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Using Acoustic Diffusors to Reduce Noise in Urban Areas

Judicaël Picaut
Laboratoire Central des Ponts et Chaussées, Division Entretien, Sécurité et Acoustique des Routes, Route de Bouaye, B.P. 4129, 44341 Bouguenais Cedex, France. Judicael.Picaut@lcpc.fr

Denis Scouarnec
Mechanics Vibrations Laboratory, Valeo Engine Cooling, 8 rue Louis Lormand, 78321 La Verrière, France

Summary
The use of acoustic diffusors to reduce noise in urban areas is investigated by computer simulation. The numerical simulations have been performed with a sound particles tracing based code, which allows to model the sound reflection, diffusion and absorption by building façades with any arrangement of acoustic diffusors. Several parameters have been studied, among which, the diffusion pattern, the relative surface on the façades, the arrangement and the size of diffusors. In addition, the combined effect of absorption and diffusion by diffusors has also been investigated. The numerical results show that a significant noise reduction can be observed on the sound attenuation as well as on the sound decay in a street, by considering diffusors creating uniform diffusion, with a relative surface larger than 20%, and if possible locating on the lower part of the façades. Lastly, and as expected, by adding sound absorption on diffusors, it increases the noise reduction.

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1. Introduction

Urban acoustics has attracted many studies in the last decades, mainly to reduce noise in urban areas. Among the noise reduction approaches, the one consisting in the reduction of the noise emission, mainly from transportation noise source, is widely considered. When technical solutions have reached their limits, or for non-mechanical sound sources (noise from human activities for example), another approach consists in correcting the acoustic properties of urban spaces to reduce the noise propagation, by increasing the sound attenuation and the sound decay in streets. As in room acoustics, several solutions can be considered, and are mainly based on absorption and diffusion devices to reduce or to optimize the noise level and the reverberation [1].

However, in urban acoustics, there are very few studies about the acoustic treatment of urban spaces. Kang has suggested to consider absorbent patches on the façades and on the ground to reduce the noise propagation in a single street, as well as in cross streets and in urban squares [2]. As expected, it was shown that both sound attenuation and sound decay increases with absorption, but non trivial results were also obtained: for example, it was shown that the noise attenuation is the highest if the absorbers are arranged on one façade, and the lowest if they are evenly distributed on all boundaries. In a recent paper, Hornikx and Forssén have investigated the use of oriented patches (absorption and diffusion) as a façade treatment to reduce noise in shielded canyons. As an interesting result, they have shown that vertical diffusion yields lower levels at the shielded side compared to horizontal diffusion [3].

In this paper, the two last studies have been extended to investigate the use of acoustic diffusors, as a façade treatment, to reduce the noise propagation in urban areas. The main objective is to determine the optimum parameters of diffusors, in terms of diffusion pattern (i.e. the scattering diagram, or the reflection law), the relative surface of diffusors and their arrangement on the façades, and the diffusor size, that produce a significant effect on the sound attenuation and reverberation in a street. In addition, the combined effect of absorption and diffusion is also studied.

This paper begins with a presentation of the numerical simulations that have been performed to study the effect of diffusors in a street (section 2). A specific attention has been payed on the modeling of the sound reflection, diffusion and absorption by building façades and by diffusors, that is the crucial point of the numerical simulations. Results are then detailed in section 3 for each diffusor parameter. Finally, the main results are summarized in section 4 and underline the optimum diffusion pattern of diffusor, as well as their arrangement, which produce a significant effect on the noise reduction in a street.

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2. Numerical simulations

2.1. SPPS numerical code

2.1.1. Presentation

In this paper, numerical simulations have been carried out with the numerical code called SPPS (Sound Particles Propagation Simulation) based on the concept of sound particles [4]. These particles are emitted from a sound source in a homogenous propagation domain, and defined by their position $\mathbf{x}$ and velocity $\mathbf{v}$ whose norm is equal to the sound velocity c. Sound particles propagate along straight lines, until they hit an object, like a scattering object or a building façade. At each collision, particles are reflected in a new direction, according to the reflection law of the scattering object or the building façade. During the propagation, sound particles may also be absorbed by objects or due to the atmospheric attenuation. Since sound particles are characterized by a constant energy, the sound energy density in a receiver volume is proportional to the distribution of sound particles in this volume. Such model is then an energetic-based approach, for middle and high frequencies use. As for classical ray-tracing based codes, a numerical simulation must be carried out for each frequency band of interest. However, in the present study, only one calculation has been carried out.

In the SPPS code, sound emission, reflection, diffusion and absorption are modeled using Monte Carlo simulations [4]. It consists in generating series of random numbers that respect the density probability of the physical phenomena to be modeled. Then, the accuracy of the Monte Carlo simulations increases with the number of sound particles that are considered.

Since the modeling of the reflection by a building façade with diffusors is the crucial element of the present study, the numerical method is detailed in the next Section.

