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Acoustic wall pressure simulation in a train using Boundary Element and Beam tracing methods

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ABSTRACT

One of the main parameters that define the comfort of a train is the noise. There are several numerical methods to perform airborne interior noise predictions, one key input of this process is the acoustic pressure around the train coming from the external acoustic sources. Many times for this wall pressure an experimental database is created from measurements. The main problems of this method are the availability for tests, the cost and the impossibility to take into account architectural changes of the new projects compared with the measurement ones.

To overcome these limitations, it is possible to replace the expensive field tests with calculations. In this study we present the assessment of the results of pressure field around a railway vehicle obtained with two computation techniques (Boundary Element Method and Ray-tracing) compared with experimental values measured on an existing train with artificial sources and real operating conditions. Results with artificial sources are promising with enough accuracy for industrial applications, on the other hand for real operating conditions the problem is a challenge because the complexity of how real sources are simulated: location, distribution, etc…

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1. INTRODUCTION

Interior noise is one of the main aspects that drives the design of modern rolling stock. Interior noise main contributing sources are: equipment, rolling noise and aero-acoustic sources. These sources generate interior noise through airborne and structure borne paths. How the airborne energy is transmitted along the train depends on the sources location, the pressure field distribution around the vehicle and also on the isolation characteristics of the different components of the train.

The present paper deals with the assessment of the results of acoustic pressure field around a railway vehicle obtained with two computation methods, Boundary Element Method (BEM) and Ray-tracing, compared with experimental values measured on an existing train with artificial sources and real operating conditions. The main challenge of the study is to find a compromise between the required accuracy and the modelling effort compatible with industrial needs while taking the particularities of the railway vehicle, the sources and the transmission path into account. The aim to perform measurements in static with artificial source is to have experimental results with a controlled excitation to avoid the uncertainties related to sound strength and directivity of real sources in real operation conditions.

A Metro train in a free-field environment has been chosen to perform this investigation. At the end the feasibility to replace the measurements with calculations is assessed.

2. PREDICTION METHODS

From the acoustic engineering point of view, the topic ‘pressure field distribution around an object’ could be considered as propagation acoustics: starting with the sound radiation and successive sound interaction with objects. But also full or partial reflection, diffraction (scattering), transmission and absorption are the distinct processes of the propagation physics... The wavelength dependence of the Sound Pressure Level (SPL) distribution around a vehicle and the proximity of other objects affect the propagation process changing the sound field. The SPL around the carbody is not only captured by the direct sound but also by the diffracted part. The methods to predict the SPL around a vehicle should be able to simulate the direct, reflected and diffracted sound as well as to take into account the ground or panels absorption.

Several predictions methods can potentially be applied for this topic: empirical/analytical methods; wave-based methods - Boundary Element Method, (BEM), Finite Element Method (FEM), Ray-tracing acoustic method- or Statistical method (SEA). Depending on the environmental conditions, frequency band, model geometrical complexity, etc…, one method could be more suitable than others.

In this paper BEM and Ray-tracing methods are explored in continuation of previous work already done within Alstom [1]. The original reasons to choose these two methods for evaluation were that comply with the requirements defined before (be able to simulate the direct, reflected and diffracted sound (not possible with SEA method) as well as to take into account the ground or panels absorption). Moreover, it is possible to simulate all the geometrical details that are not well captured with analytical models. FEM method could fulfil with those requirements but it was initially discarded due to the need of discretization of the entire domain (included the fluid) while BEM only requires discretization of its bounding surface. It was assumed that the modelling effort with FE will be higher and maximum frequency achievable would be lower than BEM or Ray-tracing.

2.1 BEM

BEM is a method well suited from the point of view of accuracy as well as computational efficiency for linear problems [2].

There are several methods related to BEM methods, basically the most commonly used are the direct BEM (DBEM) where the boundary surface should be closed because only uses the side of the boundary in contact with the air, and the Indirect BEM (IBEM) where both sides of the boundary surface are considered.

BEM Software tool used in this work is ESI-VAOne [3] using standard IBEM solver.

