Rail vehicle source models within a virtual certification process

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Summary

In the present paper vehicle noise source modelling work carried out within the Acoutrain project is presented. When the noise source system is surrounded by many reflectors, for example a radiating transformer behind roof shrouds, a single monopole with averaged transfer function is suggested to represent the source. For a source with strong directivity placed in an essentially free space, a "box-source" method is recommended to take into account of the source directivity. The total sound power is in this case divided into five independent noise sources which are obtained via standard sound power measurement methods and certain data processing. Experimental verifications are made for several cases in laboratory and in the field. Good correlation between tests and modelling results are obtained for both approaches.

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1. Introduction

The Acoutrain FP7 European research project aims at developing procedures and calculation tools to simplify the present TSI noise test procedures [1]. The overall objective is to reduce time and costs by developing methods for virtual testing of rail vehicles [2,3].

1.1. Acoustic sources on rail vehicles

Acoustic sources on a rail vehicle can be categorized in two groups: (i) noise sources associated with rail-wheel interaction, namely radiation from wheel, rail and sleepers [4] and (ii) those of vehicle components. The latter group can be divided into sub groups with (a) components for which fans, and other cooling devices, are the main source and (b) components with a vibrating shell being the main source, e.g. due to electromagnetic forces (transformers, motors) or mechanical contact (gear boxes). At very high speeds components with significant aerodynamic sources (c) become increasingly important, e.g. bogies and pantographs.

One main task is to develop assessment methodology applicable to the relevant source types, e.g. cooling fans and electromagnetic sources. Please note that rolling noise sources are not dealt with in the present paper. Several challenges are at hand. Effects of source installation onto the train can be rather complex, modifying source power as well as directivity due to, e.g., screening and by changing the inflow conditions of cooling fans.

Also, the variety of vehicle source types requires that different assessment methods are considered and integrated in the process. Moreover, standards available for source power and directivity testing, e.g. ISO 3744, generally require echo free conditions and can therefore be difficult to apply for real vehicle sources. Due to their size and weight and the need for special electric supply systems and mechanical load arrangements, such sources are today tested in reverberant lab halls for which directivity measurements will be biased.

1.2. Source descriptors

Source descriptors can be on the form of either: (i) source powers combined with directivity data or (ii) as a number of equivalent monopoles/dipoles representing the real source. To account for installation effects for real sources, calculated or measured transfer functions can be applied. Ideally, source assessment procedures shall allow for quantification of variability in the source model in view of the assessment method applied.

The most relevant present standards for experimental source characterization are therefore the "sound pressure methods" ISO 3744 and ISO 3745 on one hand and the intensity methods ISO 9614-1 and ISO 9614-2 on the other hand. The in-situ comparison method of ISO 3747 may be useful in specific cases but is not recommended if other methods are applicable (e.g. this standard is only defined for octave band measurements). The choice of method for a given test situation is supported by ISO 3740. The grade of precision for all measurements should be at least "engineering precision".

In Figure 1, a candidate flowchart for source characterization within a certification procedure is presented. Note that both pressure and intensity measurement procedures are suggested to be permitted.

2. Source directivity

Generally, vehicle sources are directive to various degree. Source components, for which the main