2.1.2. Modeling the reflection by building façades

At boundaries, sound particles may be absorbed due to the absorption coefficient α of the façade, or reflected in a new direction. As in room acoustics, sound reflection can be modeled by mixing specular and diffuse reflections, according to the size and distribution of the façade irregularities, using the usual scattering coefficient δ [5, 1]. Specular reflection is modeled using a deterministic approach (i.e. the reflection angle is equal to the incident angle), while the diffuse part of the reflection is modeled by a probability density $R(\mathbf{v}, \mathbf{v}')$, representing the probability that an incident sound particle with a velocity $\mathbf{v}$ leaves the boundary after reflection in the direction $\mathbf{v}'$.

In a numerical point of view, a first number $\xi \in [0, 1]$ is generated according to an uniform distribution, in order to model the sound absorption by the building façade. If $\xi \leq \alpha$ the particle is absorbed and disappears from the domain. Conversely, for $\xi > \alpha$, the particle is reflected in a new direction. A second uniform random number $\zeta \in [0, 1]$ is then generated and compared to the scattering coefficient δ. If $\zeta > \delta$, the particle is reflected in the specular direction. If $\zeta \leq \delta$, the direction of reflection that is in agreement with the diffuse reflection law $R(\mathbf{v}, \mathbf{v}')$ of the building façade, is obtained using random generation-based methods, such as the cumulative distribution function and the rejection methods.

In order to study the effect of acoustic diffusors on the sound propagation and reverberation in the street, several reflections laws $R(\mathbf{v}, \mathbf{v}')$ must been considered for the building façades as well as for the acoustic diffusors. Due to the lack of knowledge about the scattering pattern of building façades, arbitrary reflection laws have been considered here. Concerning acoustic diffusors, several technical solutions have already been proposed for room acoustic applications, each one with its own scattering pattern [1]. However, the main objective of the present study is to evaluate the general effect of a diffusor on the sound propagation in a street, then to determine what kind of diffusor can be used to reduce noise in urban areas, rather to evaluate the exact effect of a real room acoustic diffusors.

In this study, the specular reflection is considered as the reference one (Figure 1a). The uniform reflection law (Figure 1b), for which the sound energy is reflected in all directions with the same probability, and the classical Lambert's law (Figure 1c) have also been considered. For the last reflection law, which is widely used to model diffuse sound field in room acoustics [6, 5, 1], as well as in urban acoustics [7, 2, 8], the angular distribution of the reflected sound energy is proportional to $\cos\theta'$, θ' being the reflecting angle from the normal to the façade. It means that the probability of reflection along the normal to the façade is maximum, while it is equal to zero for grazing angles. By noting $w = \cos\theta'$, one can remark that the uniform and the Lambert's laws are proportional to w^0 and w^1 respectively. Then, these reflection laws (called normal laws on the following) can also be generalized on the form of w^n with $n = 2, 3, 4$ (Figures 1d, 1e and 1f). By increasing n, it increases the probability of reflection around the normal to the façade.

The previous laws do not depend on the incident direction of the sound field, neither on the architectural characteristics of real building façades. However, it may assume that a "realistic reflection" should be function of the distribution and the size of the façade irregularities, as well as of the direction of incident sound wave [9]. A reflection around the specular direction (called semi-diffuse reflection) is probably more in agreement with reality than uniform and Lambert's laws. Thus, in this paper, semi-diffuse reflections have also been investigated. In order to express such reflection law, a general Kirchhoff approach for the scattering from rough surfaces was used [10]. The rough surface is supposed to be random and defined by a normal distribution of the perpendicular roughness $h(Z)$, with a variance σ^2 and an autocorrelation

$$C(\tau) = \exp -\tau^2/T^2, \tag{1}$$

where T is the correlation distance. A semi-diffuse reflection law L can thus be obtained [10]:

$$L = L_0 \exp\left[-\frac{\left(v_X^2 + v_Y^2\right) T^2}{4\, v_Z^2\, \sigma^2}\right], \tag{2}$$

