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Numerical simulations of the sound propagation in non rectilinear streets

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ABSTRACT

At high frequencies, the sound propagation can be approximated by the propagation of sound particles which are reflected and absorbed at the boundaries. This propagation follows then a transport process. In urban canyons, this transport process can be reduced to a diffusion process. The resultant model allows one to obtain the spatial distribution of the acoustical energy in a street for a very low computational cost by using a classical finite elements program. This diffusion model has been previously validated in rectilinear streets for different geometrical and acoustical parameters. In this paper, more complex geometries such as varying cross-sections, bends and streets crossing are dealt with. Although the diffusion model only models the reverberant sound field, diffraction effects on the direct sound field at streets corners are not added. The obtained results are then compared to scale model experiments.

1. INTRODUCTION

In urban areas, sound is scattered multiple times at the surface irregularities, such as balconies and edges, during its propagation. As a consequence, the reverberant sound field which is created, is very difficult to model.[1,2] Numerous mathematical models have been developed but

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they are often limited to simple configurations and can not be applied to real situations (a review can be found in reference 3). The ray-tracing method[4] remains the most popular tool. However, due to the size of the calculation domain and the geometrical complexity met (bends, crossing and so on), a huge number of rays must be launched, which implies important calculation times.

At high frequency, the propagation of sound waves can be approximated as the motion of particles carrying an energy quantum. Their motions are described by a transport equation. Following appropriate hypothesis (mainly, the street width is lower than its length and height), this transport process can be then reduced to a diffusion process.[5,6] This model has been validated by comparison with numerical[7] and experimental[8] results in the case of rectilinear streets[9] in terms of spatial sound energy distribution. However, it was also shown that the diffusion model could not predict the reverberation time accurately.

In this paper, the ability of the diffusion model to deal with more complex geometries is inquired. Numerical results are compared to experimental data obtained with scale models and ray-tracing results using the Salrev[10] software.

2. MODELS PRESENTATION

A. Diffusion model

Starting with the motion of sound particles, it has been shown that their spatial and temporal distributions follow a transport process.[5] However, this problem remains time consuming to solve numerically. If the assumption is made that the street width is lower than its length and height (the facades are considered as infinite planes) and neglecting the absorption at walls, it can be shown that the transport process can be reduced to a diffusion process:[5]

$$\frac{\partial}{\partial t} w(\mathbf{r},t) - K\nabla^2 w(\mathbf{r},t) = P(\mathbf{r}_s,t), \tag{1}$$

where $w(\mathbf{r},t)$ is the sound energy density and K the diffusion constant:[5]

$$K = \frac{2-s}{s}\frac{Lc}{2}. \tag{2}$$

s is the scattering coefficient of the facades, L the street half-width and c the sound velocity. $P(\mathbf{r}_s,t)$ is a source term, which is equal to zero except at the source location $\mathbf{r}_s$. At the boundaries, the absorption is taken into account via an exchange coefficient h equal to:

$$h = \frac{c}{2}\alpha \text{ at the ground and façades and } h = \frac{c}{2} \text{ otherwise.} \tag{3}$$

Equations (1) with the boundary conditions (3) is solved numerically using a finite element solver.[6,8] The total sound field can be evaluated through[8]:

$$SPL(\mathbf{r}) = 10\times\log\left[\left(\frac{W_s}{4\pi\mathbf{r}_0^2} + (1-d_s)(1-\alpha_s)\frac{W_s}{4\pi\mathbf{r}_1^2} + cw_d(\mathbf{r})\right)\times\frac{\rho c}{P_{ref}^2}\right]. \tag{4}$$

The first term accounts for the direct sound field, the second one for the ground's reflections (d_s and α_s being the scattering and the absorption coefficients of the ground). The third one is the result of the diffusion model and stands for the reverberant sound field.

B. Salrev

Salrev is a broadband ray-tracing software using the spitting coefficient method.[10] The sound receivers are spherical and the sources are omnidirectional point sources. Diffraction effects are not simulated.

3. EXPERIMENTAL APPARATUS

Experimental data were obtained for several configurations of 1/10 street scale models (Figure 1). In the following, all dimensions and frequencies are expressed full scale. The first three configurations (Figure 2) correspond to a rectilinear street of 4 m, 7 m and 10 m width respectively, with constant height (7 m) and length (50 m). The configurations 4 and 5 (Figure 3) are characterized by a varying cross section with constant height (7 m) and length (3 0m). The configuration 6 (Figure 4) corresponds to a crossing of a main street of width 4 m and length 37 m by a minor street of width 7 m and length 14 m. Both streets have equal height (7 m). In order to produce diffuse reflections in the street, which is a main hypothesis of the studied diffusion model, acoustic diffusors have been placed on the façades. In all configurations the sound source was located at a distance x=4 m from the first street extremity, and at z=1.5 m above the ground. For configurations 1 to 3, the sound source was located in the middle of the street (i.e. y=2, 3.5 or 5 m respectively). For configurations 4 and 5, the sound source was at y=2.5 m and 1 m from the right façade. Lastly, for the last configuration, the source was located at y=1 m from the right façade of the main street.