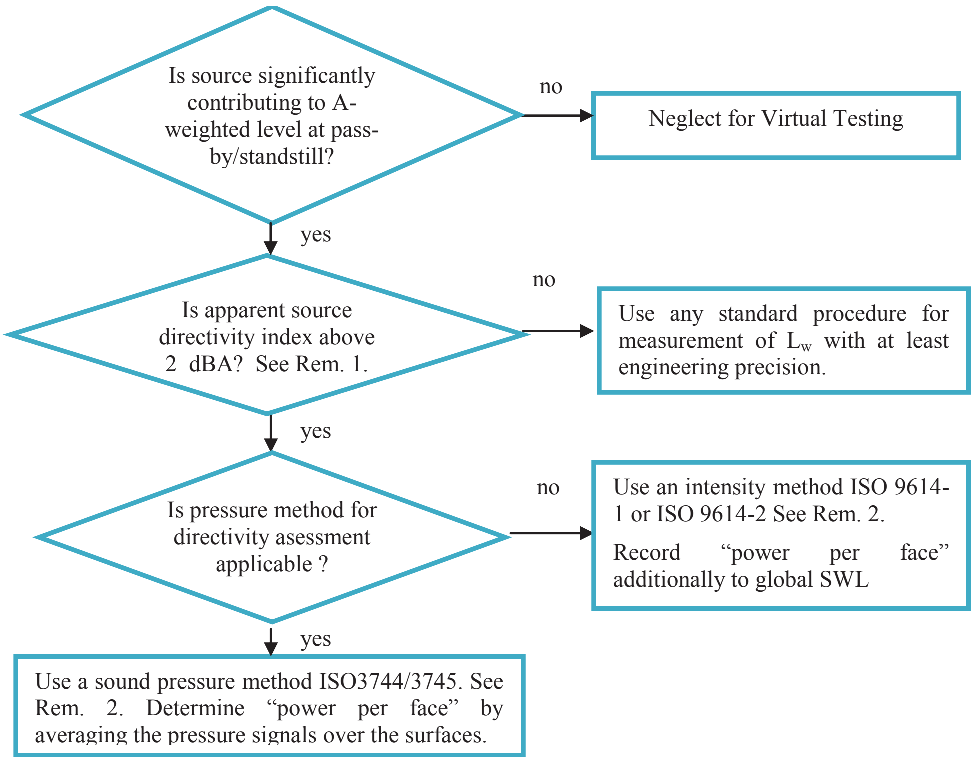

Figure 1. A candidate flow chart for source characterization within a certification process.

Remarks:

1. Equipment with a fan mounted on one or several faces of a component can a priori be regarded as directional. Transformers and motors are typically less directional (if the cooling system is considered separately). Even though a "local directivity" may be present, the sound power radiated by two faces of the same size will typically be similar.

2. Methods based on sound pressure measurements, e.g. ISO 3744 and ISO 3745, will often require acoustic treatments of the test environment, e.g. installation of absorptive screens, to comply with the standard ($K_{2A} \leq 4$ dB). Also, results from intensity based methods ISO 9614-1 and ISO 9614-2 are dependent on the acoustic environment when the "power per face" is sought. All these methods can provide information on directivity, but the use and accuracy of this information is not dealt with in the standards. Sound pressure measurements according to e.g. ISO 3744 can also be used to derive equivalent monopole sources, see Section 3.1 below and reference [8].

noise generating device is a fan integrated into the component structure, may be strongly directive due to the screening of sound from the fan by the unit itself. Sources, for which the noise generation is mainly due to shell vibrations, such as transformers, motors and mechanical gears are typically less directive.

In Figure 2 a test setup for measurement of directivity for a HVAC unit on a hemisphere according to ISO 3744 is displayed. Also directivity results are shown for selected 1/3 octave bands in one vertical plane. Measurement and presentation of source directivity is described IEC 60268, Chapter 23. This standard is developed for loudspeakers but can also be applied for other sources. Plotting of directivity in polar diagrams is detailed in the standards IEC 60268/60263. In IEC 60268 the resolution is required to be 15 degrees or better. Alternatively, in ISO 3745 sound power assessments from measurements of sound emission in a free field are described. From this measurement set-up directivity information can be calculated, but on a coarser grid. However, ISO3744/45 do not address directivity as such; it is rather used to qualify the accuracy of the sound power from the so-called apparent directivity index. Alternatively, intensity based methods can give directivity information, see Figure 1.

The tests illustrated in Figure 2 were made out-doors but acoustic tests for typical rail vehicle components are normally made in partly reverberant environments, reducing the accuracy of the directivity data obtained.

3. Modelling

3.1. Equivalent monopole representation

Depending on the mounting conditions, the same source may produce different noise levels at the wayside. For its characterization, the source can be modelled by a few distributed, equivalent monopoles, which in total produce the same sound power as the source itself [5]. Acoustical installation effects such as the properties of, e.g., a fan housing, as well as any passive mounting effects due to vehicle integration, are described by measured transfer functions. Or more specifically, Greens functions relating the monopole volume flow to the pressure at a receiving point. This relation will here be called *passive installation effects* and are defined as independent from the *active installation effects*, which represent interaction with flow, e.g. for a cooling fan, that may change the acoustic power or source strength. In the literature these active effects are often referred to as aerodynamic installation effects. Strategies for representing sources using monopoles developed in the previous EU project NABUCCO [6] and from other works [5,7], have been adapted in the present work and further developed for rail vehicle applications.