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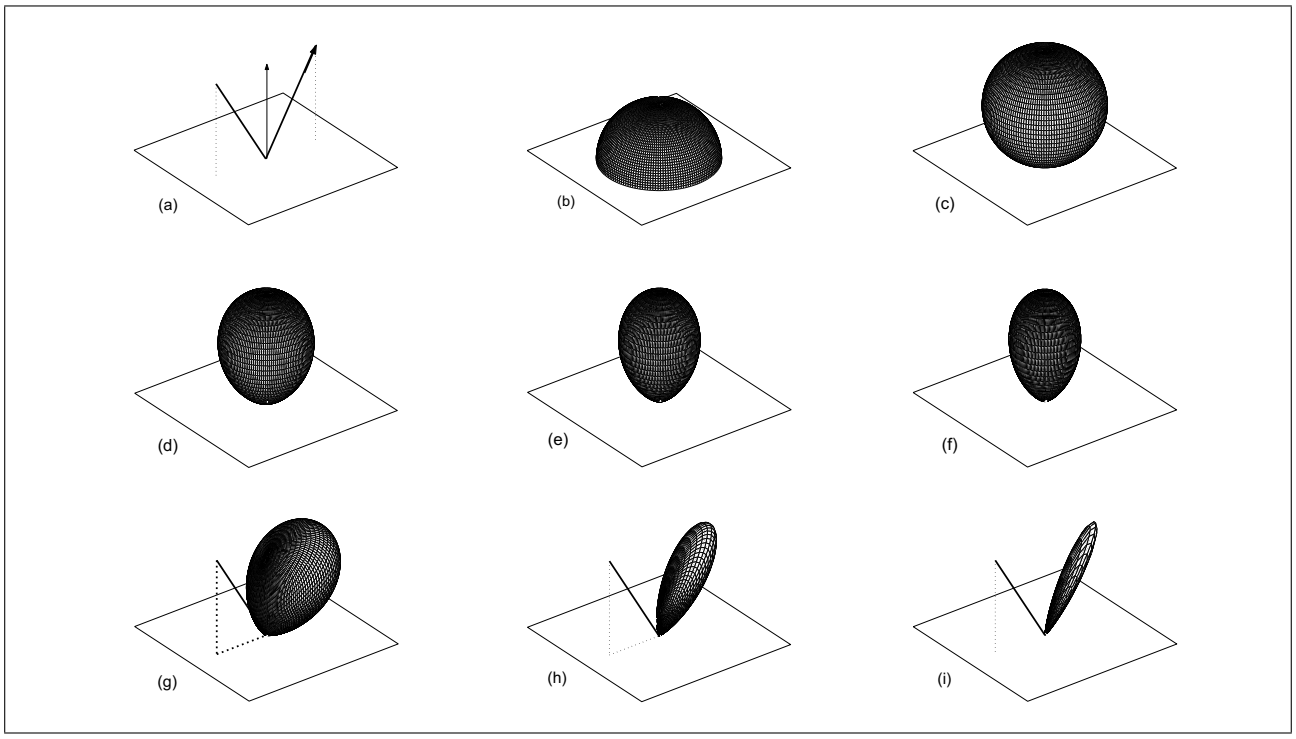

Figure 1. Building façades and diffusors reflection laws. Reference configuration: (a) specular (SP). Normal laws w^n: (b) Uniform (UN, $n = 0$), (c) Lambert (LA, $n = 1$), (d) w^2 (W2), (e) w^3 (W3), (f) w^4 (W4), (g) Semi-diffuse reflection laws with $T/\sigma = 5$ (SD5), (h) $T/\sigma = 10$ (SD10), (i) with $T/\sigma = 20$ (SD20).

where v_X and v_Y are the coordinates of the projection of the incident velocity on the rough surface (i.e. on the façades), v_Z the coordinates of the incident velocity perpendicular to the normal of the rough surface, and L_0 a normalization coefficient. In equation (2), the scattering pattern is function of the ratio T/σ. By varying this ratio, it allows to model the effect of different rough surfaces, then several conditions of reflection. As an example, Figures 1d, 1e and 1f present the reflection laws respectively for $T/\sigma = 5$, 10 and 20. When the ratio T/σ increases, the reflection becomes more specular. For small values of T/σ, the scattering pattern is close to the Lambert's one, but is still function of the incident direction.

2.2. Simulations

2.2.1. Plan of simulations

The main objective of the following numerical simulations is to determine the properties of urban acoustic diffusors, in terms of reflection law, absorption and size, as well as in terms of their arrangement and relative surface (i.e. the ratio defined by the total diffusor area to the façade area) on a building façade, that optimize the noise reduction in a street. It means that acoustic diffusors producing (1) the lowest absolute sound pressure level, and if possible, (2) the largest sound attenuation and (3) the fastest sound decay in the street, are looking for. It is important to specify that the two last criterions do not involve that the absolute sound pressure level in the street is the lowest.

To minimise the number of numerical simulations, a sequential approach has been followed. The first step of the numerical study focusses only on the reflection properties of diffusors, since it is assumed that adding absorption on diffusors will increase the effect of diffusors. Then, the absorption coefficients α_d and α_f, of the diffusors and building façades respectively, are fixed to 0. Moreover, in order to evaluate the effect of the diffusors only, the scattering coefficient δ_d of the diffusors is fixed to 1 (i.e. perfectly diffuse reflection), while the scattering coefficient δ_f of the façade is chosen as 0 (i.e. perfectly specular reflection). Firstly, a first set of numerical simulations has been realized to determine the more appropriate reflection law for the diffusors (section 3.1). Using the obtained reflection law, the following two simulations have been carried out in order to optimize the relative surface of diffusors (section 3.2), as well as the diffusors arrangement on the façade (section 3.3). Then, a new set of simulations is realized to determine the effect of the size of diffusors (section 3.4). Table I summarizes all these numerical simulation configurations.

In a second step, the combined effects of diffusion and absorption have been studied, by considering several repartitions of absorption between diffusors and building façades, as well as for several absorption coefficients (section 3.5 and Table VI). Lastly, applications for realistic streets (detailed in Table VII) are proposed in section 3.6.

2.2.2. Geometry and simulation parameters

Numerical simulations have been carried out with one million of sound particles emitted from an omnidirectional sound source with a sound power level of 0 dB. 500 time

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Table I. Configurations for the study of the effects of acoustic diffusors on the sound propagation in a street. Diffusors parameters: α_d absorption coefficient, δ_d scattering coefficient, reflection law R and size of diffusors. Façades parameters: α_f absorption coefficient, δ_f scattering coefficient and reflection law. Surface ratio p: relative surface of the façade covered by diffusors. Arrangement: diffusors arrangement on the façades. See Figures 1 and 7 for the description of abbreviations of reflection laws and diffusors arrangement.