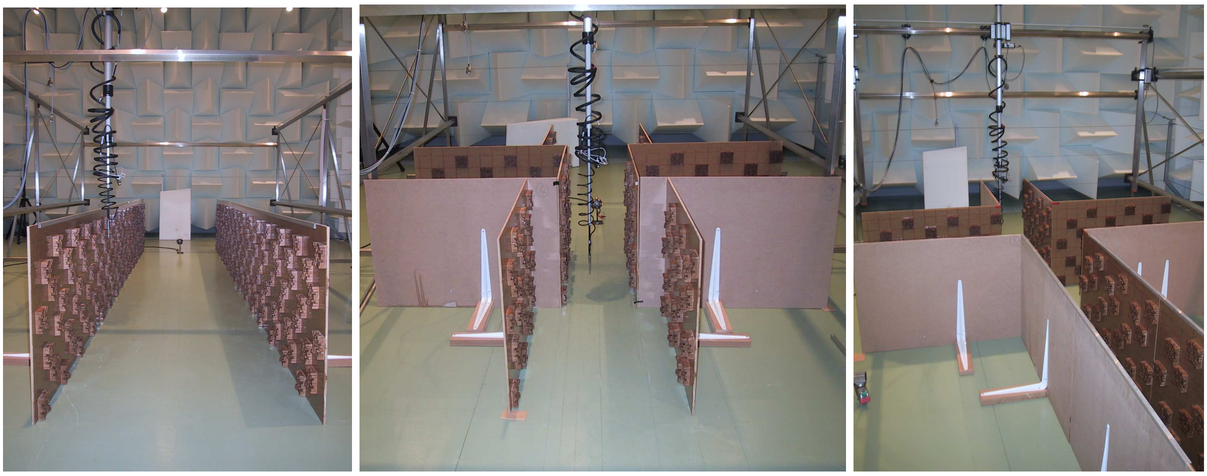

Figure 1. 1/10 scale model measurements (configurations 3, 5 and 6).

Measurements were carried out using a small dodecahedric sound source of diameter 65 mm, and a ¼" free field microphone in a vertical position (microphone oriented toward the ground) located every meter in the middle of the main street, the first measurement point being at 7 m from the source. Impulse responses (IR) were recorded for each position and processed later in order to obtain the sound pressure level (SPL) and the reverberation time (RT) for each 1/3 octave band between 100 Hz and 8 kHz. The excess of atmospheric attenuation in the scale model was also compensated using a time-varying filter applied on the IR.

4. RESULTS AND DISCUSSION

A. Numerical parameters

For Salrev, the sound receivers have a 1 m diameter. 10^8 rays are emitted and the simulations are carried out for 1 s. Calculation times are between 1h and 1h30min on a personal computer for height frequency bands. For the diffusion model, equation (1) is solved together with boundary conditions (3) by using a finite element solver.[9] The calculation domain is discretized in about 10^4 Lagrange linear elements. Calculations are about a few seconds using the same computer.

First, the boundary conditions (i.e. the absorption and scattering coefficients of the scale models), have been evaluated[11] using the experimental results of configurations 1, 2 and 3 (Figures 2). The results of a single third octave band (630 Hz) are exploited in the following. The obtained values for the absorption and the scattering coefficients minimise the error both the SPL and the RT distributions. These values are presented in Table 1 together the mean errors between the measurements and the Salrev's results on the SPL and on the RT. One can note that the obtained values are different for each street configuration, although the scale models are exactly the same (except the street width). It may be the result of the presence of acoustics diffusors on the facades. For non rectilinear configurations, these values are then used depending on the width of the street, i.e. when the street is 4m wide, the coefficients of configuration 1 are used and so on.

