/rail combined roughness and not rail roughness.

2 Proposed approach

2.1 Selected sensors

Based on the models developed in the first phase of the project, three families of vibro-acoustic sensors have been selected according to the frequency ranges as described in Table 1. Methods using other type of sensors like non-contact displacement sensors have not been investigated.

Sensors	Axle-box accelerometers	Under-bogie microphones	Microphones close to the rail
Number	2	4	2
Location	On each axle side, close to the wheel	Carefully distributed in the cavity	On each axle side, above the rail
Frequency range	125 – 1600 Hz	250 – 5000 Hz	400 – 2000 Hz

Table 1. Description of sensors selected for the indirect measurement

This selection includes sensors that have already been tested in several studies, such as axle-box accelerometers [2] and under-bogie microphones [1], but also sensors that were considered in other works but not tested during rolling, such as microphones close to the rails [4]. The results of the models and various tests carried out prior to this final validation led to the exclusion of microphones close to the wheels (see for instance refs. [3,4]). Indeed, a lack of robustness was observed, related to the fact that the wheel-on-rail resonances are very pronounced and that their frequency and damping are very sensitive to parameters that are not easy to estimate or even variable during the measurement, such as the lateral position of the wheel/rail contact point. The frequency ranges selected for each family of sensors also come from preliminary studies showing high risks of uncertainty outside these ranges. For example, above 1600 Hz, the transfer functions corresponding to axle-box accelerometers fall sharply, while below 400 Hz the sound pressure close to the rails is strongly disturbed by aerodynamic noise.

2.2 Estimation of transfer functions

Models have been developed to determine, for a representative selection of tracks, the transfer functions between the effective combined wheel/rail roughness in the frequency domain and the on-board sensors selected for indirect measurement. The selected tracks include various types of support characterized by rail-pad dynamic properties (soft, medium or stiff) and sleeper type (concrete monobloc, concrete bibloc, wooden). A single vehicle type is considered corresponding to the “Corail” vehicle of SNCF-AEF (Railway Test Agency) used for the rolling tests. A detailed description of the models used is not intended here, but the following points should be noted:

- For axle-box and track vibrations below 2000 Hz, a receptance coupling method is used, based on “rolling noise” contact models [10] and results provided by finite element models of tracks and wheelset. The wheel/rail contacts on both sides of the wheelset are considered via two degrees of freedom (vertical and lateral).
- For sound pressure close to the rails below 2000 Hz, an exterior sound radiation model is used, based on acoustic finite elements for the free-field combined with perfectly matched layers for the far-field. It includes reflections on the platform through impedance boundary conditions.
- For sound pressure radiated under the bogie up to 5000 Hz, the proposed method combines the TWINS software [10] for the calculation of sound radiated powers, with a semi-analytical propagation model based on elementary sources (monopoles, dipoles) taking into account the extended character of the track radiation.

Finally, a database of transfer functions has been built from the models and initial calibration on a standstill vehicle [7]. **Fig. 1** shows the results obtained in the case of axle-box accelerometers. It highlights the influence of the track support.

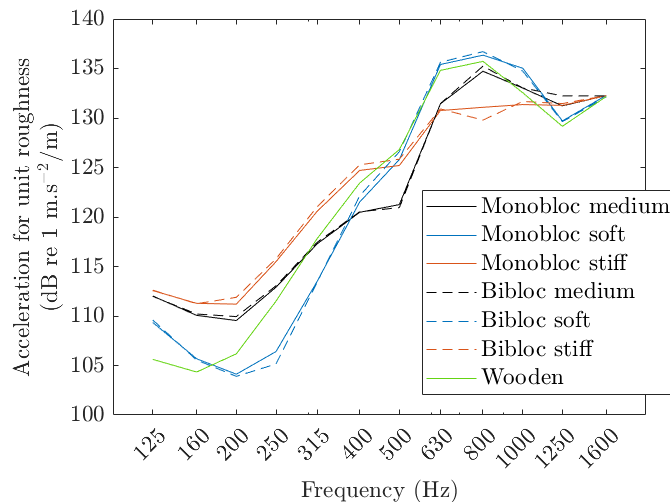


Fig. 1. Transfer functions used for axle-box accelerometers (same side, third-octave bands).

