On-board indirect measurements of the acoustic quality of railway track: state-of-the art and simulations

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ABSTRACT

Noise emission is a major concern for residents living along railway lines. For a large range of conventional speeds, railway noise is dominated by rolling noise. The contribution of the track to rolling noise is mainly driven by the level of rail roughness and the Track Decay Rate (TDR). The MEEQUAI project (on-board measurement of the acoustic quality of the infrastructure) aims to develop a system capable of measuring these characteristics using on-board instrumentation. A state-of-the-art on the subject shows that indirect measurement from vibro-acoustic sensors like axle-box accelerometers or microphones in the bogie area seems possible, but that a number of improvements could be made to the existing methods, especially in estimating the transfer functions between the effective roughness and the signals provided by the sensors. The idea is to combine modelling and measurements to optimize the estimation of the transfer functions and the location of sensors while taking into account the variability of circulated tracks. Numerical analyses of transfer functions based on axle/track vibro-acoustic models are performed. Based on the simulations results, several improvements are proposed, with a view to future tests in rolling conditions.

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1. INTRODUCTION

Environmental railway noise is a critical issue, both for welfare and legal practices. In order to guarantee a good acoustic environment, national and international laws are regularly established; among these, the European directive 2002/49/CE relates to the assessment and management of environmental noise. This directive requires Member States to realise "noise maps" and to set up action plans, in case noise issues exist.

A common methodology for the calculation of railway noise is prescribed to Member States: CNOSSOS-EU (Common NOise aSSessment methOds). One of the main features of this methodology, is that it requires input data that are typical of each noise source, instead of generic source power terms. This approach allows establishing action plans that are optimized both from the viewpoint of noise reduction and cost. Accordingly, railway rolling noise should be described through a set of track and train physical and mechanical parameters; rail roughness and Track Decay Rate (TDR) are the most influential parameters concerning the track contribution. Thus, the relevance of CNOSSOS noise maps, is linked to the quality of these input data. The measurement of rail roughness and TDR is nowadays performed on small track portions, with a high cost (need to stop the train circulation on the track portion, and slow measurement protocols).

The MEEQUAI project (on-board measurement of the acoustic quality of the infrastructure) aims at developing an industrial prototype for the on-board measurement of roughness and TDR. The MEEQUAI system lies on an inverse problem on rolling noise: the aim is to estimate the track acoustic characteristics from vibro-acoustic sensors placed on the train.

In addition to the collection of input data for noise maps, the MEEQUAI measurement system should provide brand-new solutions for maintenance and monitoring. The main asset of an on-board system is the opportunity to perform measurements on long track portions. This would allow to better identify the influence of track parameters on the acoustic quality of railways, and to efficiently manage noise action plans. Moreover, the sensors would simultaneously collect signals related to the state of track, thus giving information on rail defects, joints and switch. The monitoring of these hotspots is time-consuming and expensive with current procedures.

Railway noise is related to several sources, such as rolling noise (caused by the rail-wheel contact), traction noise from equipment, aerodynamic noise. The contribution of each of these sources depends on train speed, but for a large range of operational speeds, rolling noise can be considered as the main source [1].

Roughness on the wheel and rail running surfaces induces vertical vibration of the wheel and rail systems, that are influenced by physical phenomena acting at the rail-wheel contact. The main wavelengths of roughness that are relevant to acoustic issues, are between about 5 and 500 mm. The vibration is transmitted into the wheel and track structures, leading to sound radiation.

2. TRACK CHARACTERISTICS MEASUREMENT

Two kinds of methodologies exist for assessing roughness and TDR: direct or indirect measurements.

Direct roughness measurement consists in estimating the vertical irregularities of the two rails using fixed measuring rules or mobile trolleys. Direct measurement of the TDR

consists in estimating the attenuation of vertical and lateral vibration waves along the rail using a fixed accelerometer and mobile impact hammer excitation.

Unlike direct measurements where sensors are applied directly to the rail surface, indirect measurements focus on quantities that result from wheel/rail interaction, such as noise or vibrations of axle-boxes or rail, and from which the actual combined roughness and/or TDRs are deduced. Indirect measurements are made in the time domain. They can be performed in a fixed frame (pass-by measurement) or on the train itself (on-board measurement).

