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Accounting for the effect of diffuse reflections and fittings within street canyons, on the sound propagation predicted by ray tracing codes

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ABSTRACT

Diffusion on building facades and fittings within a street can significantly affect sound propagation in urban areas. These phenomena are however not reproduced by the widespread outdoor sound propagation models that are based on ray codes algorithms, because their modeling would induce increased computational costs. In this paper, a set of 32 175 simulations is achieved with a sound particle tracing code to quantify the errors made when neglecting acoustic diffusion within street canyons, according to the street geometry (width, height, distance between the point source and the receiver), the acoustical properties of the street (diffusion and absorption coefficient of the facades, absorption coefficient of the ground), and the acoustical properties of the fittings (mean free path and average absorption coefficient), in the case of a receiver height of 1.5 m. The diffuse reflections can lead to reduction of 2 dB to an increase of 4 dB of sound pressure levels in the absence of fittings, and can lead to an increase of 10 dB of sound pressure levels in the presence of fittings, for the most unfavorable configurations. The influence of the acoustical parameters and the influence of the street geometry on sound attenuation are closely linked to each other. Moreover, acoustic diffusion results in an overall sound level increase if one considers a linear point source distribution. Finally, regressions are proposed that estimate the impact of diffusive reflections and street fittings on sound propagation as a function of the input parameters. These regressions can now be advantageously used to refine sound levels estimations within street canyons, when using classical outdoor sound propagation models, in the range of the parameters tested.

1. Introduction

Accurate sound propagation modeling is crucial to evaluate urban noise mitigation action plans. Models should ideally reproduce all the phenomena that affect sound levels while being implementable on large urban areas. For example, the recent increasing power of computational resources enabled the development of time-domain methods [1–3], which potentially take all these phenomena into consideration. This allows the evaluation of novel noise abatement solutions such as vegetation or green roofs, and improves sound levels estimation inside shielded urban areas [4,5]. However, these methods are constrained to the street scale due to large computation times and fastidious data modeling. For practical reasons, to calculate sound propagation over larger areas, as required for noise mapping at the city scale or for evaluating the noise impact of traffic strategies, geometric models are generally used. Ray-tracing algorithms are currently implemented in most of the software products used by acoustical consulting firms, because they offer a good compromise between accuracy and computation times [6,7], provided that receivers are properly defined [8]. However, these methods often reproduce sound reflections in a simplified way, considering fully specular reflections.

Diffusive reflections on building facades play an important role in street canyon sound propagation [9], in addition to the street geometry and its acoustical properties [10]. Onaga et al. showed that the impact of diffuse reflections caused by building facades on sound levels depends on the acoustic characteristics of urban streets: diffuse reflections cause an increase of sound levels at short distances, and a decrease at larger distances; the range of increase is higher in high-facade streets [11]. Moreover, recent studies showed that the shape of balconies can influence significantly sound spectrums [12,13]. Another phenomenon that has received little attention, and which can modify sound distribution within street canyons, is the multiple diffusive reflections by urban facilities or vehicles located on the street [14]. Walerian et al. proved that vehicles can accurately be modeled as semitransparent screens [15]. These works underline the need to account for

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diffusive reflections and street fittings to enhance street canyon sound predictions. This should be done without increasing computation times to benefit softwares based on ray tracing codes.

In this paper, the sound particle tracing code SPPS, which efficiently accounts for these phenomena [17], is used to quantify the influence of diffuse reflections and street fittings, on sound propagation within street canyons. The objective is to determine the corrections to apply to include these phenomena in sound propagation calculations achieved with ray tracing codes.

A set of 32 175 simulations, described in Section 2, is obtained by combining different configurations of street geometries and acoustic parameters. These simulations are used in Section 3 to determine for each simulation the correction $C = A - A^0$, which is the difference between the sound attenuation A between the source and the receiver calculated with acoustic diffusion (diffuse reflections on facades and diffusion by fittings), and the sound attenuation A^0 calculated under the same configuration but with classical conditions (empty street and perfectly specular reflections). Statistical regressions are determined in Section 4, which enable interpolating the corrections C in the range of the tested parameters values. Finally, Section 5 concludes on practical considerations relative to this work.

2. Methods

2.1. Sound propagation calculation

2.1.1. Principle

Sound propagation calculations are achieved with the sound particle tracing code SPPS, which was first proposed for rectangular rooms [16], and generalized more recently for any arbitrary shapes [17], using the graphical user interface I-simpa [18]. The flowchart of SPPS can be found in [16].

