ACOUSTICS 2012

Railway equivalent noise sources definition: ESM implementation and optimization

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Within the scope of a better integration of railway system in environment, prediction of trains pass-by noise is a growing concern for railway operators. SNCF has therefore developed the software VAMPPASS dedicated to pass-by noise simulation. The synthesis method implemented in VAMPPASS requires the definition of equivalent noise sources representative to real noise sources on the train. Equivalent sources definition is mainly based on experimental characterization. Measurement methods based on 1D-array devices have been optimized on a real train and post-processing methods have been developed for identifying mono-multipole equivalent sources, defined with the spherical harmonics formalism. This kind of method needs a heavy optimization process, applied on several parameters. It can imply large error coefficients on the radiated pressure field. The present study aims to investigate the potential of Equivalent Source Method (ESM, a transfer matrix based method) to fulfil the requirements of VAMPPASS.

In the first chapter, the ESM basis is presented. The second chapter is dedicated to the ESM implementation on a train scale model, with multi-monopoles equivalent sources. In the third chapter, improvements of the ESM for VAMPPASS requirements are discussed: the multi-dipoles equivalent sources model has been validated, and a genetic algorithm method has been used to optimize the equivalent noise sources locations.

1 Introduction

The numerical simulation of pass-by noise in the railway field is a growing issue: it is today very helpful for rolling stock design step, for a better integration of railway network in the environment and will be tomorrow required for the certification of rolling stock.

Within this context, accurate numerical acoustic models of rolling stocks, such as VAMPPASS at the SNCF, are developed: generally the vehicle is modeled as a set of noise point sources, each real source being represented by one or several point sources. The identification of these equivalent point sources can be achieved with experimental-based methods: the real noise sources are measured on the train or in laboratory under representative mounting conditions and a dedicated post-processing method allow defining relevant equivalent noise sources.

At SNCF I&R, several post-processing methods have been tested such as the decomposition of the radiation pattern of the real source on spherical harmonic coefficients (see [1]). More recently, the use of the so-called Equivalent Sources Method (ESM) has been implemented. It has been carried out with various types of point sources (monopole, dipole); some improvements have been proposed to adapt the ESM to railway specific noise sources, and particularly the use of Genetic algorithms to optimize the location of equivalent noise sources.

2 Equivalent source method

2.1 Presentation of the method

The Equivalent Source Method is used to model a complex real noise source with a set of monopoles. Based on a measurement of the pressure field radiated by the real source, ESM allows determining equivalent monopole sources whose combined radiation pattern is equivalent to the measured one [2, 3, 4].

The number and the locations of the monopoles are chosen a priori. Their combined sound radiation can then be easily written at any measuring point as:

$$p(\vec{x}_i,\omega)=\frac{j\rho\omega}{4\pi}\sum_{k=1}^{n}\left(\frac{e^{-jk\left\|\vec{r}_k-\vec{x}_i\right\|}}{\left\|\vec{r}_k-\vec{x}_i\right\|}\right) \quad (1)$$

where $\underline{x_i}$ is the location of the receptor, $\underline{r_k}$ the location of each point source k.

A transfer matrix can therefore be developed, corresponding to the transfer between the sound power of the n monopoles and the sound pressure at the N measuring points:

$$\underline{P}=\underline{\underline{H}}\,\underline{Q} \quad (2)$$

where $\underline{P}$ is the sound pressure on the N measuring point vector, $\underline{Q}$ is the sound power of the n monopoles vector and $\underline{\underline{H}}$ the transfer matrix, $\underline{\underline{H}}\in C^{N\times n}$. In the present problem, $\underline{Q}$ is the unknown data.