Direct measurements have a number of advantages over indirect measurements: they allow the separation of rail and wheel contributions, they are accurate and free from perturbations coming from the railway environment. That is why they are the only measurement methodologies accepted in a normative framework (standards EN 15461 and EN 15610). Nevertheless, direct measurements require stopping train traffic, and are thus limited to small track portions.

2.1. Roughness measurement through axle box accelerometers

Roughness can be estimated from axle-box acceleration $\Gamma_{B.E.}(f)$. For a single rail, one can estimate effective roughness as:

$$|r_{eff}|^2 = |H_{r-B.E.}|^2 |\Gamma_{B.E.}|^2 \tag{1}$$

where $|H_{r-B.E.}|$ is the roughness-axle box acceleration transfer function.

This method, originally proposed by British Rail Research [2] is exploited by the Swedish railway company Banverket (TRC "Strix" [3]), and for the RailMeasurement "High Speed Rail Corrugation Analyser" (HSRCA) [4]. The correctness of the method has been proved in the framework of the TRANRED project, on the London subway [5]. A similar technique has been proposed for the rail surface monitoring, during the MONA project [6]. Some information is available on the setup and validation of this methodology on the Czech railway network by VUKV [7].

2.2. Roughness measurement through microphones

Early systems exploiting microphone signals were based on a comparison of measured noise levels with noise patterns; these systems do not allow to estimate an absolute roughness spectrum. This methodology has been employed in the ABN system (AxleBox Noise measuring device) [8], the system proposed in the framework of the MONA project [6], the NoiseMon system developed for the British railway network [9], and the SMT (Specially Monitored Track) system developed by the Deutsche Bahn [10].

More recently, it has been proposed to use transfer functions, to estimate effective roughness spectra $r_{eff}(f)$ from pressure $p(f)$ measured by on-board microphones:

$$|r_{eff}|^2 = |H_{r-p}|^2 |p|^2 \tag{2}$$

where $|H_{r-p}|$ is the roughness-acoustic pressure transfer function.

Different measurement systems are available, each with a specific technique for estimating the transfer function (experimentally or numerically) and a determined number and position of microphones. Among these, the ARRoW (Acoustic Rail-Influence Recording on Wheels) system [11], the SNCF LECAV method which has not been tested on a rolling train yet [12], the system developed in the framework of the Quiet

Track project and tested on the Stockholm subway [13], the Belgian Infrabel system, and the Danish SWECO system.

2.3. Other roughness measurement techniques

Other systems exist for roughness measurement, which are based on optical techniques [14], eddy current sensors, or strain gauges fixed on wheels. However, these systems are hardly fitted on vehicles in operational conditions.

2.4. MEEQUAI strategy

The systems and methodologies presented in previous sections are summarized in Table 1.

Frequency range	Sensors	Measurement system
100-600 / 1000 Hz	Axle box accelerometers	TRC Strix, HSRCA, TRANRED
500 / 1000 - 1500 Hz	Rail near-field microphone	LECAV
500 / 1000 - 5000 Hz	Under coach microphone	MONA, Quiet Track
1500 - 5000 Hz	Wheel near-field microphone	ARRoW, LECAV, SWECO

Table 1: Review of on-board roughness measurement systems.

These methods suffer from certain limitations. First, their relevant frequency range is limited. An optimisation of the position of sensors allows overcoming this limitation; moreover, the combination of different types of sensors (as proposed in the LECAV method [12]) is convenient in terms of frequency range of application.

The second limitation is linked to the precision of transfer functions, which are usually measured during calibration tests. The calibration neither take into account the variability of parameters that can influence track dynamics (such as sleeper and railpad configuration), nor the variability of kinematic parameters (train speed and contact point position); all these parameters directly affect the shape of transfer functions. Combining numerical and experimental methods for the estimation of transfer functions is a way to overcome this weakness.

Further constraints can be related to acoustic or vibration perturbations, as well as couplings between the two rail sides. Sensor redundancy in the context of inverse methods techniques can improve the quality of the acquired signal, and is a solution to deal with this constraints.

Finally, there are few cases of measurement systems of the track dynamic characteristics: on the LECAV method [12], pairs of microphones measure the acoustic signal in the rail near-field, and compare it to a benchmark of related track architectures; in the framework of the Quiet Track project, the difference between noise levels measured in the wheel vicinity and under the coach, allows calculating the TDR [15]. The first system has not been tested in operational conditions, while the latter gives inaccurate results. A method based on rail near-field microphones seems to be the most effective to be investigated: it does not depend on the level of excitation (since relative signals are considered), and the comparison with benchmark signals (eventually obtained by numerical simulation) makes it a robust procedure.