For this approach, the source is described using one or five monopoles placed around the source. The single monopole is applicable for cases when directivity can be neglected. For cases with significant directivity five monopoles should be used, placed at the center of each rectangular surface of an ISO box, an imaginary box enclosing the source when positioned on a rigid surface. The monopole strengths are computed from ISO pressure measurements of the source sound power using simple formulas or from the individual face results of an intensity scanning measurement according to ISO 9614-1/2. The passive installation effect is thereafter obtained from measured or computed spatially averaged transfer

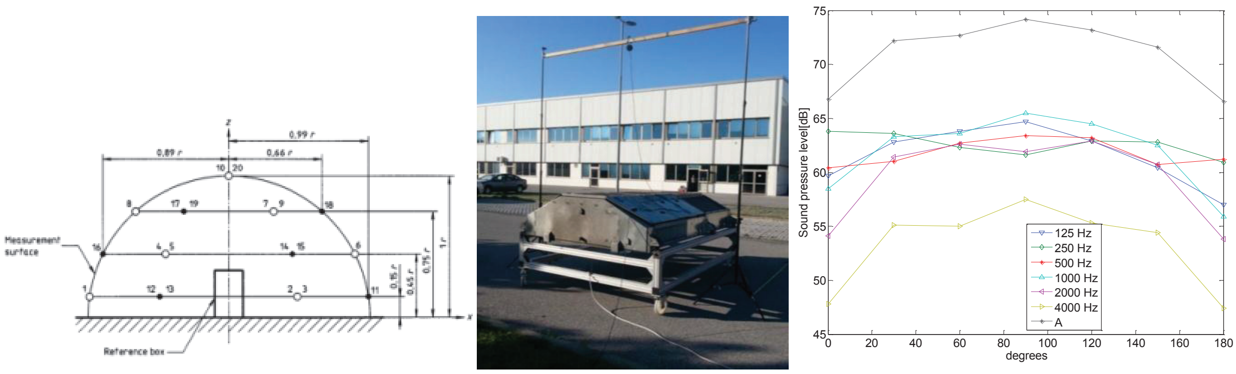

Figure 2. Measurement of sound pressures on a hemisphere according to ISO 3744 for an air-conditioning unit.

functions from five locations around the source to a suitable reference position outside of the source region.

A supplier typically provides only the sound power of a fan integrated in a unit under a certain working condition (load). To use the equivalent monopole method, one needs also a correct power distribution on the five surfaces of the ISO sound power test box. If a single monopole is used, the overall sound power data is enough, but for the full method the power must be distributed on the five surfaces of the ISO test box. Note that these five surfaces do not have to coincide with those used later in the installation for defining the monopole positions and measuring the transfer functions. But these surfaces should be geometrically similar to the ones of the ISO test box.

Since the prediction is based on transfer functions (passive system effects), the active installation effect, e.g. the interference between flow and for instance a heat exchanger, cannot be described by the method. This part of the effect has to be included in the "source definition" which sometimes can be important for the accuracy of the prediction.

3.2. Multipole expansion

For a distributed, coherent sound source, one may divide the whole surface of the source into many sub-surfaces and treat the source as a combination of several elementary radiators. The sound pressure levels at the observation points can then be expressed by using equivalent monopoles as

$$\mathbf{p} = \mathbf{H} \cdot \mathbf{q}, \tag{1}$$

where $\mathbf{q}$ is the source strength vector associated with the elementary radiators, $\mathbf{H}$ is the transfer function matrix and $\mathbf{p}$ is the sound pressure vector. The influence of the shape of the source as well as the environment is included in the transfer functions. If the source strength vector and the transfer function matrix are known, one can calculate the corresponding sound pressure levels at any observation point. Theoretically, the more monopoles are used, the more accurate the prediction will be for a coherent sound source.

Equation (1) can be expressed in the form of a power spectrum, for the observation point j, as

$$p_j^2 = \left| \sum_{i=1}^{N} H_{ji} q_i \right|^2 = \sum_{i,k} H_{jk} * H_{ji} \cdot q_k * q_i \quad j = 1,2 \ldots \tag{2}$$

A practical noise source is often only partially-coherent at the most. In many applications, the sound sources are surrounded by many reflectors or located in a "box-like" structure. The sound field near the source is somewhat "reverberant" in a certain sense. This also makes the distributed sub-sources much less coherent. For these types of sources, all products of cross-terms in Equation (2) vanish after the space and frequency band average due to the low level of coherence.