2.3 Inversion method

The indirect measurement method is based on a pre-processing of the signals coming from the different sensors on a given length of track, including the detection of possible short defects, the spectral analysis, the suppression of the contribution of the wheel roughness (see refs. [6,9]), as well as the identification of the track support. These steps are not detailed in this paper although they are important from a practical point of view. For this paper, the contribution of the wheel roughness is kept in the signals since the validation is performed in terms of combined roughness.

The inversion method itself assumes linearity between the combined effective roughness of the two rails and the signals from the sensors. For a set of N sensors, the linear relationship between the signals z_i from the sensors grouped in a vector $\{z\}$ and the combined effective roughness of right and left rails r_R and r_L , can be written as:

$$\{z\} = \{C_R\}r_R + \{C_L\}r_L \quad (1)$$

where vectors $\{C_R\}$ and $\{C_L\}$ contain the track-specific transfer functions between the sensors and the combined effective roughness of left and right rails. The spectral analysis of the signals from the sensors leads to the estimation of a spectral matrix $[S_{zz}]$ of dimension $N \times N$.

Considering a probabilistic context and assuming a decorrelation between the combined effective roughness of both rails, Eq. (1) leads to:

$$[S_{zz}] = [C_R C_R^*] S_{r_R r_R} + [C_L C_L^*] S_{r_L r_L} \quad (2)$$

where $S_{r_R r_R}$ and $S_{r_L r_L}$ stand respectively for the roughness spectra of the right and left rails. In terms of auto-spectra, Eq. (2) may be written as:

$$\{\text{diag}(S_{zz})\} = |\{C_R\}|^2 S_{r_R r_R} + |\{C_L\}|^2 S_{r_L r_L} \quad (3)$$

where the components of vector $\{\text{diag}(S_{zz})\}$ are the measured auto-spectra whereas the vectors $|\{C_R\}|^2$ and $|\{C_L\}|^2$ contain the moduli of the squared transfer functions between the sensors and the combined effective roughness of both rails.

Assuming the same roughness on both rails, the estimation of the combined effective roughness is thus performed for each sensor family using a least squares method in the frequency domain, from the measured signal spectra in third octave bands and transfer functions:

$$\hat{S}_{rr} = \underset{S_{rr}}{\text{argmin}} \left\| \text{diag}(S_{zz, \text{mes}}) - (|\{C_R\}|^2 + |\{C_L\}|^2) S_{rr} \right\| \quad (4)$$

Using transfer functions in third octave bands and estimating only an average roughness for both rails increases the robustness of the method. The post-processing of the effective roughness includes the conversion of the spectra into the wavelength domain using the rolling speed V and the correction by the DPRS contact filter $H(\lambda)$ [10]:

$$\tilde{S}_{rr}(\lambda) = H^{-1}(\lambda) \hat{S}_{rr}(f) \quad \text{with } \lambda = \frac{V}{f} \quad (5)$$

2.4 Calibration method

An additional partial calibration method is also proposed. It consists in adjusting the transfer functions using calibration gains α_i^2 defined for each sensor by rolling on a reference track with known roughness spectra:

$$\alpha_i^2 = \frac{S_{z_i z_i, \text{mes}}}{|C_{Ri}|^2 S_{r_R r_R, \text{mes}} + |C_{Li}|^2 S_{r_L r_L, \text{mes}}} \quad (6)$$

In this equation, roughness spectra $S_{r_R r_R, \text{mes}}$ and $S_{r_L r_L, \text{mes}}$ must be obtained by using a direct measurement method whereas the transfer functions C_{Ri} and C_{Li} correspond to the reference track. The calibration should preferably be performed using the spectra obtained after removing the contribution of wheel roughness. In case this pre-processing is not possible, calibration would have to be carried out using the combined wheel/rail roughness spectra which also implies a prior measurement of the wheel roughness spectra. Whatever the track, the relation between uncalibrated and calibrated transfer functions is then given by:

$$|C_{Ri}|_{\text{cal}}^2 = \alpha_i^2 |C_{Ri}|^2 \text{ and } |C_{Li}|_{\text{cal}}^2 = \alpha_i^2 |C_{Li}|^2 \quad (7)$$

It is important to note that the gain is relative and track-independent which allows the variability of the transfers with the track support to be retained for later measurements, thanks to the models. The calibration factors are also independent on speed. The speed effect is only taken into account in the post-processing step (see Eq. 5).