One of the limitations of this method is the computational resources needed and the time computation that could limit the maximum frequency that can be achieved. The main problem is the memory limitations to store and invert the BEM matrices. Improvement on the solver has been performing lastly by the software companies in order to solve all these limitations. Also, the parallel computing option can be used to extend the simulation to larger scattering and radiation problems.

The number of nodes of the faces defining the domain will determine the size of the problem. This number of nodes depends on the geometrical size of the domain and the maximum frequency to be reached (in general the element size is the acoustic wavelength /4).

2.2 RAY TRACING

Ray acoustics is based on the assumption that sound propagates along rays that are normal to wave fronts. Waves are simulated by rays, as in optics, and follow reflection, diffraction and transmission laws. It follows the Fermat's principle (minimum path length) with specular reflexion, and geometrical theory of diffraction. The hypothesis of validity is that details are coarser than a few wavelengths. Since the acoustic wavelength is normally of the same order as the dimensions of the interacting objects then the validity of the models is for mid-high frequencies only.

The ray tracing acoustic tool used in this study is ICARE [4]. It uses beam-tracing, volumes propagating wave-fronts, from point sources to receivers. Sound diffraction is, in general, relevant for surfaces similar or smaller than the wavelength and can be included in ICARE using low order diffractions up to third order.

The main parameters that will determine the computation time are diffraction number (number of diffractions that one ray can meet), diffraction lines defined on the model, subdivisions number (number of rays after diffraction), number of reflections and number of sources

3. EXPERIMENTAL SET-UP

3.1 Static with artificial source

Wall pressure measurements in static, in free field and on a ballasted track have been done on an Alstom Metro using an omnidirectional loudspeaker with a known sound power level (SWL). The loudspeaker is placed in two different positions (lateral and underframe). Several microphones have been placed in different positions (underframe, sidewall, roof).

3.1.1 Ground characterisation

The train is placed in a ballasted track. The ground absorption used is obtained from measurements [5] for a ballast 170 mm depth.

A measurement on the ballasted track without the train has been performed with a omnidirectional loudspeaker. The objective is to confirm the assumed absorption is correct. Several microphones have been positioned in front of the omnidirectional source at different distances and height. Then the same situation has been simulated with BEM/Ray-tracing in order to confirm the good floor impedance/absorption choice.

3.1.2 Train and Sound Pressure Levels (SPL) positions measured

A section of a Metro Train including one half of a vehicle, a gangway area and part of a second car has been instrumented. In Figure 1 the mesh of sensors is shown.

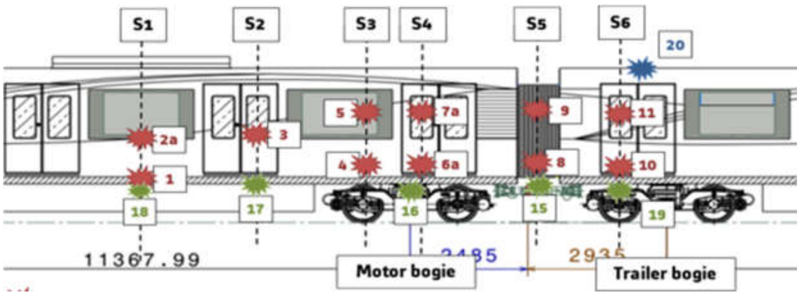


Figure 1: Metro at static wall pressures mesh and microphones

3.1.3 Source locations

Measurements have been performed with 2 source locations (Figure 2). One lateral close to one wheel (position A) and the second one inside the bogie (position C). The aim is to reproduce similar positions as the rolling noise location (position A) and the equipment inside the bogie (position C)