This matrix can be decomposed on its singular values (singular value decomposition or SVD process):

$$\underline{\underline{H}}=\underline{\underline{U}}\,\underline{\underline{S}}\,\underline{\underline{V}}^{H} \quad (3)$$

where $\underline{\underline{U}}\in C^{N\times N}$ and $\underline{\underline{V}}\in C^{n\times n}$, $\underline{\underline{V}}^{H}$ is the transpose conjugate matrix of $\underline{\underline{V}}$. $\underline{\underline{S}}$ is a Nxn matrix, with the singular values of $\underline{\underline{H}}$ on its diagonal:

$$\underline{\underline{S}}=\begin{pmatrix}\sigma_1 & & 0\\ & \dots & \\ & & \sigma_n\\ 0 & & \end{pmatrix} \quad (4)$$

where $\sigma_1\geq\sigma_2\geq\ldots\geq\sigma_n\geq 0$

In [5], Marki proposes an interpretation of both matrices $\underline{\underline{U}}$ and $\underline{\underline{V}}$. According to the equations (2) and (3), the pressure at the measuring points can be written:

$$\underline{P}=\sum_{k=1}^{N}\underline{u}_k\sigma_k\left(\underline{v}_k{}^{H}\underline{\underline{Q}}\right)=\sum_{k=1}^{N}\underline{u}_k a_k \quad (5)$$

The acoustic pressure at the measuring points is equal to the weighted sum of the vectors $\underline{u_k}$: these vectors can therefore be seen as acoustic field modal vectors. $\underline{\underline{U}}$ is then a modal matrix.

From the equation (2), the inverse problem can be written:

$$\underline{Q} = \sum_{k=1}^{n} \underline{v}_k \frac{1}{\sigma_k}\left(\underline{u}_k^H \underline{P}\right) = \sum_{k=1}^{n} \underline{v}_k b_k \quad (6)$$

In the equation (6), the volume velocity vector $\underline{Q}$ appears as a weighted sum of vectors $\underline{v}_k$: they can be seen as surface mode vectors or source mode vectors.

To sum up, it is important to note that the number and the locations of the equivalent monopoles are chosen a priori. From the equation (2), the unknown volume velocity vectors $\underline{Q}$, which gathers the acoustic powers of all the equivalent monopoles, is assessed by the inversion of the transfer matrix $\underline{\underline{H}}$, multiplied by the pressure at measuring points vector. The inversion of the transfer matrix $\underline{\underline{H}}$ is carried out according to the decomposition presented in the equation (3).

In case of a low signal/noise ratio, the calculation of $\underline{Q}$ can be optimized by using regularization methods such as the Truncated singular Value Decomposition (TSVD), the Damped Singular Value Decomposition (DSVD) or the Tikhonov method (see [2, 3, 4]).

Once $\underline{Q}$ is determined, the equivalent pressure field can be compared to the measured one:

$$\varepsilon = \frac{\left\| \underline{P} - \underline{\underline{H}}\,\underline{Q} \right\|}{\left\| \underline{P} \right\|}$$

where ε is the global error.

2.2 Sensitivity analysis

The ESM sensitivity to some input parameters has been studied such as the location and the number of the equivalent sources, which are the 2 a priori chosen parameters.

In a first step, the relevancy of the resulting acoustic field calculated with the ESM has been tested with regards to the number of equivalent point monopole sources.

The ESM is computed with 135 equivalent monopole sources. The real source corresponds to only 1 of these monopoles that radiates. The transfer matrix $\underline{\underline{H}}$ is computed. Note that $\underline{\underline{H}}$ is independent of the source power vector; it only depends on the geometry of the problem (the positions of equivalent sources in regards with the positions of the microphones). $\underline{\underline{U}}$, $\underline{\underline{V}}$ and $\underline{\underline{S}}$ are computed and the 135 equivalent sources acoustic power vector $\underline{Q}$ is calculated. As the matrix $\underline{\underline{S}}$ has been built with ordered singular values of $\underline{\underline{H}}$, it seems sensible to use only the *k* first vectors $\underline{v}_k$ of the matrix $\underline{\underline{V}}$ to reset the acoustic field. The figure 1 illustrates the solution $\underline{Q}$ on the source reconstruction grid according to the locations of the equivalent monopoles, for several values of *k*.