3.2.1. Single monopole approach

Assume the strengths of the equivalent sub-sources at all points are the same, $q_i \equiv q/N$, with N being the number of sources, the formula may be approximated as

$$p_j^2 = \left| \sum_{i=1}^{N} H_{ji} q_i \right|^2 \approx \overline{\left| H_j \right|^2} \cdot \overline{q}^2 \qquad j = 1,2 \ldots, \tag{3}$$

Here $\overline{\left| H_j \right|^2}$ is the "average" transfer function:

$$\overline{\left| H_j \right|^2} = \frac{1}{N} \left| \sum_{i=1}^{N} H_{ji} \right|^2 \xrightarrow{\text{octave band average}} \frac{1}{N} \sum_{i=1}^{N} \left| H_{ji} \right|^2, \tag{4}$$

and we assume the sound pressure is expressed in 1/3 octave band or wider.
The last approximation is based on the fact that the summation of all products of cross-terms of different transfer functions approaches zero after band average. $\overline{q}^2$ is the strength of the equivalent monopole source (square of the volume velocity) and can be obtained from the measured sound power, W, as

$$|q|^2 = \frac{4\pi c}{\rho \omega^2} W \tag{5}$$

This approach is denoted one-monopole method with space-average transfer function. Physically, this is an incoherent model with the total source strength equally distributed to all source positions concerned. To take possible influence of the surrounded environment into account, five monopole positions located at the center of the five surfaces enclosing the sound source (excluding the ground), are suggested.

3.2.2. Box source method (five monopoles)

For cases when the source is directive we can generalize the single monopole model and use five monopoles i.e. one on each side of an imaginary box enclosing the source. Formally this is straightforward and means that Equation (2) can be rewritten as,

$$\tilde{p}_i^2 = \sum_{j=1}^{5} \left| H_{ij} \right|^2 \cdot \tilde{q}_j^2 \,. \tag{6}$$

The transfer functions H_j are used as measured.

4. Application examples

4.1. A converter cooling system

The simplified equivalent monopole method described in Section 3.2, is tested for data obtained from a passenger vehicle converter cooling system mock-up displayed in Figure 3.

4.1.1. Measurements of transfer functions

Five transfer functions between points at the center positions of the sides of an imaginary box around the source with the plywood mock-up/box in place, see Figure 3, are measured using calibrated loudspeaker monopole sources [8]. Two face-to-face mounted 100 mm loudspeakers are used for the range 0.1-1 kHz and a 15 mm tube connected to a baffled loudspeaker system for the frequency 1-5 kHz. The direct method is used for all measurements meaning that the source is moved between the positions of the equivalent monopoles. A reciprocity approach is also possible.

Figure 3. Converter mock-up with cooling fan and heat exchanger in plywood box with dummy electronics.

4.1.2. Results

Comparisons of prediction and measurements of sound levels at a reference point at $\bar{x}$= (-2.5,-1.9, 1.5) [m], are illustrated in Figure 4 in narrow bands and in 1/3 octave bands. For this case with a small source directivity [8], it was possible to reduce the model to only one monopole, as in Equation (3). The agreement in 1/3 octave band is quite acceptable above 0.2 kHz and the overall level is correct within 1 dBA.

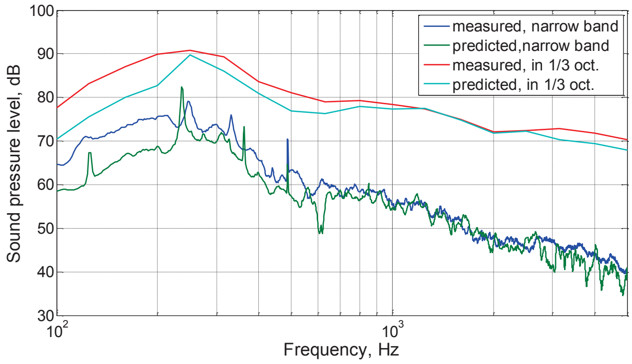

Figure 4. Measured and predicted sound levels at the reference point from Equation (3) with average transfer functions according to Equation (4).