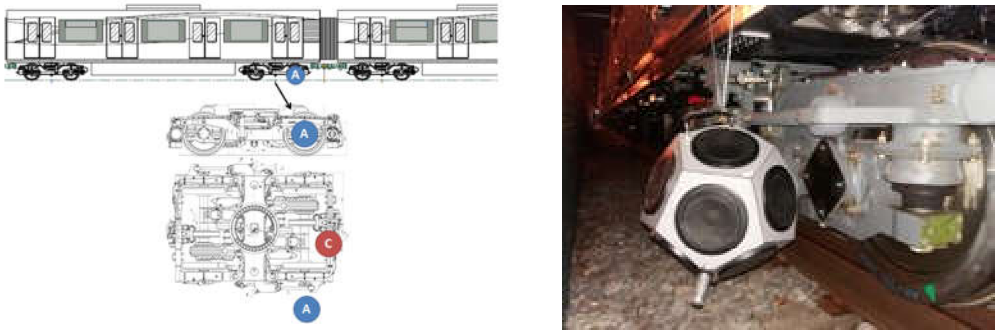


Figure 2: Omnidirectional source positions. Photo of position A.

3.2 Real operation case at constant speed

Acoustic wall pressures measurements have been performed at 80 Km/h on the same train as the static ones (see 3.1) in a free-field ballasted track where the acoustic track characteristics (rail roughness and track decay rate) have been measured. Additionally wheel roughness has been also measured. Acoustic wheel and track characteristics have been used to obtain the representative rolling noise sound power levels by using the tools TWINS [6]. It is important to point out that measurements below 200 Hz are polluted by wind around micros, therefore only frequencies above are compared.

The wall pressure positions locations have been the same as the static ones.

4. SIMULATIONS and RESULTS ASSESSMENT

The evaluation of the numerical prediction methods has been made with respect to calculation accuracy and usability in an industrial context.

Usability in an industrial context is evaluated basically checking the computation time needed with normal hardware resources available in the industry and if the modelling process is affordable.

The accuracy is defined here as the closeness of agreement between a calculated value and a measured value. The measurement uncertainty assessment is out of this study and the available values are taken as the true value except for dynamic measurements where measurements are only valid above 200 Hz

For static simulation, the compared curves will be the Transfer functions (TF) = SPL simulation – SWL of the source. For dynamic measurements, SPL levels are compared directly. In static the gap between the simulation and measurement values will be shown as a function of the frequency. In addition the global values of the gap frequency spectrum will be provided in two ways: the average of the gap per band (numerical difference, positive or negative; if it is positive simulation is overestimating and if it is negative simulation is underestimating) and as the average of the absolute value gap per frequency band. A global gap will be obtained for all the points, and it will be used as an indicator to assess the global accuracy of the TF simulation.

The criteria used to evaluate if the simulation is good enough for a dynamic case is a frequency weighted gap. Frequency weighted gap consists in the application of a weighting filter per frequency band to the simulated SPL. This weighting filter is calculated taking into account the contribution of each frequency band to the measured SPL.

The study in static conditions has been already partially published [7] for BEM results and low frequency until 460 Hz, in this paper the study is extended to higher frequencies in BEM and Ray-tracing results

4.1 Static simulation with artificial source

4.1.1 Models

4.1.1.1 BEM

The first assessment needed is the evaluation of the maximum frequency that can be reached with a reasonable calculation time in the studied problem depending on the computational resources available. Two computational resources have been evaluated:

Some details of the models (Table 1 and Figure 3)

Computation resources	1 advanced one workstation (16 cores, CPU 2* 2x Intel(R) Xeon(R) CPU E5-2620 v4 @ 2.10GHz, RAM 128 GB.). Max freq: 800 Hz
	5 advanced workstation working in parallel. Max freq: 1500 Hz
Frequency band	20 – 800/1500 Hz in 20 Hz band
Wetted nodes	40645 (model up to 800 Hz)
	86783 (model up to 1500 Hz)
Time computation	15 min/band. Total 16 hours (model up to 800 Hz)
	19.2 min/band. Total 1 day (model up to 1500 Hz)