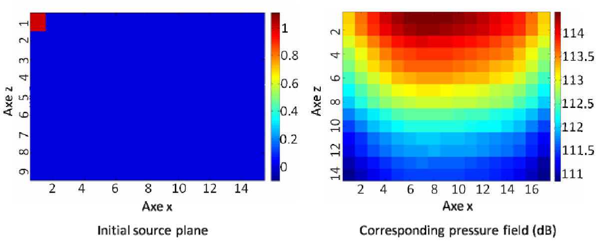
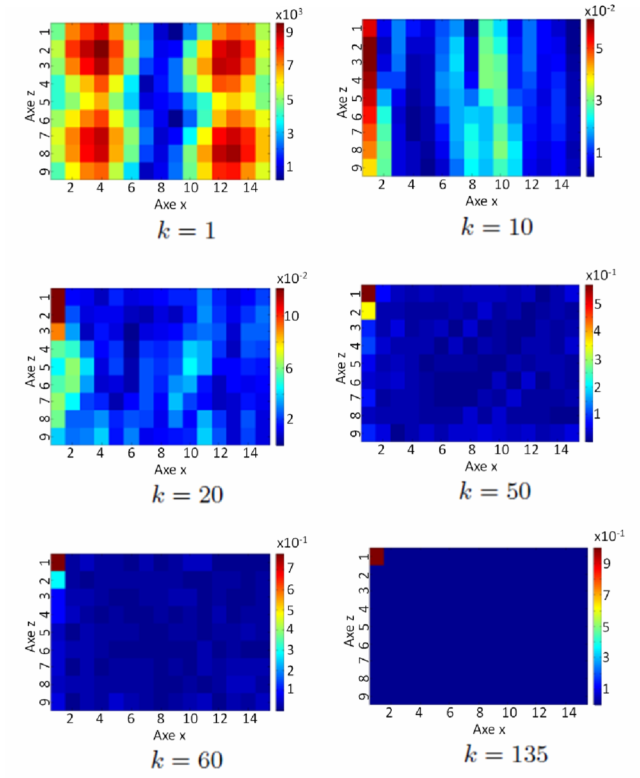


Figure 1: (a) Initial source plane and its corresponding pressure field



(b)

Figure 1 (b): source plane from ESM, with various numbers of equivalent sources taken into account

It is obvious that below 60 equivalent monopoles, the solution does not fit at all the real source setting. It means that most of the time, the ESM is very sensitive to the number of equivalent sources: the high order surface modes can significantly contributes to the global solution.

In a second step, the sensitivity of ESM has been tested with regards to the location of the equivalent noise sources. Most of the time, it is very difficult to determine the real source location as railway vehicle noise sources are very extensive. The ESM reliability has been tested with a controlled (simulated) point monopole source: the location of this source is considered as indistinct, and the equivalent monopole source rebuilt with ESM has been a priori located on various positions around the real point source.

If the equivalent source is settled at the exact location of the real source, there is no error.

If the equivalent source is settled at 0.01mm from the real source location, the error ε is around 0.03%. If the equivalent source is now settled at 0.1mm from the real source location, 3% of error is observed.

This second part of the sensitivity analysis points out that the ESM is very sensitive to the location of the real/equivalent sources.

3 ESM for railway noise sources

3.1 Real source characterization

The following study has been carried out on a set of laboratory measurements, presented on figure 2. These measurements have been performed on a scaled and simplified traction car, to quantify the installation effect on railway auxiliary systems' noise (roof mounting, encapsulation with skirts…).

The array microphones is composed of 288 measuring points, located at 5cm from the body of the mock-up. The set-up is placed on a reflecting ground.