	Diffusors				Façades			Surface ratio	Arrangement
	α_d	δ_d	Law R	Size	α_f	δ_f	Law R	p	
Reflection laws (sect. 3.1)	—	—	—	—	0.0	1.0	variable	—	—
Relative surface (sect. 3.2)	0.0	1.0	UN	1 m×1 m	0.0	0.0	SP	variable	RE
Arrangemetnt (sect. 3.3)	0.0	1.0	UN	1 m×1 m	0.0	0.0	SP	50%	variable
Size (sect. 3.4)	0.0	1.0	UN	variable	0.0	0.0	SP	50%	RE, RA
Absorption (section 3.5)	variable	1.0	UN	1 m×1 m	variable	0.0	SP	50%	LO, LF, RA

increments with a time step of $\Delta t = 2$ ms have been considered, leading to a total time of propagation of 1 s. In the first step of the simulations (sections 3.1 to 3.5), an empty canyon street S1 of size $8 \times 40 \times 8\,\mathrm{m}^3$ (width × length × height) has been considered. In section 3.6, related to realistic streets, two empty streets S2 and S3 have also been studied, of size $8\times60\times8\,\mathrm{m}^3$ and $8\times60\times12\,\mathrm{m}^3$ respectively. The sound source is located at position (6.5, 30.5, 1.5) for S1 and (6.5, 50.5, 1.5) for S2 and S3.

A line sound source has not been studied in this paper, since it is assumed that the effect of diffusors are the same both for omnidirectional and linear sources.

The pavement is considered as a perfectly reflecting surface ($\alpha = 0$, $\delta = 0$). In order to only study the effect of the acoustics diffusors on the sound propagation in the street, atmospheric attenuation has not been considered in the numerical simulations. The sound velocity c was fixed to 340 m/s.

2.2.3. Acoustics parameters

Three acoustic parameters have been studied to evaluate the effect of diffusors on the propagation in a street.

Firstly, the absolute sound pressure level in the street has been considered. Since an experimental study has shown that the sound energy is quite uniform on a narrow street section [11], the sound pressure level has been estimated by averaging the sound energy on each street section (along the $y - axis$), in order to have a global estimation of the effects of acoustic diffusors in the street. However, further numerical simulations (not presented in the paper) for several horizontal and vertical receiver lines in the street have shown similar results to the global estimates. To characterize the effect of diffusors for a street configuration, by comparison with the same street without diffusors but with perfectly specular reflecting façades, a mean sound level difference $\overline{\Delta L}$ (in dB) is considered. It is obtained by calculating the mean difference of sound pressure level between both configurations, as

$$\overline{\Delta L} = \frac{1}{N}\sum_{n=1}^{N} L_{\mathrm{ref}}(y_n) - L_{\mathrm{conf}}(y_n), \tag{3}$$

where $L_{\mathrm{ref}}(y_n)$ and $L_{\mathrm{conf}}(y_n)$ are the sound pressure level calculated at the street section y_n, for the reference street and the street with diffusors, respectively, and where N is the number of street sections. In the whole paper, the sound pressure level have been estimated every meter from the sound source, leading to $N = 40$ for S1 (from $y_1 = 0.5$ m to $y_{40} = 39.5$ m), and $N = 60$ for S2 and S3 (from $y_1 = 0.5$ m to $y_{60} = 59.5$ m). When $\overline{\Delta L} > 0$, the sound pressure level in the reference configuration is, on average, larger than for the configuration with diffusors, which corresponds to a positive effect of diffusors. In contrary, when $\overline{\Delta L} < 0$, the diffusors produce a negative effect. This coefficient only expresses an average behavior of the sound pressure level along the street in comparison with the reference configuration. However, it does not mean that the sound level difference is the same along the street.

Secondly, to qualify the sound attenuation for each configuration of diffusors (i.e. the sound pressure level as a function of the distance from the sound source), an attenuation coefficient m in dB per meter has also been introduced. To avoid the effect of the direct field, which is preponderant close to the sound source and that is the same for all configurations, the attenuation coefficient m have been obtained through a linear interpolation of the sound levels between $y_1 = 0.5$ m and $y_{26} = 25.5$ m in the street S1 (i.e. from 35 m to 5 m from the sound source) and between $y_1 = 0.5$ m and $y_{46} = 45.5$ m (i.e. from 55 m to 5 m from the sound source) in the streets S2 and S3. To compare with the reference street, the relative deviation σ_m (in percent) of the sound attenuation has also been calculated, as

$$\sigma_m = \frac{m_{\mathrm{ref}} - m_{\mathrm{conf}}}{m_{\mathrm{ref}}} \times 100\%, \tag{4}$$

where m_{ref} and m_{conf} are the sound attenuation of the reference street and the studied configurations of diffusors, respectively. When the relative deviation is positive, it corresponds to an increase of the sound attenuation, which is a wanted effect.