Table 1: BEM model description

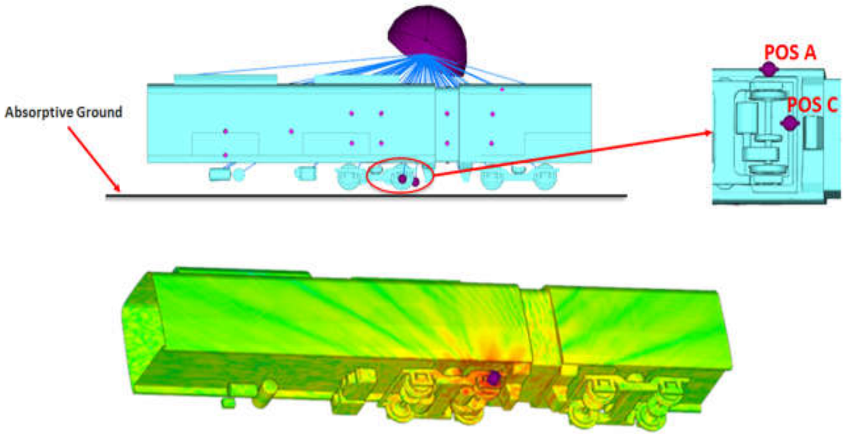


Figure 3: Metro BEM model. Microphone & sources location. Pressure contour example.

4.1.1.2 RAY-TRACING

As explained previously, the main parameters that will determine the computation time are diffraction number (number of diffractions that one ray can meet), diffraction lines defined on the model, subdivisions number (number of rays after a diffraction), number of reflections and number of sources

In this case, the computation time is guided by the geometry, not the frequency domain. The geometrical simulation could be performed in a reasonable calculation time up to 8000 Hz with one advanced workstation

Some details of the models (Table 2 and Figure 4):

Computation resources	1 advanced one workstation 8 cores, CPU Intel(R) Xeon(R) CPU E5-1620 v3 @ 3.50GHz, RAM 128 GB.
Frequency band	20 – 8000 Hz in 1/12 octave band
Ray parameters	2 diffractions, 10 subdivisions and 9 reflections.
Time computation	30 min/band. Total 2 days

Table 2: Ray-tracing model description

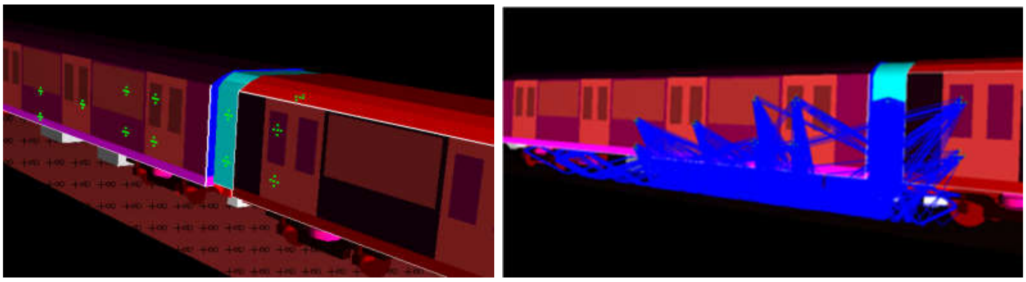


Figure 4: Metro Ray-tracing model. Microphone & sources location. Rays generated example

4.1.2 Results

As an example see in Figure 5 the results of one point at the lateral of the gangway. As mentioned in the introduction the TF simulated and measured, as well as the gap between them are shown.