Table 1: *Values of absorption and scattering coefficients at 630 Hz.*

	Configuration 1 (width 4m)	Configuration 2 (width 7m)	Configuration 3 (width 10m)
α	0.16	0.07	0.02
s	0.55	0.5	0.65
Mean error on SPL	1.1 dB	1.0 dB	1.1 dB
Mean error on RT	6.0%	6.9%	8.8%

B. Rectilinear streets

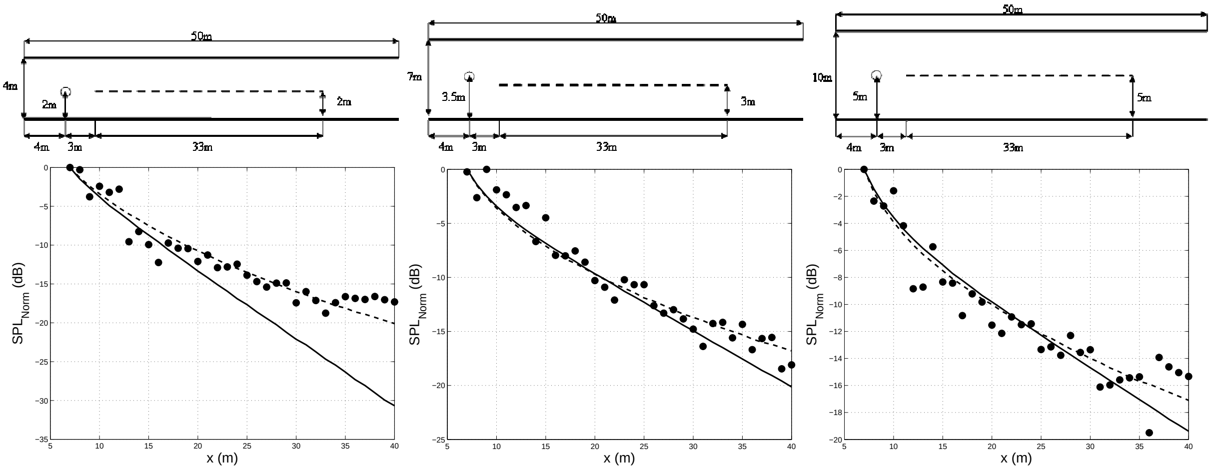

Figure 2: Configuration 1 (left), configuration 2 (middle) and configuration 3 (right), sketch (above) and SPL distribution (below): (●) experimental data, (▬) diffusion model, (▪▪▪) Salrev.

For the rectilinear streets, the agreement between the diffusion model and the experimental results is very good for configurations 2 and 3 (mean error of 1.3 dB and 1.4 dB respectively) and of the same order as the Salrev results (see Table 1). On the other hand, the error for configuration 1 is very high, up to 13.4 dB. This error is due to the diffusion constant value of eq. (2). As the street is narrow, the obtained value is low (i.e. the medium is not very diffusing, the energy remains around the source), which results in a high spatial decay of the sound energy. This result is quite surprising because the narrow street meets the hypothesis of the diffusion asymptotic development and such discrepancy has not been observed previously.[9] Obviously, all street configurations with a 4m wide branch will suffer of such error in the following.

C. Streets with varying cross-section

Despite the error made in the case of the 4m street width, the results obtained by the diffusion model in varying cross-section configurations (Figure 3) are in good agreement with the experimental results. The error is about the same order of magnitude as the Salrev's results. For the diffusion model, the mean errors are 1.4dB and 1.6dB for configuration 4 and 5 respectively, whereas the same mean errors are 1.5dB and 1.1dB with Salrev.

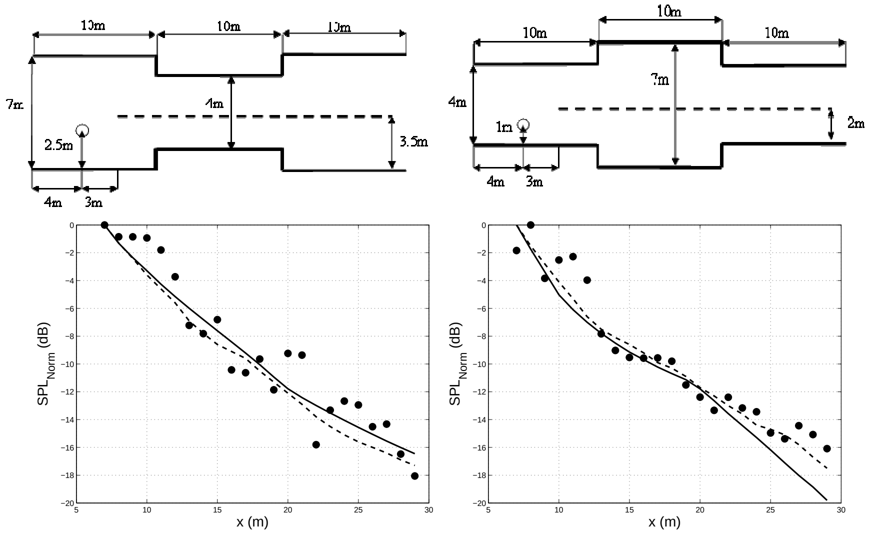

Figure 3: Configuration 4 (left) and configuration 5 (right), sketch (above) and SPL distribution (below): (●) experimental data, (—) diffusion model, (▪▪▪) Salrev.