4.2. A strongly directional HVAC source.

In the following, the results of an analysis of the directional HVAC source, as displayed in Figure 2 are presented; see also reference [8]. Five monopoles, at the centres of the sides of an imaginary "box" around the condenser fan at (0.3,0,0), (0,0.3,0), (-0.3,0,0), (0,-0.3,0) and (0,0,0.2) [m] respectively (with the fan centre at the origin), are used to represent the source. As indicated in Equation (6), only absolute values of the transfer functions are used, while the monopoles can be operating either in phase or in anti-phase.

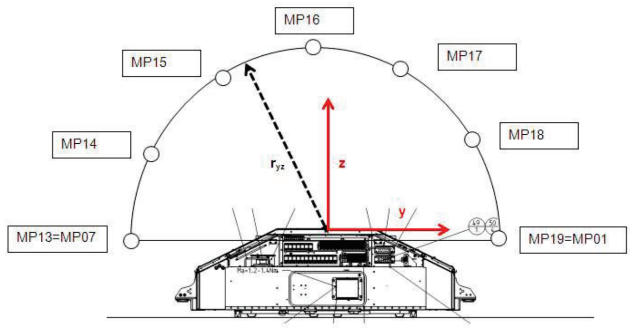

Figure 5. Coordinate system for directivity analysis. The x-axis is pointing out of the paper.

Comparison of measurements and the synthesized data in the two vertical planes are shown in Figure 6 for A-weighted results and for two one-third octave bands. The calculated transfer functions used do no account for any screening by the unit itself, e.g. for points in the x-y plane. However, acceptable results are still obtained by adjusting the strengths of the monopoles and the relative phase relation (+/-180°). The maximum A-weighted error is less than 2 dB(A). Still better results can be expected if measured transfer functions are used. More examples of modelling strongly directive sources are presented in reference [8].

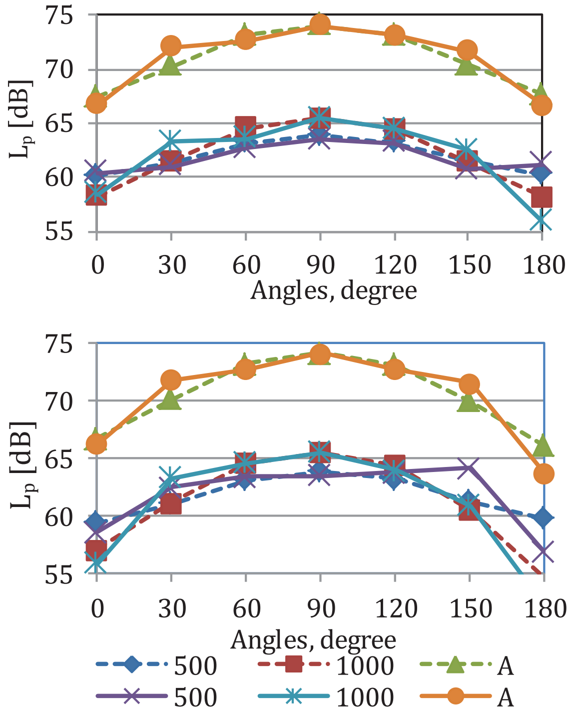

Figure 6. Sound pressure levels in the x-z plane (upper) and y-z plane (lower). Solid: measured; Dashed: predicted.

5. Concluding remarks

To systematically apply virtual testing to replace measurements within a certification process requires accurate source models. The source representation chosen shall allow for determining the acoustic effect of the source installation on the vehicle, such as that of screens. In addition, methods should preferably provide results together with error bounds. A simplified equivalent monopole approach has been proposed in which a directional sound source is modelled by five independent monopoles mounted on a rigid box, each located at the center of a surface. The sound field is then the summation of the contributions from the five independent monopoles. The source strengths can be obtained either by intensity method or be calculated from the total sound power plus the directivity pattern. In most cases only the paths with direct sound need to be accounted. For non-directional sources a single monopole is enough, when used together with averaged transfer functions as in Equation (4).

The method has been validated by tests on simple sources as well on a converter cooling fan mock-up and an HVAC system. The results are promising and the approach is attractive from a practical point of view, since it can handle directivity but still only requires input in the form of sound power from an ISO box measurement. To handle the acoustic installation effects transfer functions for a maximum of five points around the source are needed. It is suggested that guidelines for application of the proposed method are developed and included in relevant ISO standards.

Acknowledgement

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6. References:

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