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Synthesis of Noise of Operating Vehicles: Development within SILENCE of a Tool with Listening Features

E. Bongini¹, S. Molla², P.E. Gautier¹, D. Habault², P.O. Mattéi², and F. Poisson¹

¹ I&R SNCF, 45 rue de Londres, 75379 Paris, France

² LMA, 31 chemin Joseph Aiguier, 13402 Marseille, France

Tel.: +33 1 53 42 71 95; Fax: + 33 1 53 42 97 84

estelle.bongini@sncf.fr

Summary

The European Integrated project SILENCE is dedicated to the reduction of railway and road noise in urban areas. Within this context, SNCF and LMA collaborate in the sub-project B in order to develop a pass-by sound simulation software. This global modelling tool will support parametric studies on the reduction of the noise of a train or a car pass-by, by providing standard indicators (time signature, sound pressure level) and sound samples. It will be used to determine the best combination of optimised sources, developed by manufacturers, in order to reduce the global pass-by noise. In the software, each simulation is based upon the definition of the acoustic sources and the pass-by scenario. Each physical acoustic source on the vehicle is represented by one or several point sources. These point sources radiate either pure tones or broadband noise. A dedicated algorithm is used to simulate each type in an efficient way to reduce the computation time. The characteristics of the sources are obtained either from numerical models, or from standstill and pass-by antenna measurements (carried out in the SILENCE project). As a large source such as a cooling system can not be modelled by several point sources located at close positions, a radiation pattern is allocated to the point source. Dedicated studies are in progress to measure the radiation pattern of classical sources on a train (two series of measurements on a 1:14 scale-model and on a train).

1 Introduction

SILENCE is an integrated research project funded by the Sixth Framework Programme of the European Commission. SILENCE will provide relevant technologies for efficient control of surface transport noise, innovative strategies for action plan for urban transport noise abatement and practical tools for their implementation, and will bring about a significant reduction of people's exposure to noise, especially in urban conditions.

Within this framework, subproject B is dedicated to the development of a tool for modelling exterior noise of both road and rail vehicles (train, tram, car, etc). The tool will combine a precise estimation of the sound level and sound synthesis. It will be used to assess the impact of the modification of a single source on the pass-by noise, both level and auralisation.

This global modelling tool is called VAMPPASS, an acronym for Vehicle Acoustic Modelling for Pass-by Prediction and Audio Synthesis Software. This software will supply standard indicators, such as time domain signature, sound pressure level and third octave band analysis. It will be used to determine the best combination of optimised sources, i.e. to obtain an effective reduction of the overall pass-by noise according to the standards. Moreover, it will help generating listening test samples for psychoacoustic studies.

This paper first deals with the global modelling scope: the output required and the constraints. Then, the synthesis method is described. Finally, the acoustic source characterisation within this scope is presented.

2 Global Modelling Scope

The global modelling tool has to handle various requirements:

- It has to manage several operational conditions (mean traffic flow conditions, pass-by acceleration, braking, on different types of infrastructure, and so on) and the impact of pass-by evolution on the acoustic source characteristics,
- It has to allow simulation of a pass-by in the time domain to produce listening samples in addition to pass-by indicators such as $L_{Aeq,tp}$, time signature,
- The project being dedicated to global noise reduction with optimisation of each source, the tool has to keep an acoustic representation in which each physical source is represented, identifiable and easily modifiable
- Finally, the tool is dedicated to parametric studies which implies low computation time.

The vehicle is acoustically represented as a set of equivalent point sources. Furthermore, the synthesis method has to manage pass-by scenarios with several traffic conditions, thus a time-frequency representation is chosen for the source and vehicle global definition.

3 Synthesis Method – Acoustic Source Model

The synthesis method has to manage both the vehicle building as a set of acoustic sources and the time evolution defined through a pass-by scenario. Fig. 1 shows the tool architecture.