Finally, the decay of sound energy in the whole street was also estimated, and expressed in terms of early decay time (EDT) and reverberation time (RT30) using the backward integration method [12]. As above, the relative deviation σ_{RT} (in percent) of the sound decay has also been calculated, as

$$\sigma_{\mathrm{RT}} = \frac{\mathrm{RT}_{\mathrm{ref}} - \mathrm{RT}_{\mathrm{conf}}}{\mathrm{RT}_{\mathrm{ref}}} \times 100\%, \tag{5}$$

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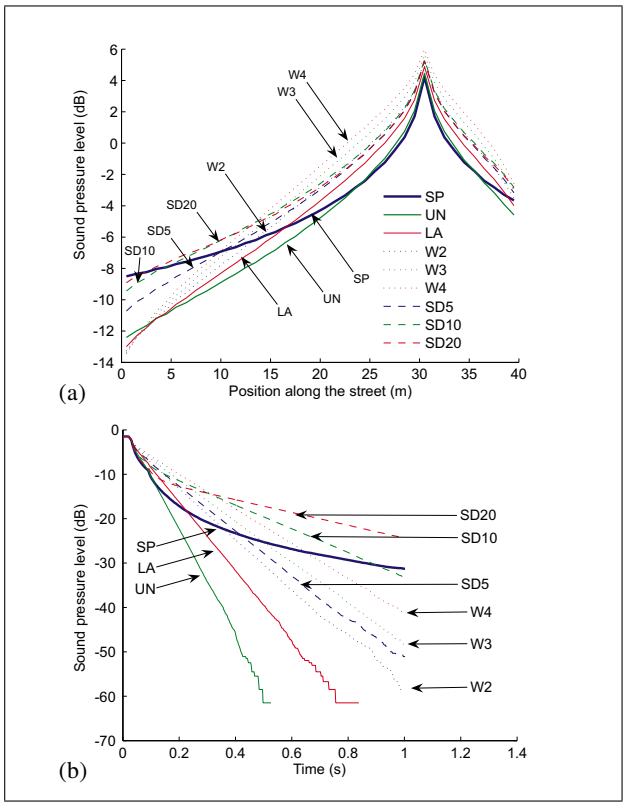

Figure 2. Effect of the façade reflection laws on the sound propagation along the street: (a) sound attenuation and (b) sound decay in the street.

where RT_{ref} and RT_{conf} are the reverberation times (RT30 or EDT) of the reference street and the studied configuration, respectively. When the relative deviation is positive, it corresponds to a decrease of reverberation time, which is a wanted effect.

All numerical results have been summarized in Tables II–V for the first step of simulations, in Table VI for the second step (effect of absorption), and in Table VII for the application to realistic streets. All the results are discussed in the next sections.

3. Results

3.1. Effect of the reflection laws

In order to evaluate the optimal reflection laws of acoustic diffusors, the entire façade has been treated as a single acoustic diffusor. Results are shown at Figures 2a and 2b respectively for the sound attenuation and the sound decay in the street. In this Section, the building façades are perfectly reflecting and diffusing ($\alpha_f = 0$, $\delta_f = 1$).

3.1.1. Sound attenuation

Close to the sound source (almost on the first 10 meters), the specular reflection law produces the best sound attenuation in comparison with other reflections laws. At these distances, the sound field is mainly feed by the direct field and the first reflections. With the specular reflections, the sound energy goes away from the source, while for other reflection laws, due to the back-diffusion effect [11] (Figure 3), many scattering by building façades occur, allowing the sound energy to come back to the sound source, increasing the sound field close to the source. It must be noted that the SPPS code uses a volume receiver rather than a point receiver. It explains why the sound pressure level at the source position is not infinite.

When the distance from the sound source increases, this behavior is reversed: specular reflections are still energetic, while, for other reflection laws, due to the multiple diffuse reflections through the openings, the sound field decreases. It can be noted that these results about the far field effect are consistent with other studies on the effect of diffusion, as well as the effect of the scattering coefficient, on the sound propagation in street [2, 8, 3]. Indeed, it was also shown that the effect of diffusion on the sound pressure level appears as an increase at short distances from sources, and as a decrease at larger distances.

Table II. Effect of diffusor reflection law on the sound propagation in a street, in terms of global sound decay (RT30, EDT) and sound attenuation (m, $\overline{\Delta L}$). Symbol * mentions configurations that have a significant effect of the noise reduction in the street. The relative deviation σ_m and σ_{RT} (in %) by comparison with the reference configuration SP is also given in parenthesis.

Reflection laws	RT30 (s)	EDT (s)
SP	2.81	0.54
UN*	0.51 (82%)	0.53 (2%)
LA	0.77 (73%)	0.72 (−33%)
W2	1.04 (63%)	0.93 (−72%)
W3	1.31 (53%)	1.16 (−115%)
W4	1.53 (46%)	1.39 (−157%)
SD5	1.18 (58%)	1.00 (−85%)
SD10	2.19 (22%)	1.15 (−113%)
SD20	3.82 (−36%)	0.76 (−41%)
Reflection laws	**m (dB/m)**	**$\overline{\Delta L}$ (dB)**
SP	0.25	—
UN*	0.41 (−64%)	1.03
LA	0.47 (−88%)	0.35
W2	0.51 (−104%)	−0.25
W3	0.55 (−120%)	−0.79
W4	0.57 (−128%)	−1.26
SD5	0.40 (−60%)	−0.65
SD10	0.36 (−44%)	−1.17
SD20	0.33 (−32%)	−1.11