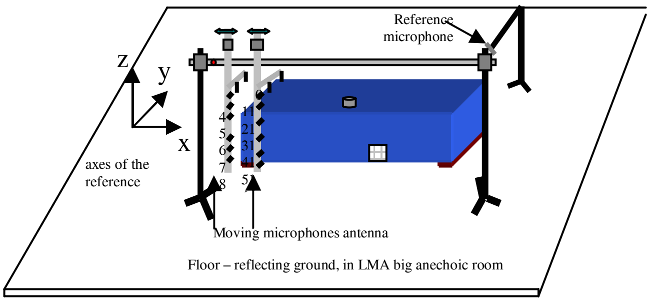


Figure 2: measurement set-up

The methodology, applied for each tonal component identified on the real source, was the following:

- The radiated pressure of an HP cooling source, mounted on the car-body of the mock-up, is measured on a microphone array
- The locations of the point monopole sources are chosen a priori, around the location of the real noise sources
- The transfer matrix is inversed
- The monopoles' acoustic powers vector $\underline{Q}$ is calculated
- The sound pressure due to this vector $\underline{Q}$ is re-propagated to compute the error ε between the real sound field and the equivalent sound field.

Moreover, the ESM has been adapted to take into account the ground effect, particularly important with the reflecting ground used in the measurement set-up. It has been demonstrated that, with a mastered simulated acoustic field, if this ground effect (with image source model) is not taken into account in the ESM, ε can reach 70% in case of a real source close to the ground.

In the following part of the paper, the results will be presented for the real acoustic noise field of the roof mounted source, first at 1862Hz (corresponding to 133Hz for a real scale train) and at 6328Hz (corresponding to 452Hz for a real scale train).

3.2 ESM with equivalent monopoles

The ESM has been applied for the acoustic measured fields illustrated in the figure 3.

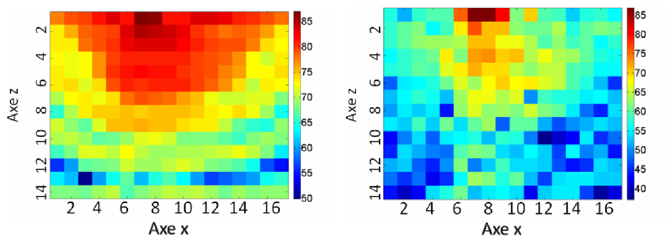


Figure 3: real pressure fields at 1862Hz (left) and 6328Hz (right)

For the real source radiating at 1862Hz, the ESM is applied with 1053 equivalent monopoles, corresponding to 1 equivalent source every 0.5cm, distributed on a 2D-grid ($\underline{x}$, $\underline{z}$) of 5cm on both sides of the real source (all the equivalent noise sources are located on a same plane, ($\underline{x}$, $\underline{z}$)).

With such a discretization the error ε on the rebuilt acoustic fields is null.

The number of sources is then reduced to 280 sources, corresponding to 1 equivalent monopole every 1cm, on the same 2D-grid. This new equivalent noise sources grid implies 1.5% of error on the rebuilt acoustic field. The equivalent source distribution and the rebuilt acoustic field are illustrated on figure 4.

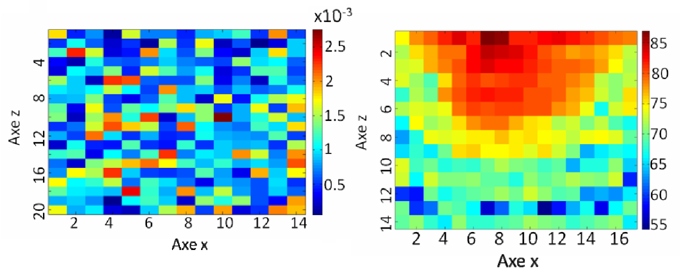


Figure 4: results obtained with 280 monopoles: sources distribution (left) and the reconstructed pressure field (right, in dB)

With equivalent monopoles distributed every 2cm, which means 70 equivalent sources, the error ε is equal to 155%. This representation is no more acceptable.