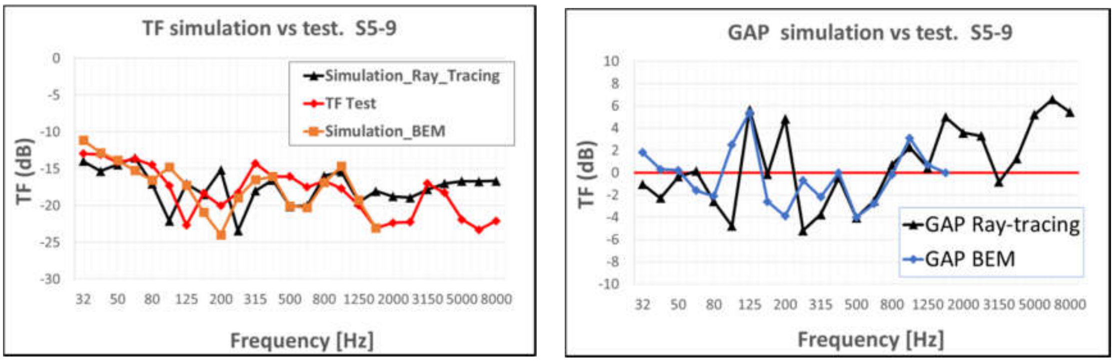


Figure 5: Metro static results, source position A. Point S5-9

4.1.3 Results assessment

The gap and the absolute value have been averaged for all the points and per areas in order to show an overall accuracy of the method.

In the following table, it is summarized all the gaps simulation vs measurements obtained with BEM and Ray-tracing methods.

FREE-FIELD COMPLETE CAR	METHOD	Uncertainty (dB)* Absolute value		Uncertainty (dB)* value		Time computation per 1/12 octave frequency band
		Near area	Far away	Near area	Far away	
Low-mid frequency *(up to 1500 Hz)*	**BEM**	2	3	0.5	1	20 min
	Beam-tracing	3	4	1	1.5	30 min
High frequency *(1500 to 8000 Hz)*	**Beam-tracing**	4	7	3.5	6	30 min

Table 3: Results summary. Metro free-field ballasted track. BEM and Ray-tracing methods

The main conclusion is that the accuracy is good enough for both methods being a little bit better for BEM. BEM method can be used for low-mid frequencies and Ray-tracing can reach also high frequencies. The accuracy is slightly better for the points near the source than far away.

4.2 Real operation case at constant speed

4.2.1 Sources simulation

This is a key and a challenging point due to the complexity of representing the real sources: location, distribution, directivity, strength, etc…

Basically the main sources contributing to the wall pressures in this type of train and speed in real operation are: Rolling noise (Wheel, rail and sleeper contribution), traction motor and gearbox.

It should be noted that in other type of trains and depending on the evaluated speed other sources could be important as for instance: auxiliary equipment, noise coming from the aero excitation, etc…

4.2.1.1 Rolling noise

4.2.1.1.1 Sound power level

As noted before the rolling noise is represented as the wheel, rail and sleeper acoustic radiation. The acoustic power radiated for each element has been calculated thanks to the TWINS software [6] which is a track wheel interaction noise software commonly used by the railway manufacturers for assessing the acoustic radiation of wheel and track design on railway rolling noise.

The inputs for TWINS are the wheel and track design, wheel and track roughness measured as well as the rail pad stiffness obtained from the track decay rate also measured. All these inputs were available for the measured case

4.2.1.1.2 Radiation behaviour

Sound radiation behaviour from wheels and track is represented as [8]:

- Wheel: a) Radial motion as a omnidirectional source and b) Axial motion as a dipole distribution
- Rail: a) Vertical motion as a omnidirectional source and b) Lateral motion as a dipole distribution
- Sleeper: Omnidirectional source.

So both in BEM and Ray-tracing predictions the wheel radial motion, rail vertical motion, and sleeper have been simulated by monopoles; and for the wheel axial and rail lateral with dipoles.

4.2.1.1.3 Sources distribution

For the wheels: two monopole (radial) and two dipoles (axial) are created, one per each face of the wheel. See an example in Figure 6 the sources location for both numerical models.

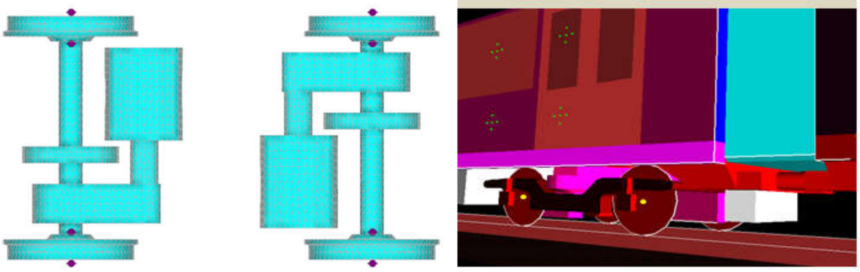


Figure 6: Wheel radial monopoles in BEM model (left) and Ray-tracing (right)

For the rail, an excitation per wheel contact point with the rail is applied. As the radiation is in both sides two monopole (vertical) and 2 dipoles (lateral) are created in ray-tracing, one per each face of the rail geometry which is included on the model. In BEM as the rail geometry is not included only with one monopole and one dipole is enough.