3.1.2. Sound decay

Observations are similar for the sound decay in the street. For the first propagation times, the sound energy decreases faster for the specular reflection, due to a maximum absorption of sound by the openings. This is particularly visible on Figure 4 by zooming Figure 2b, and by considering the following explanation. Firstly, since the studied configurations do not include façades absorption, the sound pressure level remains constant in the street as long as the sound particles reach the openings. Due to the source location (30.5, 6.5, 1.5), the times t_1, t_2 and t_3 for which the

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decay curves change, correspond to the sound absorption by the open top ($t_1 = (8-1.5)/c \approx 0.02$ s), by the end extremity ($t_2 = (40-30.5)/c \approx 0.03$ s), and by the first extremity ($t_3 = 30.5/c \approx 0.09$ s). Since the specular reflection does not produce back diffusion effect, the decrease of the sound energy is then very fast. Then, for longer propagation times, due to the multiple diffuse reflection on the building façades, the sound decay increases for diffuse reflection laws in comparison with the specular reflection. Finally, as presented in Table II, RT30 are longer for all diffuse reflection laws than for the specular reflection.

It can be noted that the behavior for the SD20 reflection law does not follow the last result, since it produces an increase of the RT30. For this last reflection law, the latter part of sound decay is quite similar to the specular one. However for the early part, and as explained above, due to the back-diffusion effect, the sound decay is shorter for the specular reflection law. Finally, between −5 dB and −35 dB, the sound decay is longer for the SD20 reflection law, while for all other reflection laws the latter part of the sound decay is prevailing.

This decrease of the sound decay for street with diffuse reflection is in agreement with the experimental observation done by Hornikx and Forssén [3], about the effect of diffusion on the reverberation time RT10 in a street. Indeed, it was shown that the RT10 is longer for specular façades than for façades with diffusion patches. Conversely, as already discussed by Kang [2], the EDT with specular reflection is shorter than for all other reflection laws: with specular reflection, the image sources by building façades are well separated, leading to lower ratio of initial to later energy than for a diffuse reflection. Finally, it can be also noted that, excepted for the specular reflection, all reflection laws produces a linear decay, including the semi-diffuse reflections. Thus, it seems that a linear sound decay can be obtained with a minimum of sound diffusion around the specular reflection. More diffuse is the reflection law, more faster the linear decay appears.

3.1.3. Conclusion

At first, considering all results, and as already shown by several authors, by adding diffusion on the building façades, it increases the sound decay and the sound attenuation. Moreover, due to the back-diffusion effect, the sound pressure level increases close to the sound source while it decreases for larger distances. More precisely, the uniform reflection law (UN) seems to have the more significant effect on the absolute sound pressure level, as well as on the sound attenuation (Table II). Near to the sound source, the sound attenuation is very close to the specular one. When the distance from the sound source increases, the absolute sound pressure level obtained with the uniform reflection law is lower than for all other reflection laws, excepted at the street extremities where particular effects occur. On average, the sound level difference $\overline{\Delta L}$ between the uniform reflection and the specular one is almost 1 dB. However, this difference increases along the street, to reach 4 dB at the first street extremity.

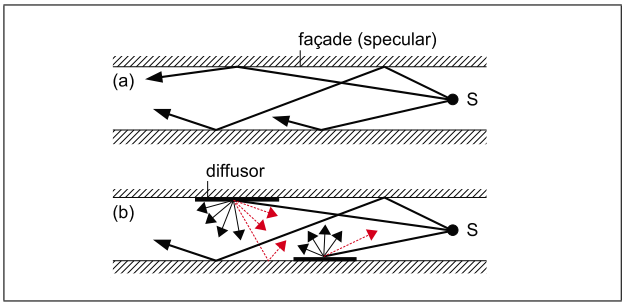

Figure 3. Illustration of the horizontal back-diffusion effects: (a) perfectly specular reflection on façades; (b) façades with acoustic diffusors producing diffusion and particularly back-diffusion (red arrows with dashed lines).

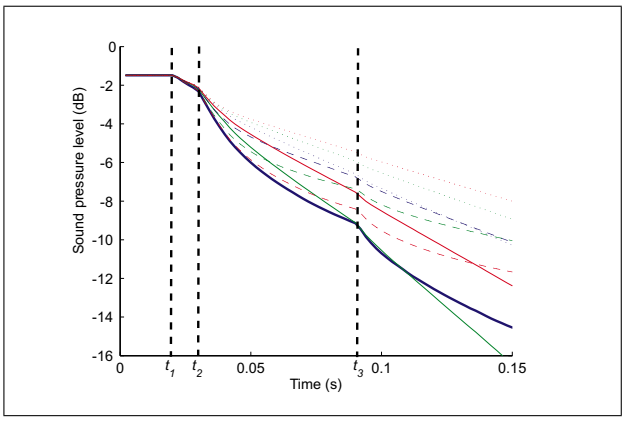

Figure 4. Illustration of the effect of sound absorption by the openings at the top (at time t_1), at the end extremity at $y = 40$ m (close to the source, at time t_2), and at the first extremity at $y = 0$ m (at time t_3), on the sound decay, for each reflection law (zoom of Figure 2).