The idea behind the MEEQUAI system is to set up a measurement system for roughness and for the track dynamics characteristics, that overcome the mentioned limitations, and is based on the solutions proposed for each one of those limitations.

3. NUMERICAL ANALYSES

Numerical analyses have been performed, in order to estimate numerically the transfer functions needed for the methods introduced in Section 2. Moreover, numerical simulations helps optimising the number and position of on-board sensors, and to analyse the reliability and variability of sensor signals.

3.1. Rail-wheel interaction and track variability

In order to calculate the acceleration-roughness transfer function, one first needs to estimate the relationship between roughness and dynamic forces at contact. This relationship can be easily inferred from a wheel-rail interaction scheme, like the one proposed in [1] and recalled in Figure 1.
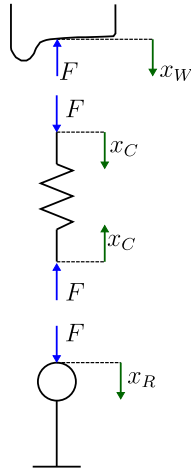
Figure 1: Wheel-rail interaction scheme.

Displacements of the wheel, rail, and contact subsystems (x_W), (x_R), (x_C), are related to the dynamic force at contact (F) by the relations:

$$(x_W) = [A_W](F_W) \qquad (x_R) = [A_R](F_R) \qquad (x_C) = [A_C](F_C) \tag{3}$$

where $[A_W]$, $[A_R]$ and $[A_C]$ are the receptance matrices at contact point, for the wheel, rail, and contact subsystem respectively. By continuity of displacements at the contact point, displacements can be related to the effective roughness (r_{eff}):

$$(r_{eff}) = (x_R) + (x_W) - (x_C) \tag{4}$$

Therefore, by imposing the equilibrium of forces at contact:

$$(F) = [A]^{-1}(r_{eff}) = ([A_R] + [A_W] + [A_C])^{-1}(r_{eff}) \tag{5}$$

Receptance matrices can comprise coupling terms between different directions, and between the two rail sides. In this paper, we only consider the lateral and vertical directions of the track reference system, thus dealing with a 4x4 size matrix problem. Terms of matrices $[A_W]$ and $[A_R]$ are obtained by Finite Element calculation on track and wheelset models (see Figure 2 for these FE models); terms of matrix $[A_C]$ are obtained
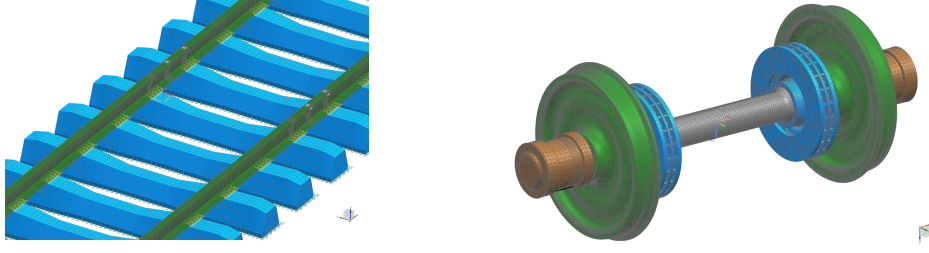
Figure 2: Finite Element models for track and wheelset.

analytically, based on the Hertz contact theory, where additional lateral creep terms have been taken into account [1].

The track F.E. model is composed of solid elements for rail and sleeper, while railpads and ballast are modelled as discrete springs. In order to simulate an infinite rail length, "anechoic terminations" are included: rail material damping is gradually increased when moving towards the rail end, thus preventing any reflections at the end. This modelling strategy is compliant for the calculation of TDR.

Several track configurations have been modelled by Finite Elements, so that the variability of transfer functions with track parameters could be analysed. The parameters which are considered are: track platform (ballast / concrete platform), railpad dynamic properties (stiffness and damping), rail profile, sleeper configuration (mono/bi-bloc concrete, wood). Thanks to this sensitivity analysis, we have determined the most influential parameters for the track dynamic behaviour: railpad stiffness, sleeper mass, and track platform.

The weelset F.E. model is composed of solid elements for all the components (wheel, axle, brakes, axlebox), except for bearings, which are simulated through a set of discrete springs in a radial pattern.