Since each vehicle is described by a superposition of N equivalent sources $\{S_n\}_{n=1..N}$, the pressure p at point M and time t , for such a vehicle is:

$$p(M, t) = \sum_{n=1}^N p_{S_n}(M, t) \quad (1)$$

$p_{S_n}(M, t)$ is the pressure radiated from the source S_n , received at the time t at point M . Considering the sources within the scope of the present application, a sinusoid plus broad-band noise approach is chosen for the simulation. So, a source with a given

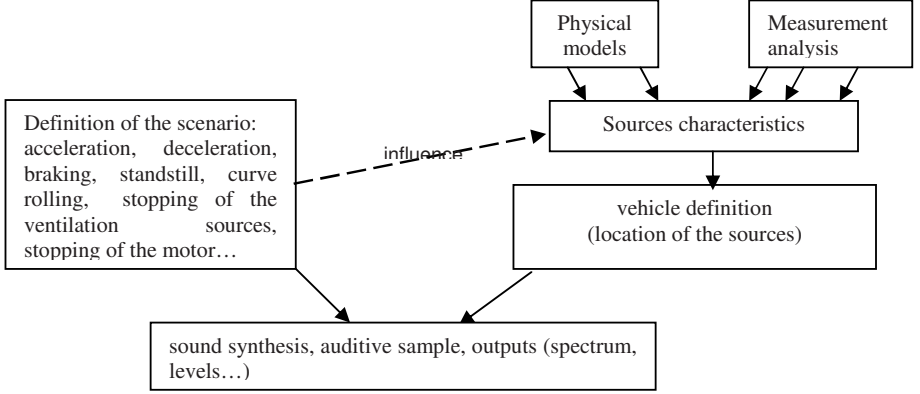


Fig. 1. Tool architecture

spectrum is split into two contributions: a monofrequency contribution and a broadband one. An additive synthesis approach is used for the monofrequency components. The level, phase and directivity of the sources are the only parameters introduced in the software. For a stationary omnidirectional harmonic source S , with a circular frequency ω , a wavenumber k , emitting at a unit amplitude at the distance $d(S, M)$ from M , the pressure is written:

$$p_S(M, t) = A(t) \Re \left(e^{ikd(S, M) - i(\omega t + \phi)} \right) \quad (2)$$

where Φ is the phase at the origin.

Furthermore, the broadband noise contribution at the receiver point M of each source is described in a time-frequency representation that takes into account its evolution during pass-by. The time-frequency representations of each source are summed to represent the overall signal. The time signal of the overall broadband noise is obtained with an inverse short time Fourier transform:

$$P(M, t_n) = ISTFT(\hat{P})(t_n) = \sum_{m=-\infty}^{+\infty} g(t_n - mR) \frac{1}{N} \sum_{k=0}^{N-1} \hat{P}_m(k) e^{j2\pi km/N} \quad (3)$$

where g is a convenient window, $\hat{P}_m(k)$ is the short-time spectrum of the signal at receiver point M , in window m and frequency f_k and R controls the overlap. This method allows short computation times.

The Doppler effect and other effects of the vehicle motion can be taken into account directly in the time-frequency representation describing the broadband noise and also implemented in the pure tone components. Moreover, this synthesis method allows to take into account propagation conditions by introducing ground effect with a model specified in [1]. The ground reflection is taken into account by introducing image sources. In this case, the same time-frequency patterns are obtained for the source itself and its image, with a temporal shift induced by the reflection.

4 Source Characterisation

The vehicle is represented as a set of equivalent acoustic point sources. Each physical acoustic source is usually represented by one equivalent source, to ensure an easy identification between equivalent and real sources. To represent one equivalent point source with one real source simplifies vehicle definition, but it implies additional data in the source definition. Particularly, equivalent sources present directivity patterns that must integrate the complexity of the radiation patterns and the extension of the real source.

The sources are thus described by their location, their spectral characteristics and their directivity patterns. In the Silence project, most of sources to be identified are traction noise sources. In urban conditions, aeroacoustic sources are not significant and rolling noise is provided using the TWINS software [2] or antenna measurements presented below. Different measurements methods, supplemented with analytical models, can be used to provide traction source characteristics.

Two-dimensional (2D) antenna measurements have been carried out to locate acoustic sources in real operating pass-by. They have required 64 microphones randomly distributed on a plane antenna (see Fig. 2) and these measurements are post-processed with beam forming algorithms after having removed the Doppler effect. These measurements provide relative levels between identified sources (see Fig. 3).