3 Results

3.1 Rolling tests at railway test centre (CEF2)

The method was first tested in France with sensors installed on one wheelset of the ‘‘Corail’’ test vehicle running at several speeds on a 400 m track section of the Tronville-en-Barrois railway test center (CEF2). A trainset consisting of five wagons was used for rolling tests. Prior to the rolling indirect measurement, direct measurements of the wheel roughness (for the instrumented axle) and the rail roughness were carried out. On the track section, no significant short defects were identified, which was a necessary condition for the validation of the method. The track support consists of bi-bloc concrete sleepers. Measurements of the receptance and the track decay rate (with hammer and during pass-by) were used to identify the average stiffness of the rail-pads. The stiffness obtained is between the medium and stiff values used in the track selection.

A first test of the indirect method was carried out at 80 km/h using the initial transfer functions determined for a medium bi-bloc track for the three families of sensors. The results are compared with the direct measurements in terms of wheel/rail combined roughness (i.e., without suppression of the wheel contribution) in **Fig. 2**. The maximum deviations obtained are close to 5 dB per third of an octave, with the exception of those corresponding to the under-coach microphones at large wavelengths which are more pronounced. The partial calibration at speed 80 km/h at CEF2 was then tested,

considering that the rail-pad stiffness was between soft and medium. With this calibration, the maximum differences between the direct and indirect measurements obtained at other speeds on the same section are around 3 dB per third of an octave, as shown in **Fig. 3**, whereas the roughness estimation obviously becomes perfect at 80 km/h.

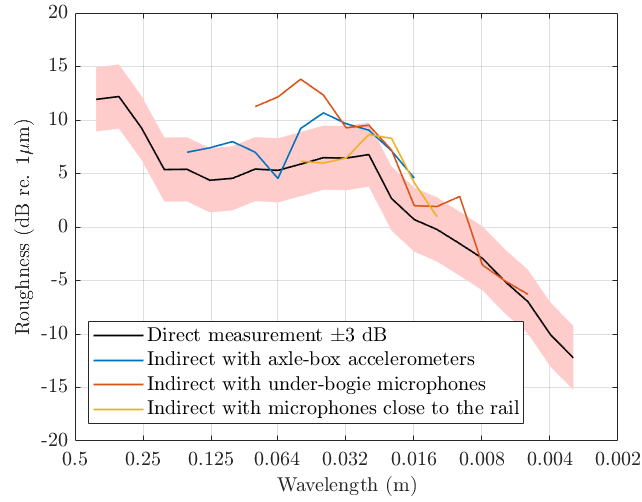


Fig. 2. Comparison of direct and indirect measurements without partial calibration (CEF2)