It has to be noticed that the radiation of the real source at 1862Hz corresponds to a very extensive source, with a large spread of sound energy on the microphone array. This case is one of the worst cases in term of equivalent noise sources representation, as it has already been noticed in [1].

The real source is therefore studied in a second step at 6328Hz: at this frequency the source is far more directive (see figure 3-b) and so fare less extensive and ESM should be efficient with a lower number of equivalent monopoles.

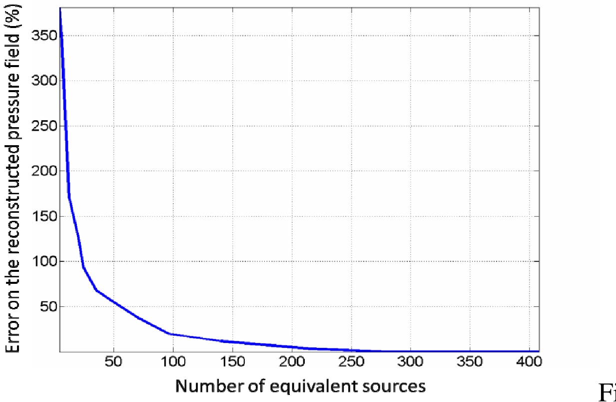


Figure 5: error on the reconstructed pressure field function of the number of equivalent monopoles

The figure 5 presents the variation of the error ε on the pressure field, with regards to the number of equivalent monopoles: with 280 equivalent sources the error is equal to 0.3% whereas with 70 equivalent monopoles, the error is equal to 38%. In case of extensive real source, the more the source is directive, the more efficient the ESM is, with low number of equivalent noise sources.

To sum-up, the ESM using monopole equivalent source model requires a large number of equivalent sources to represent reliably the pressure field of an extensive real source. But, the equivalent sources are characterized to be used in a numerical model for vehicle pass-by simulations of rolling stocks that consist most of the time of more than 20 real sources. The use of 70 equivalent monopoles to represent 1 real source is therefore not conceivable for such an application. Some variants of the ESM have been tested in order to reduce the number of required equivalent sources to reliably represent the real acoustic fields. First, monopole model is turned into dipole model. Then, the locations of the equivalent sources are optimized with genetic algorithm methodology.

4 Adaptation of the ESM

In this paragraph we present some improvements to adapt the ESM to the current problem, in order to fulfil the requirements of pass-by simulation software such as VAMPPASS. The objective is to reduce the number of equivalent sources while guaranteeing the accuracy of the solution.

4.1 Dipole equivalent noise sources

In order to facilitate the reconstruction of complex radiation patterns, the use of dipole equivalent sources is investigated.

First the dipole model is validated with simulated signals, and with no constraint on the number of equivalent sources. If some nodes of the source reconstruction grid coincide with the location of the real dipole sources, the pressure field can be reconstructed with no error by radiation of the obtained dipole equivalent sources. Then the error ε increases when the real source is shifted from the nodes of the source reconstruction grid, as with monopole equivalent source model.

The dipole ESM is now carried out with real measurement signals. The radiation at 6328Hz of the HP-cooling placed on the roof of the train scale model (please refer to paragraph 3.1) is considered. The source reconstruction grid is the same as defined in paragraph 3.2, and the mesh step is varying from 1cm to 10cm (4 to 280 nodes). Three different dipoles (oriented according to the x, y and z axe, respectively) are placed on each node. Therefore 12 to 840 equivalent dipoles are used. Figure 2 shows the error ε on the reconstructed pressure field, function of the number of equivalent dipoles.