It is based on a geometrical approach, which assimilates the sound field to numerous sound particles, each carrying an infinitesimal energy [19]. Two approaches can be considered. In the probabilistic approach, the energy of the particle is constant, and the particle may disappear at any time step following probabilistic laws shaped by the physical phenomena (absorption by surfaces, atmospheric absorption, etc.); hence the number of particles decreases with time. In the energetic approach, the energy of the particle diminishes according to the physical phenomena that occur during the propagation; hence the number of particles is constant along the time. In this study, the probabilistic approach is used, which allows reduction of computational times while keeping a consistent accuracy for the present study.

The sound particles are emitted by the sources following a predefined directivity, and then propagate within the domain of propagation at the sound speed, following trajectories that depend on the speed profiles and atmospheric turbulences. One assumes here a homogeneous atmosphere and thus straight particle trajectories, which is a valid assumption under street canyon configurations and at short distances. Sound particles travel independently (no collision between particles) until they encounter a surface or a fitting object, where they can be absorbed or reflected. The resulting rarefaction of particles at increased distances from the source is consistent with the geometrical spreading of a spherical wave. Moreover, the atmospheric absorption is taken into account by considering the probability that the sound particle disappears from the propagation domain due to air absorption.

Finally, the sound pressure level SPL at a receiver, modeled by a spherical volume, is deduced from the sum of the individual energies carried by each particle that crosses the sphere during a given time step, weighted by the time of presence of the particle within the receiver.

2.1.2. Diffusion by building facades

One main interest of the sound particle approach is its ability to consider sound diffusion [20]. When a collision to a surface occurs, the sound particle can be absorbed or reflected, according to the acoustical properties of the surface [16]. In the probabilistic approach of SPPS, the absorption coefficient α of the surface defines the probability of a particle to be absorbed. If not absorbed, the particle is reflected in a specular or diffusive reflection, in function of the scattering coefficient d of the surface. Thus $d = 0$ corresponds to a fully specular reflection (as in classical ray codes) and $d = 1$ corresponds to a fully diffuse reflection, according to a Lambert's law [21–23].

2.1.3. Diffusion by fittings within a street

During propagation, sound particles can be scattered by fitting objects in the propagation domain. The diffusion caused by the fittings located on the particle trajectories is reproduced statistically, adapting to outdoor sound propagation the approach proposed in [24]. Considering a subdomain of volume V_c, defined by N_c scattering objects (i.e. with a density expressed in objects per m^3 $n_c = N_C/V_c$) of scattering surface s_c and with an absorption coefficient α_c, then, the probability density function $f(r)$ that a particle collides a scattering object on a distance r is written:

$$f(r) = \nu_c \exp(-\nu_c r), \tag{1}$$

where ν_c is the diffusion frequency $\nu_c = n_c q$, where q_c is the apparent scattering surface of the objects. In a practical way, q_c is determined by assimilating each fitting to a sphere with the same surface [18], as depicted in Fig. 1, and thus $q_c = s_c/4$. The mean free path λ_c, which is the mean distance between two collisions, is given by $\lambda_c = 1/\nu_c$.

In practice, the SPPS code uses the method of the cumulative distribution function $p(R)$ to model the diffusion process, defined by:

$$p(R) = \int_0^R f(R)dR = 1 - \exp(-\nu_c R), \tag{2}$$

and giving the probability that a particle encounters a scattering object along a propagation distance R. This function is null for $R = 0$ and equal to unity for $R = \infty$. The numerical simulation of the diffusion process is obtained by considering the inverse cumulative distribution function:

$$R = -\frac{1}{\nu_c} \ln(1 - \xi), \tag{3}$$

where ξ is a random number between 0 and 1. Then, for each particle entering into a sub-domain, a random number is considered, giving the distance R of collision with a scattering object. When the particle has reached the distance R in the sub-domain, the particle is scattered into a new direction according to the

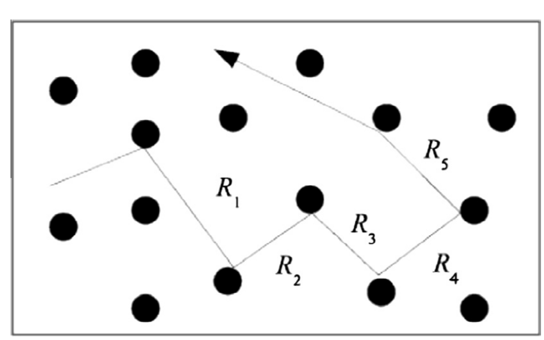

Fig. 1. Principle of the sound particle tracing code SPPS, illustration of the diffusion by fitting objects.