3.2. Axle box acceleration - roughness transfer functions

Axle box acceleration can be calculated from mechanical transfer functions between the contact point and a point on the axle box:

$$\left(\Gamma_{B.E.}\right) = \left[B_W\right]\left(F\right) = \left[B_W\right]\left[A\right]^{-1}\left(r_{eff}\right) \tag{6}$$

Inertance matrix $\left[B_W\right]$ terms are derived from the same F.E. calculations that give the receptance matrix elements. The equations presented here are the core of a Matlab$^{®}$ code that allows evaluating the rail-wheel contact (Figure 3).

The wheelset selected to test the method belongs to a SNCF Corail train. An Experimental Modal Analysis test campaign has been realized on this wheelset, in order to validate the FE model in the frequency range [50-2000 Hz]. The validation of the axle box components happens to be challenging, when bearing data are not completely. That is why, it has been decided to use measured $\left[B_W\right]$ terms and to rely on numerical data only when a fully validated FE model is available; numerical $\left[A_W\right]$ terms are more easily correlated, and can be used even when wheelset data lacks. Therefore, what is foreseen is an hybrid numerical/experimental calibration methodology, depending on the availability of wheelset data.
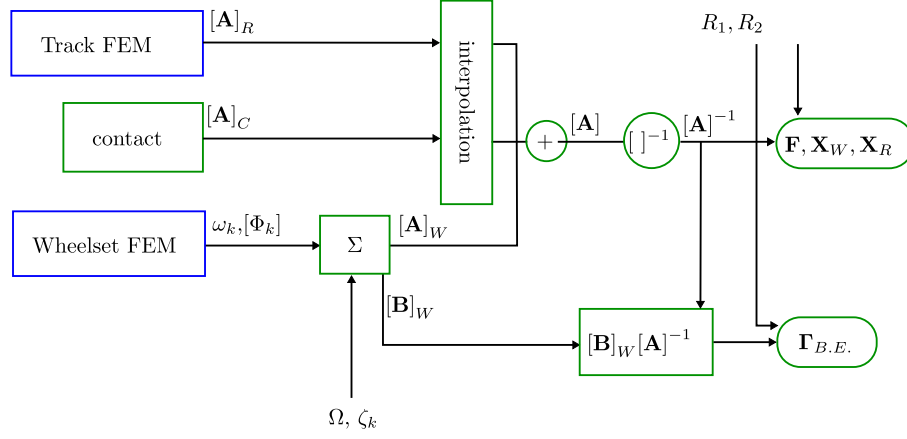
Figure 3: Code schematics for the wheel-rail interaction.

3.3. Acoustic pressure - roughness transfer functions

Acoustic wheel and track near-fields have been calculated by solving an exterior radiation problem on an acoustic Finite Element model. For both structures, a weak fluid-structure coupling has been assumed. The acoustic boundary condition is enforced as a displacement field on the structure surface, which has been calculated through F.E. calculations on the models of Figure 2, for a unit vertical force at the wheel-rail contact. The acoustic mesh is fitted to the frequency range: different meshes are used for single frequency ranges, and each mesh is designed to have 4 elements per wavelength. Far-field conditions are simulated through Infinite Elements, whose interpolation order is carefully chosen to attain convergence on power indexes. A baffle plane is included, in order to take into account the ballast. In addition, ballast acoustic absorption properties are included in the model, through an impedance boundary condition on the baffle plane; the impedance values are determined analytically and based on a Delany-Bazley model [1].

For wheel radiation, the attention has been focused on wheel resonances up to 5 kHz, and in particular on *Rn* (radial modes with *n* nodal diameters) and 1*Ln* modes (axial modes with 1 nodal circle and *n* nodal diameters), which contribute the most to rolling noise. The acoustic pressure field has therefore been estimated at wheel resonances; as an example, Figure 4 shows the pressure field at the frequency corresponding to the wheel *R*2 mode (larger contribution to rolling noise). The general trend for the pressure field, as frequency increases, is to become more and more complex and directional, as a result of acoustic waves recombinations. As a whole, the field pressure is more homogeneous at frequency corresponding to wheel radial modes, than at axial modes. The presence of a partially absorbing baffle makes the acoustic field way more complex than the case of a free wheel in space.