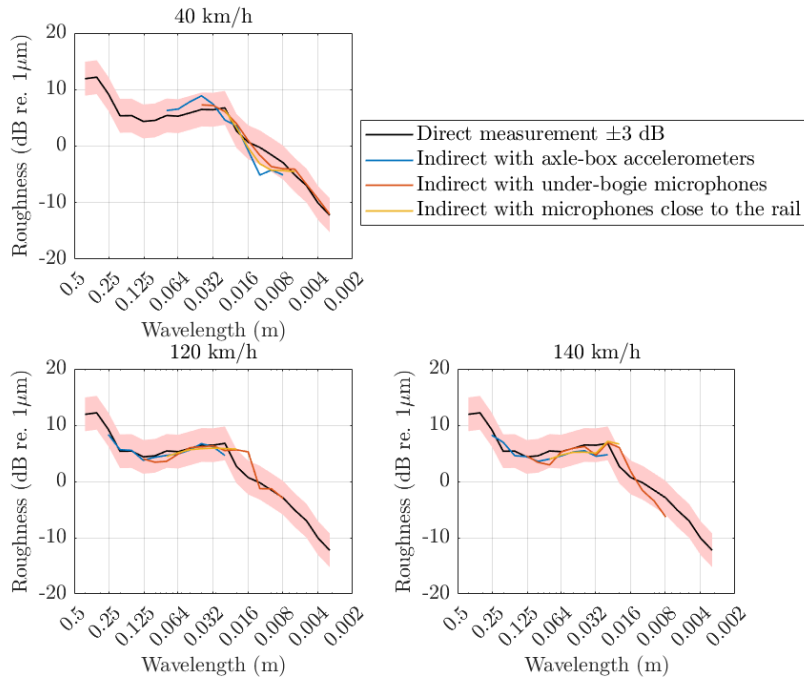


Fig. 3. Comparison of direct and indirect measurements with partial calibration (CEF2)

3.2 Rolling tests on French Railway network (RFN)

The method was then tested on the French national network (RFN). Indirect and direct roughness measurements were compared on several track sections of the network. The results are given in **Fig. 4** for two particular sections, travelled at 80 km/h:

- Pierrelatte: the track support is made of bibloc concrete sleepers with rail-pads of medium stiffness (softer than those identified at CEF2).
- Mâlain: the track support is made of wooden sleepers.

It must also be emphasized that the roughness measured on these sections are much lower than those measured at CEF2. The results given in **Fig. 4** are obtained with the partial calibration performed at CEF2 for a speed of 80 km/h. Compared with the perfect estimation with calibration at 80 km/h on CEF2 (calibration speed and track), they are impacted by the variation of the actual track support. However, the proposed hybrid method (a relative calibration gain allowing the variability of the transfers with the track support) induces a contained degradation of the results except for those obtained from the microphones close to the rail during the passage on the section characterized by wooden sleepers.

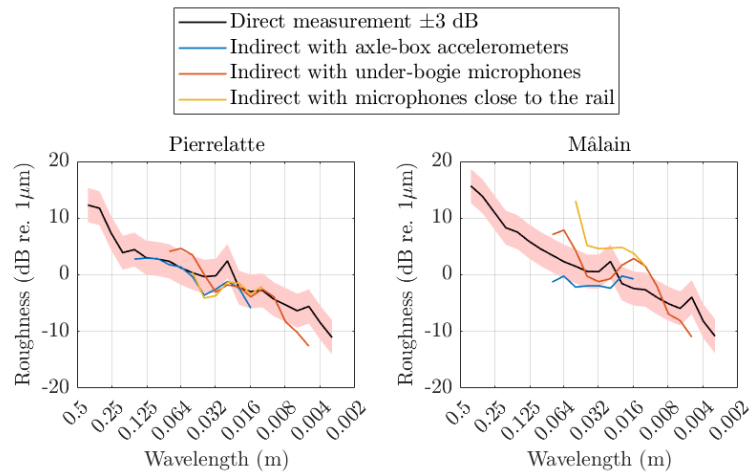


Fig. 4. Comparison of direct and indirect measurements with partial calibration (RFN)

4 Conclusion

In this paper, a multi-sensor method is proposed for the indirect on-board estimation of the rail acoustic roughness. The combination of several families of sensors allows a wider wavelength band to be covered, whereas the use of models for estimating the transfer functions between sensors and roughness allows some parametrisation of the transfer functions, particularly with regard to speed and track support. The principle of partial calibration finally combines the accuracy of the experimental calibration and

the parameterization allowed by the models. The performance of the method is tested through measurements while driving on different track sections, at several speeds, showing encouraging results with maximum errors mostly around ± 3 dB per octave. Although still higher than the uncertainties of direct measurements, the errors become acceptable considering the global rolling noise levels calculated from the estimated roughness. It remains to work mainly on the realism of the vibro-acoustic track models to further improve the accuracy. A prototype of an industrial system using the method developed in the MEEQUAI project is currently being tested on an SNCF vehicle travelling on some parts of the French railway network and recording data along the way. For the moment, it is planned that the system will be linked to an operator's database allowing the identification of the track type from the GPS location. However, a method aiming at identifying the track type using the sensors is currently under study, which would make it possible to dispense with the link to the database.

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