For the sleeper the monopole source is applied in the middle of the sleeper position. It is considered that only two sleepers are contributing, and they are located on the wheel axes.

4.2.1.2 Traction motor

The sound power used for the traction motor corresponds to type tests measurements of the equipment in a test bench at the motor speed of 80 Km/h

Taking into account that the acoustic power per face of the motor are quite homogeneous it has been considered only one monopole without the motor geometry included on the model.

4.2.1.3 Gearbox

The sound power for the gearbox corresponds to type tests measurements of the equipment in a test bench at the speed and torque equivalent to 80 km/h constant speed.

The modelling approach has been the same as for the motor in case of ray-tracing and one monopole per each of the six faces, including in this case the gearbox geometry of the BEM model.

4.2.2 BEM

A standard IBEM solver has been used to perform the simulation.

The model has been created using as a reference the static one, reducing the studied area to the bogie and gangway. It has been performed simulation with one advanced workstation. Some details of the model (Table 4 and Figure 7)

Computation resources	1 advanced one workstation (16 cores, CPU 2* 2x Intel(R) Xeon(R) CPU E5-2630 v3 @ 2.40GHz, RAM 128 GB
Frequency band	20 – 1780 Hz in 1/12 octave band
Wetted nodes	35866
Time computation	16 min/band. Total 21 hours

Table 4: BEM dynamic model description

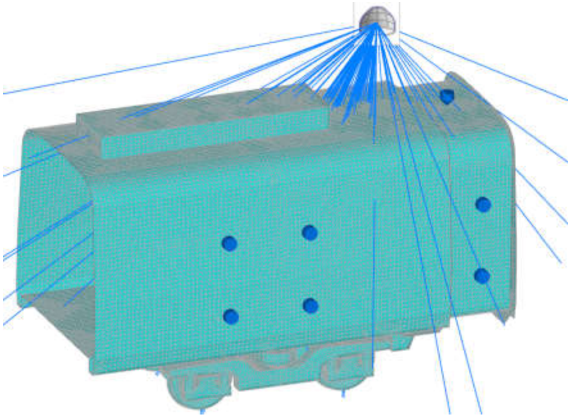


Figure 7: Metro BEM model. Microphones and BEM

4.2.3 RAY-TRACING

The model used is the same as the one for static. The main difference is the higher number of sources. This causes an important increasing of computational time (Table 5). It should be noted that computational time in ray-tracing is independent from the frequency range because computational time depends mainly on the geometrical calculation of rays emitted and diffracted.

Computation resources	1 advanced one workstation 8 cores, CPU Intel(R) Xeon(R) CPU E5-1620 v3 @ 3.50GHz, RAM 128 GB.	
Frequency band	20 – 8000 Hz in 1/12 octave band	
Ray parameters	2 diffractions, 10 subdivisions and 9 reflections.	
Time computation	Static	30 min/band. Total 2 days
	Real operation conditions	4 hours/band. Total 16 days

Table 5: Ray-tracing model description. Comparison computational time static vs real operation

4.2.4 Results

See in Figure 8 the weighted gap results for three points in BEM and Ray-tracing simulations.

