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Engineering methods to predict noise levels at reference points with known source properties

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ABSTRACT

Two engineering methods are proposed to predict the sound pressure levels at a given point when the sound power level of a noise source is known and the transfer function between the source and the reference point can be obtained. The first method is applicable when the source is surrounded by many reflectors, or inside a box-like structure. A single monopole with average transfer function is suggested for this situation. For a source with a strong directivity placed in an essentially free space, the "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 ordinary sound power measurement methods. Experimental verifications are made for several cases in laboratory. Satisfactory results are obtained for both methods.

1. Introduction

In industry people often need a relatively simple method to predict the sound pressure level at a certain location if the source properties are known. An example of that is the early European research project *PIANO* [1], which deals with the pass-by noise of road vehicles. Project *Acoutrain* [2], on the other hand, aims at developing procedures and calculation tools to simplify the present TSI (Technical Specification for Interoperability) noise test procedures. The overall objective of the project is to reduce the time and costs by developing methods for virtual testing of rail vehicles. A very important step for that is to be able to predict the rail side noise at the specific reference points when a new element with known acoustic properties is used to replace an old one.

The multi-monopole expansion method is often used to calculate the sound radiations by vibrating bodies [1,3–5], when the sources are treated either as uncorrelated [1] or correlated [3–5]. The approach can yield quite good results if a suitable number is selected for the monopole sources. Tedious and careful measurements are sometimes involved in this approach in order to get complete source information of a machine when coherent source model is used. An alternative is to use single-monopole source approach, since the source strength can then be obtained directly from the sound power measurements. However, this approach usually oversimplifies the real problems. The prediction error is hence dependent on the location of the observer: The approach may yield fairly good predictions for the sound pressure levels at certain locations and very bad predictions for some others.

Broadband noise sources are commonly seen in industry. The sound pressure levels are usually expressed in a third octave band, or even A-weighted sound pressure level only, for those applications. Simplified models may be introduced for those cases, since environment influence on the sound pressure levels will be "smeared out" with a certain frequency band average and makes the signals less fluctuate in the reference points. This paper tries to use this feature and to make a compromised method between the multi-monopole and single-monopole method for industry applications.

2. Equivalent monopole with space-average transfer function

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

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

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In the formula **q** is the source strength vector associated to the elementary radiators, **H** is the transfer function matrix and **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 points. Theoretically, the more monopoles are used, the more accurate the prediction will be for a coherent sound source.

Eq. (1) can be expressed in the form of power spectrum, for the observation pint j, as

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

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, or within the box-like structure, is somewhat "reverberant" in a certain sense. This fact also makes the distributed sub-sources much less coherent. For these types of noise sources, all products of cross-terms in Eq. (2) vanish after the space and frequency band average due to the low level of coherence. Assume the strengths of the equivalent sub-sources at all points are same, $q_i \equiv q/N$, N the number of the total equivalent sources, the formula may be approximated, when the sound pressure is expressed in 1/3 octave band or wider, as

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

In formula (3) $\overline{|H_j|^2}$ is the "average" transfer function expressed as

$$\overline{|H_j|^2} = \frac{1}{N}\left|\sum_{i=1}^{N} H_{ji}\right|^2 \xrightarrow{\text{Octave\_band\_average}} \frac{1}{N}\sum_{i=1}^{N} |H_{ji}|^2 \tag{4}$$

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 (mean-square value of the volume velocity) and can be obtained from the measured sound power, W, as

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

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

The above mentioned technique does not work for a source with a relatively strong directivity when the source is located in a free space. However, the situation is different if the source is placed inside a box-like structure: The ultimate radiation, and the signal the observer received outside the structure, is actually from the surface of the box-like structure. The original source distribution inside is not important for the observers outside if the observer does not "see" the source directly. The "box-like" structure here means a structure or structures enclosing the source with several reflecting surfaces. Examples of the structure can be an open-top box, a box with several large holes, or even several screens to enclose the majority part of the sound source. The sound field inside the structure is very much influenced by the reflections from the walls. In the extreme case when the structure is a closed box with thick walls, the reverberant sound is dominant inside the box and there might be no influence of the source directivity at all for the observers outside. The frequency band average, when the results are expressed in 1/3 octave band or wider, will further reduce the fluctuations of the results. The mean and the maximum errors between the prediction and measurements are expected to be reduced greatly when average of the transfer paths is taken.

3. Measurement verification

3.1. A centrifugal fan in a box-like structure

The first measurement is made for a cooling system used in train (a centrifugal fan plus a heat exchanger) together with the mock-up of the enclosure used in a real train. The mock-up is in principle a half-box covering the system with the inlet side fitted with a heat exchanger and the outlet side totally open. In order to adjust the flow rate, several computer cases are placed at the outlet side to block the opening partially, see Fig. 1. In a real case the outlet side is often filled with a lot of other obstacles such as cables.

The sound power level of the system is measured in the hemi-anechoic room in MWL, KTH, which is qualifies in accordance with ISO standard [6]. Since the sound introduced by the interference between the airflow and the heat exchanger cannot be modelled by the method, the fan plus the heat exchanger together are considered as the "source" in this case. The measurements are performed twice for two different conditions: source in free space and source placed inside the mock-up. The sound power from the first measurement is used to calculate the strength of the equivalent monopole, $\frac{4\pi c}{\rho\omega^2} W$, while the sound pressure levels at certain points measured in the second case are used to compare with the predictions.

One reference point (−2.5 m, −1.9 m, 1.5 m), is selected for the comparison purpose, where the origin of the coordinate is at the projection on the ground of the center of the sound source. Five transfer functions, each from the center of one side to the reference point and with the coordinates listed in Table 1, are measured by using a calibrated point source. The squares of the transfer functions are averaged to get the space-average transfer function as shown in Eq. (4). Eq. (3) is then used to calculate the predicted sound pressure level at the reference point. The comparisons between the measurements and prediction are shown in Fig. 2.

Fig. 1. A centrifugal fan inside the mock-up. The computer cases are used to reduce the size of the outlet.