Fig. 2. 2D antenna measurements

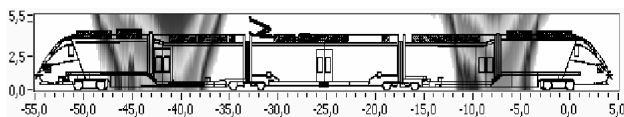


Fig. 3. Example of cartography from plane antenna measurements

A one-dimensional (1D) antenna method has been also developed: it consists on a vertical microphone array (see Fig. 4). The train pass-by very slowly in front of this antenna. Real sources are managed during pass-by to isolate them from each other. Train position relative to the antenna is determined with a system of reflecting strips regularly attached on the train and a photosensitive cell on the vertical array.

The locations of the equivalent sources are determined with the maps that give for each $1/3^{\text{rd}}$ octave band, the overall level versus the lateral position of the train and the microphones heights (see Fig. 5). The position of the maximum of the sound power level, at one frequency band, provides the position of the equivalent source.

These measurements allow to locate precisely maximum level of each real source, for several frequency ranges. These measurements are also used to characterise the level and the spectrum of each source.

According to the frequency, real sources that are too close cannot be separated with the antenna. The separation of the contributions requires further information. Analytical models can provide spectral characteristics of each source that can help for level



Fig. 4. 1D antenna measurements

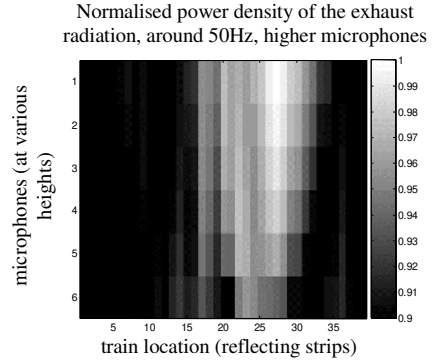


Fig. 5. Cartography post-processed from 1D antenna

allocation. For example, the blade passing frequency and its harmonics of a fan indicate which pure-tone components can be allocated to the fan source.

For a total identification of close sources, vertical antenna measurements can be used with a microphone very close to each source. Thus, the coherence between the microphone close to the source and antenna measurements indicate if the source contributes to the field recorded by the antenna. This method is valid as long as the coherence between near field and far field is not lost because of the Doppler effect or any propagation effect between source and antenna.

After the separation of contributions of each source from the other, the contribution of each source is separated between broadband noise and pure tone components. Determination of the pure-tone components is realised using the Loudness spectrum. The loudness density takes into account the masking phenomena: when several pure tone signals are present together, some of them are masked by the others and so not heard as a harmonic component (depending on the frequencies and the levels of the signals). For vertical array measurements, noise source signals are considered as stationary signals and loudness can be implemented with Moore's model [6]. The loudness density highlights the frequency ranges of high energy density that will be heard. To determine the frequency and the level of the pure tone components, the Power Spectral Density is used.

For example, on the left of Fig. 6, at least six pure tones can be identified on the power spectral density (100Hz and its harmonics), whereas on the right, the loudness density indicates that only three of them will be heard (100 Hz, 200 Hz and 400 Hz). These three components are modelled by pure tones.

The remaining part of the energy of the signal is represented by a broadband noise source. The third-octave band power spectrum of this source is computed from the total power spectrum from which the contribution of the pure tone components is subtracted.

Finally, the 1D antenna measurements are also used to determine the directivity pattern allocated to each equivalent sources. Evolution of the level during source pass-by provides a horizontal pattern whereas the radiated field measured by the