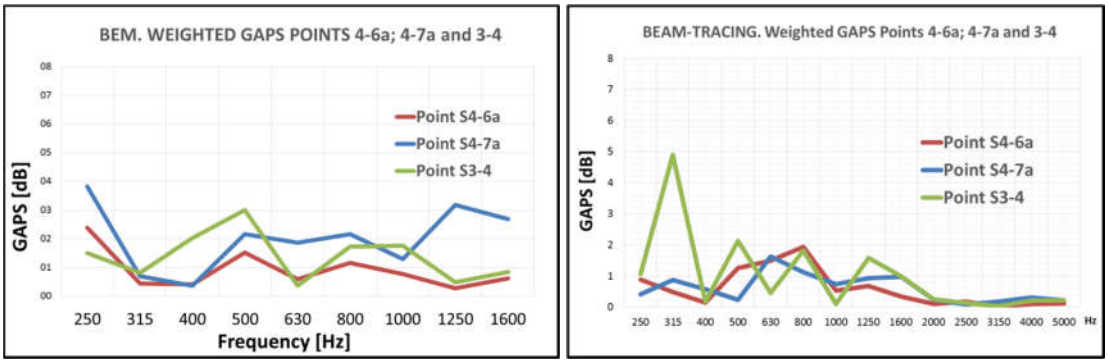
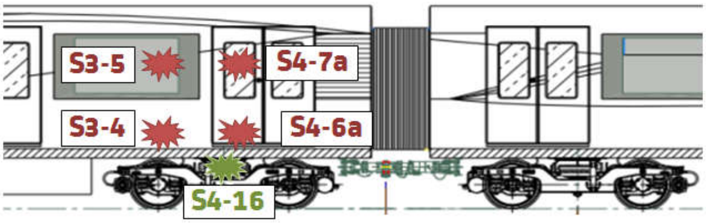


Figure 8: Metro real operation BEM (left) and Ray-tracing (right) weighted gap for three points

See in Table 6 the weighted gap results obtained for both methods in the most representative points of the area where more energy exist during real operation conditions.



LpAeq [dB(A)] @80 km/h	Method	LATERAL				UNDERFRAME	Time computation per 1/12 octave
		S3-4	S3-5	S4-6a	S4-7a	S4-16	
Frequency weighted GAPS [dB] 200-1600 Hz	BEAM-TRACING	1.6	1.8	1.0	0.8	0.7	4 hours
	BEM	1.4	1.7	1.0	1.9	1.3	16 min
Frequency weighted GAPS [dB] 1600-5000 Hz	BEAM-TRACING	0.5	1.3	0.2	0.1	1.3	4 hours

Table 6: Real operation weighted gaps results BEM vs Ray-Tracing

It can be concluded that both methods have an equivalent accuracy for simulation in real operation conditions. It is important to point out that the reason because the gaps are better than in static conditions is because in this case we are presenting the weighted gaps.

5. CONCLUSIONS

In this paper the results of two numerical methods to calculate the acoustic pressure around a train in static and real operation conditions have been presented.

Due to the high computation resources needed, BEM method is suitable for low-mid frequencies however ray-tracing can be used for the whole frequency band.

For a single excitation in static conditions the accuracy is good enough to be used in an industrial project environment. This means that models used are able to represent the physics of the problem in a broadband frequency range. Those results have set the basis for dynamic simulations. Static simulations could be applied to substitute TF measurements used to build databases to predict acoustic wall pressures in dynamic. Nowadays, those databases are built with costly measurement campaigns, therefore the savings due to the use of simulation could be important. Moreover computation time is acceptable with typical project schedules. As general trend, BEM is a little more accurate than Ray-tracing.

In real operation conditions it can be concluded that both methods have an equivalent accuracy but in terms of usability in an industrial context (computational time) is clearly better the BEM method. The obtained accuracy is good enough to substitute measurements by simulation.

6. OPEN POINTS AND NEXT STEPS

There are still some questions and options to be evaluated in the future:

- Interior noise is highly affected by the acoustic insulation of the train. Therefore the weighted function used to evaluate gap between measurements and simulation will be different giving more importance probably to low frequencies in the simulation.
- More detailed modelling of sources radiation to take into account the directivity of multipole sources as well as of more complex sources (e.g. rolling noise).
- Study the variation of the track geometry and its influence on the simulation models. It could have an important effect by screening, reflecting and diffracting the noise at mid-high frequencies
- Extend BEM simulations to higher frequencies.

7. ACKNOWLEDGEMENTS

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