As mentioned above, the absolute sound pressure level and the sound attenuation coefficient m are not systematically correlated: although the absolute sound pressure level is low for the uniform law, the sound attenuation m is not the greatest one.

The sound decay for the uniform reflection law is also very important, with a decrease of RT30 around 80% in comparison with the specular reflection. Excepted with the Lambert's one, RT30 for all other reflection laws are more than twice than for the uniform reflection.

In conclusion, the uniform reflection law seems to have the most significant effects on the sound propagation in the street, both in terms of absolute sound pressure level, sound attenuation and sound decay. However, close to the sound source and for the first times of arrival of the sound energy at a receiver, the specular reflection seems to produce the same effects. At this step, and in a practical point of view, these results would suggest that it could be interesting to leave unchanged part of the façade that is very close to the sound source, while treating the other part using diffusors with uniform reflection. However, as it will be presented in section 3.3.4 about the RA configuration, this suggestion is not valid because of the back-diffusion effect.

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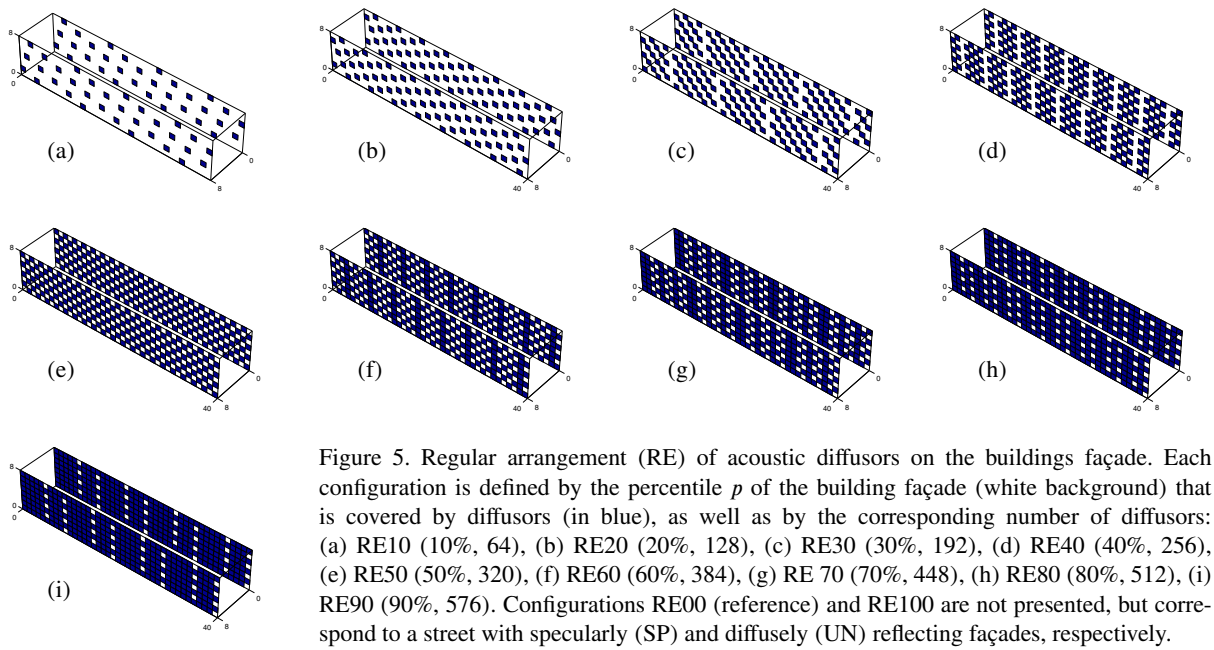

Figure 5. Regular arrangement (RE) of acoustic diffusors on the buildings façade. Each configuration is defined by the percentile p of the building façade (white background) that is covered by diffusors (in blue), as well as by the corresponding number of diffusors: (a) RE10 (10%, 64), (b) RE20 (20%, 128), (c) RE30 (30%, 192), (d) RE40 (40%, 256), (e) RE50 (50%, 320), (f) RE60 (60%, 384), (g) RE 70 (70%, 448), (h) RE80 (80%, 512), (i) RE90 (90%, 576). Configurations RE00 (reference) and RE100 are not presented, but correspond to a street with specularly (SP) and diffusely (UN) reflecting façades, respectively.

3.2. Effect of the relative surface of diffusors

In a realistic street, due to the presence of windows and doors particularly, a façade can not be entirely treated with acoustic diffusors. Thus, it is important to evaluate the relative surface p of diffusors (in %), in comparison with the whole surface of the building façade, that produces a significant effect on the sound propagation in the street. The effect of the diffusors arrangement will be examined in section 3.3. In the present study, only regular arrangement (RE) with diffusors of size 1 m×1 m, with varying relative surface p (from 0 to 100%) are considered (Figure 5).