D. Crossing

For the crossing configuration, the SPL distribution is measured along two sections (Figure 4). Along section C1, the diffusion is in rather good agreement with both the experimental data and Salrev until reaching the second part of the street (after the crossing). After this point, the diffusion model overestimates the sound attenuation. Part of this error may be due to the error made for the SPL distribution in the 4 m wide street (Figure 2). Another reason can be seen in the SPL distribution of section C2. There, the spatial decay of sound energy is underestimated compared to the experimental data and Salrev's results (i.e. more energy flows through the lateral sides of the crossing). The distribution of the sound energy is gradual as it diffuses around the corner. On the other hand, both experimental data and Salrev's results show clear discontinuities of the SPL distribution at y=-2 m and 2 m (Figure 4); the energy flowing out the street to the crossing is mainly directed along the street main direction. This absence of directivity of the reverberant field in the diffusion formalism has been already pointed out as only the irrotational part of the active intensity is considered.[12] Concerning Salrev, the agreement with the experimental results is very good along section C1 with a mean discrepancy equal to

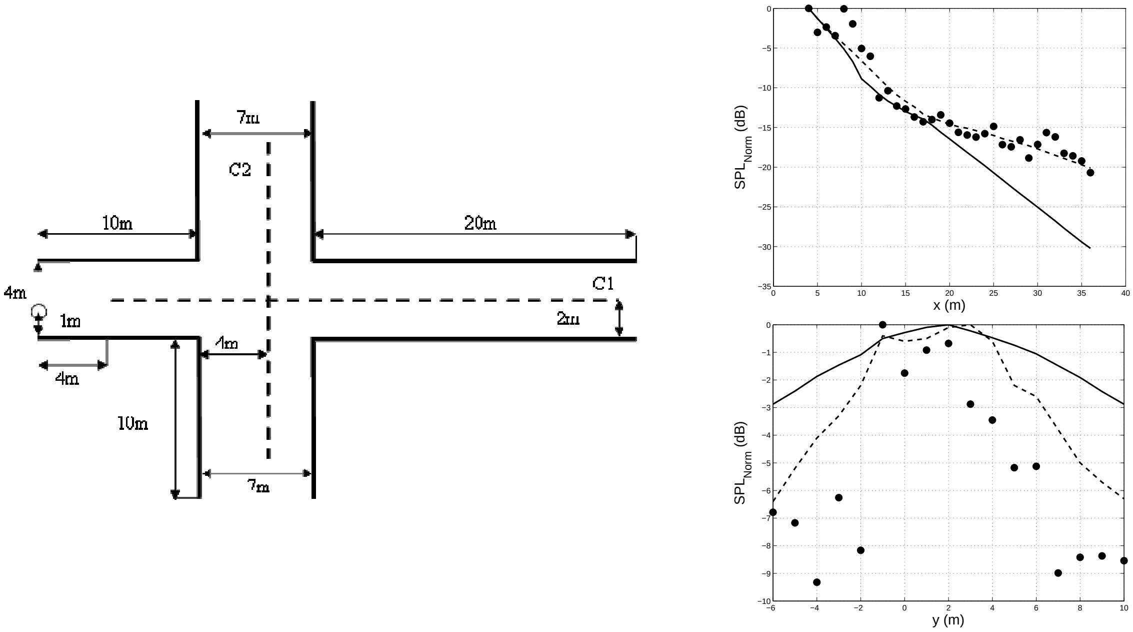

Figure 4: Configuration 6, sketch (left), SPL distribution (right) along C1 (top) and along C2 (bottom): (●) experimental data, (▬) diffusion model, (▪▪▪) Salrev.

1.1 dB. Despite neglecting the diffraction effects, the results of section C2 are rather good with a mean error of 2.6 dB.

5. CONCLUSIONS

Experimental measurements on scale models have been carried out for various geometries met in urban areas, such as streets with varying cross sections and crossing. Measurements in rectilinear streets allow one to deduce the values of the absorption and scattering coefficients of the boundaries. Then, these configurations have been simulated using the ray-tracing Salrev and the diffusion model for urban acoustics. Results obtained with Salrev are in very good agreement with the experiments with mean errors close to 1 dB for the considered mid-frequency (630Hz full scale third octave band) despite neglecting the diffraction occurring at street corners. Given correct boundary conditions (absorption and scattering coefficients values), ray-tracing method remains an efficient tool to predict the short range (a few streets connected together) acoustic field despite the resulting calculation load. On the other hand, the diffusion model needs only a few seconds to simulate the sound level distribution in a district. However, this study shows that flaws remain in the model. Mainly, the behaviour around streets corners is unrealistic, as the directionality of the reverberant sound field is neglected. Further developments need to be carried out in the future to correct these flaws.

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