It is possible to identify an optimal position for the microphone, based on two requirements on the acoustic near-field impedance, $Z' = \dfrac{p}{\rho_0 c_0 V_n}$:

– Z' should be stable along a line that runs out of the wheel, so that some flexibility on the exact microphone position can be allowed;

– $|Z'|$ should be as close as possible to unity, in order to limit errors in the transfer function calibration.
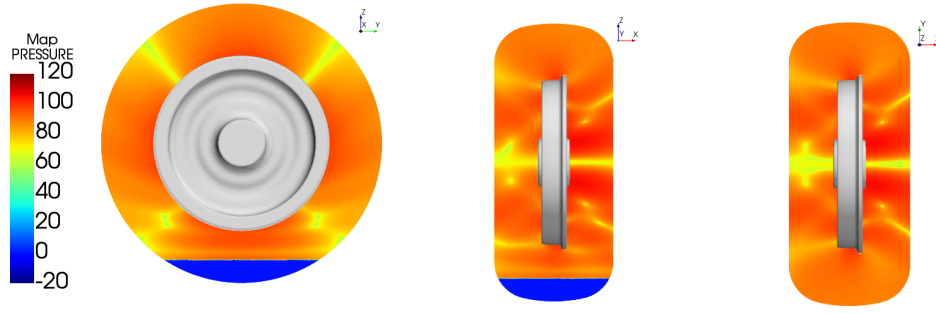
Figure 4: Wheel acoustic near-field [in dB] at 1646 Hz (R2)

Concerning track radiation, the analysis has been focused on 20 frequencies in the [0 - 2000 Hz] range. The track model includes 8 sleepers; this track length has been chosen as a good comprise between a reliable representation of the track dynamics in the longitudinal direction, and computational burden (which can be quite high for truck structures). As an example, Figure 5 shows the acoustic pressure field around the track, at 1 KHz. The rail on which the vertical force is applied, is the one the negative y side; this is also visible in the acoustic field, since this rail radiates the most. The pressure field is quite stationary in the longitudinal direction, and radiation patterns are clearly visible in this direction: this is though to be due to the proximity of the so called "pinned-pinned frequency".
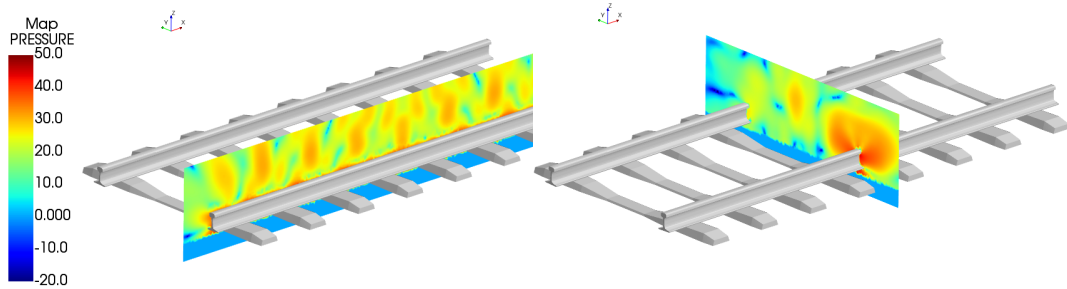

Figure 5: Track acoustic near-field [in dB] at 1 kHz.

Based on the criterion already introduced for the wheel radiation, an optimized position for the rail near-field microphone has been identified. The detailed position of the wheel and rail near-field microphones is outside the scope of this paper.

Future static tests will validate the numerical analyses, and confirm the positions hence identified. The definite sensor positions will allow defining the design of the MEEQUAI prototype; a final test campaign will consist in measurements of transfer functions in operational conditions.

4.   CONCLUSIONS

On-board measurement of the track acoustic quality is necessary to characterize the railway network on a wide scale. The challenge not only concerns the input data for noise

maps, but is also critical with respect to maintenance action plans. A state-of-the-art shows that indirect measurements of roughness and track dynamic characteristics from on-board vibro-acoustic sensors is viable, but a number of improvements is necessary, especially when concerning to the estimation of transfer functions. The MEEQUAI project aims at combining calculation and measurement, optimizing the estimation of transfer functions and the position of sensors, and taking into account the variability of track architectures. Finite Element simulations have been performed, to calculate the axle box-roughness and acoustic pressure-roughness transfer functions. Upcoming actions of the project involve the validation of calculation through static tests, and the development and test of inverse methods in operational conditions.

5. ACKNOWLEDGEMENTS

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