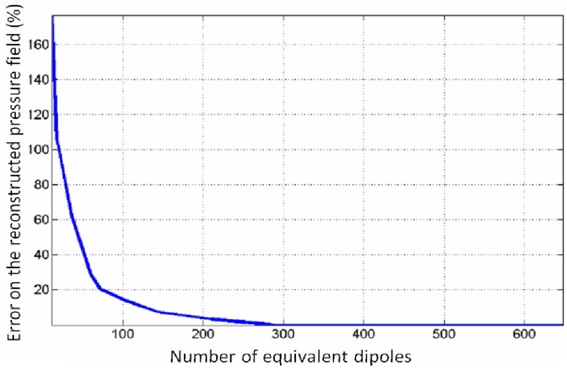


Figure 2: sensitivity of the ESM to the number of equivalent dipoles

This method presents a benefit in comparison to the monopole ESM. 72 equivalent dipoles give a 20% error rate while 70 equivalent monopoles give a 38% error rate. 288 equivalent dipoles give a solution with no error while 288 equivalent monopoles give a 38% error rate.

This development gives better results, but the method's efficiency depends greatly on the number and the location of the equivalent sources: it is similar to the phenomena observed with the monopole ESM. Next paragraph presents a further improvement of the method: the optimization of the equivalent source locations.

4.2 Optimisation of the sources locations

As shown in previous paragraphs, if the number of equivalent sources is reduced the accuracy of the solution obtained with ESM is highly dependent on the right location of the equivalent sources. Therefore a genetic algorithm has been associated with ESM in order to optimize the locations of the equivalent sources as well as their power. The interest of such algorithm comes from the fact that it can give a rounded solution to an optimization problem within a reasonable computational time, by proceeding in an iterative way. The principle is to evaluate the accuracy of a population of potential solutions, and to create a new generation by mixing and transforming the best individuals of the previous one [6,7].

Here an individual is a set of 10 equivalent source locations. The potential locations are selected over 99441 nodes distributed on the reconstructed source 2D-grid. A generation is composed of 10 individuals, whose accuracy is evaluated by the inverse of the error ε after the ESM process (ε being the relative error between the reconstructed pressure field and the measured pressure field), according to the *roulette wheel method*. The transformation step consists in crossing and mutating the best individuals of a generation *n* to form the generation *n+1*. At each generation, 25 cross-over and 300 mutations are computed, according to random processes. The accuracy of the solutions increases at each iteration: the transformations are designed with a high rate of hazard in order to limit the focusing on a given individual. Therefore a unique solution cannot be reached with high certainty using such a method. The process stops after 4500 generations.

For the real roof-mounted source, at 6328Hz, the best solution obtained gives a 26% error rate with 10 equivalent monopoles, whereas the classic ESM carried out with 10 equivalent monopoles without any optimization of the locations ends up with a 150% error rate.

These results are very encouraging, and further improvements of ESM combined with genetic algorithm could allow completely fulfilling the requirements of VAMPPASS inputs.

5 Conclusion

This paper has presented the application of the Equivalent Method Source within the field of railway noise. This source characterization will allow train acoustic models to be compiled in pass-by simulation software.

However, the noise sources on railway vehicles are most of the time very extensive: it is therefore very challenging to represent them with a set of few point sources. Indeed, this study has shown that the basic ESM based on monopole source model is often not efficient: the acoustic field radiates by one real source (equipment source such as cooling or exhaust) is reliably reconstructed only if a large number of equivalent sources are used: more than 70 monopoles are required. As a rolling stock is nowadays composed of more than 20 noise sources, this representation is not acceptable.

ESM has therefore been adapted to this context: a dipole source model has been tested. It has shown that this model can improve the efficiency of the method but the number of required point sources remains very high.

The second adaptation of the ESM has been conducted to improve the determination of the locations of the equivalent sources. A genetic algorithm has been used to optimize the location of a reduced number of equivalent sources. With such a methodology, a reasonable error on the reconstructed pressure field is obtained with only 10 equivalent monopoles. This last adaptation of the ESM is very encouraging: the noise sources on a rolling stock could be efficiently characterized:

- With a low number of equivalent noise sources
- With a reliable reconstructed pressure field

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