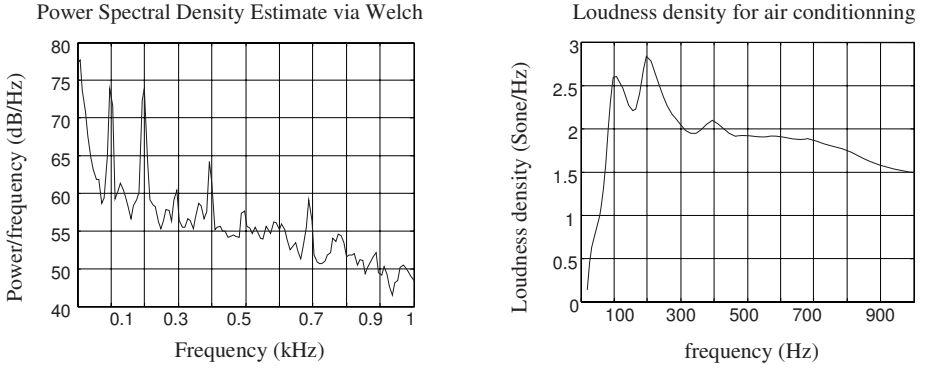


Fig. 6. Power spectral density and Loudness spectrum of an air-conditioning system

several microphones vertically distributed provides a vertical directivity. These data can be used to identify the measured directivity with a simple model as a monopole or dipole. This identification process is supplemented with analytical models that provide radiation patterns expected for specific sources (fans, pipes) in free-field. For example, in the low frequency range, a fan can be considered as a dipole [3, 4]. A baffled pipe at low frequency ($kr < 3$, where r is the radius of the pipe and k the wave number) can be considered as a monopole [5].

However, the 1D antenna measurements provide very complex radiation patterns, thus identification with simple sources is mostly not satisfactory. It appears that the diffraction due to the source environment (close environment such as the cavity of the diesel powerpack or the ring around a fan, or the more distant environment such as the train body) has a significant impact on the radiated field. To study this impact, either numerical simulations or dedicated measurements can be carried out.

In the case of railway traction noise sources, numerical simulations proved to be unsuitable: on the one hand, the phenomena occurred in the low frequency range that implies that the whole train body has to be modelled (large wavelengths); on the other hand, relatively small boundary elements are required for the reliability of the calculations; these two conditions lead to non-feasible computations in realistic times.

Dedicated measurements have been performed on a 1:14 scale driving-car model, with a diesel powerpack compartment and a ringed fan on the roof. This model is studied to characterize the diffraction effects produced by the car body. The sources (fan or motor) are replaced by loudspeakers with controlled radiation behaviour. The pressure field is measured with two vertical microphones arrays, and four microphones suspended over the roof.

First post-processing consists of maps of the transfer functions between input voltage of loudspeakers and pressure at microphones. These maps show that the radiated field becomes more complex as frequency increases, with the occurrence of shadow/image sources.

In addition to these first results, more measurements have to be carried out to separate the diffraction phenomena. For example, for a laterally embedded source, the effect of the back cavity and the effect of the train body have to be separated.

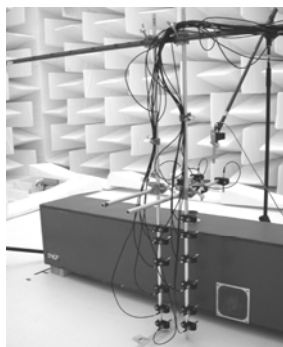


Fig. 7. Experimental 1:14 scale train model

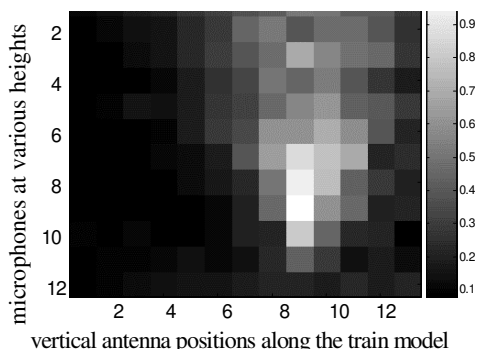


Fig. 8. Transfer functions between laterally embedded loudspeaker and microphones, along the train for motor compartment radiation at 3696 Hz, corresponding to 264 Hz at full scale

5 Conclusions

The global modelling software described is operational. It provides the acoustic indicators to characterize the pass-by and the sound samples to conduct listening tests in the laboratory. A user-friendly interface is in progress. Source characterisation has been performed for a regional train as an example. Various measurement methods are proposed according to the requirements of the software to define the sources. The combination of measurement methods, analytical models and previous analysis on specific phenomena such as diffraction, allows to the positions, spectrum and directivities of all the sources to be characterised and then the train or car model to be assembled.

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