Diffusors are characterized by a perfectly uniform reflection law ($\delta_d = 1$, $\alpha_d = 0$), while the building façades produce perfectly specular reflections ($\delta_f = 0$, $\alpha_f = 0$). Configurations RE00 ($p = 0\%$) and RE100 ($p = 100\%$) correspond to a façade without diffusor (reference configuration SP) and a façade entirely covered by diffusors (UN configuration) respectively. The two last configurations have already been studied in the last section. The global sound attenuation and the sound decay in the street are presented at Figure 6 for several values of the relative surface p.

3.2.1. Sound attenuation

As expected, Figure 6a and Table III firstly show that the absolute sound pressure level decreases with p and secondly that the sound attenuation increases with p. Close to the sound source, the sound attenuation is however less influenced by the relative surface p, while the sound level difference increases with the distance from source. At the first street extremity ($y = 0$), the sound level difference is almost 3 dB for $p = 50\%$ and 4 dB for $p = 100\%$ respectively, in comparison with the reference configuration RE00.

3.2.2. Sound decay

Concerning the sound decay, and as expected again, Figure 6b and Table III shows that the sound decay decreases in the street when the relative surface of diffusors increases. Moreover, the decay curves also become more linear when p increases: from $p = 50\%$, the sound decay is mainly linear on the range $[0, -40]$ dB.

It must be noted that the sound decay curves for $p = 20\%$ and $p = 30\%$ are switched, although all other results (as well as for the sound attenuation) are logically ordered with p. This particular behavior may be due to the presence (or not) of acoustics diffusors at special location close to the sound source.

3.2.3. Conclusion

When the relative surface of acoustic diffusors is greater than 50% (RE50 and the following configurations), the sound decay and the sound attenuation are mainly similar: discrepancies with the configuration RE100 (i.e. the building façade is entirely diffusing) are less than 8% for RT30 and 10% for m. As example, in comparison with the reference configuration RE00, the RT30 decreases of 80% and the sound attenuation increases of 48% for the configuration RE50.

In practice, it would be difficult to treat 50% of the building façades with diffusors). It can be observed that with $p = 20\%$, the RT30 decreases of almost 75%, and the sound attenuation increases of 24%, which is already a significant noise reduction. In conclusion, even with 20% of the building façade by acoustic diffusors with uniform diffusion, the effects on the sound decay and on the sound attenuation are significant. By increasing the relative surface of diffusors, it increases these effects. However, from $p = 50\%$, the results are almost unchanged.

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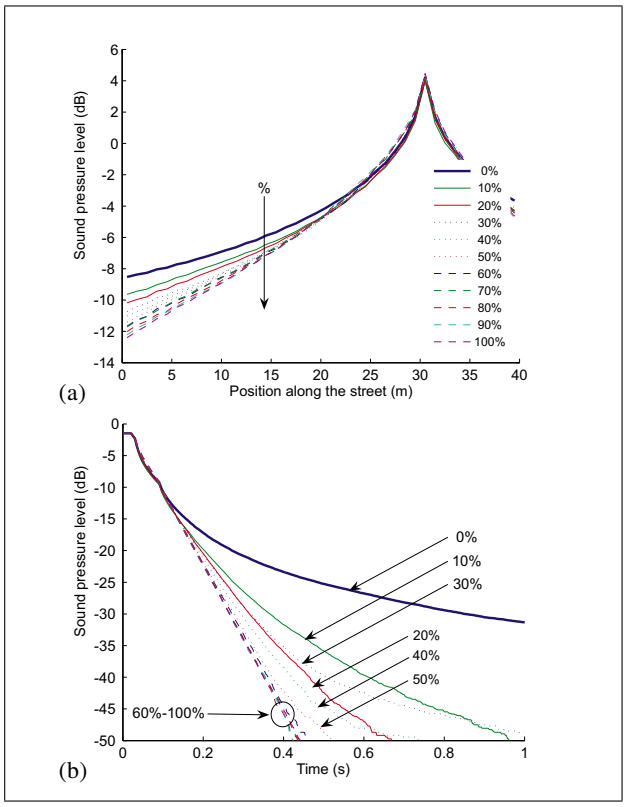

Figure 6. Effect of the relative surface p (in %) of acoustic diffusors, on the sound propagation along the street: (a) sound attenuation and (b) sound decay in the street. Percentile are relative to the surface of the building façade covered by diffusors (see Figure 5). Configurations RE00 (0%) and RE100 (100%) correspond to a street with specularly (SP) and diffusely (UN) reflecting façades, respectively.

3.3. Effect of the diffusors arrangement

The sound propagation in a street can also be influenced by the diffusors arrangement on the building façades. Several kinds of configurations have then been studied in this Section, with the same relative surface of diffusors $p = 50\%$.

In particular, the overall coverage of one façade has been considered: left façade (LF, Figure 7b) or right façade (RF, Figure 7a). Alternative configurations have also been studied: firstly by considering one horizontal arrangement of diffusors at several façade heights: on the lower part of the façade (LO, Figure 7d, from $z = 0\,\text{m}$ to $z = 4\,\text{m}$), middle part (MI, Figure 7e, from $z = 2\,\text{m}$ to $z = 6\,\text{m}$), and upper part (UP, Figure 7f, from $z = 4\,\text{m}$ to $z = 8\,\text{m}$); secondly, by considering diffusors only on the half of the façades, away from the source (HA, Figure 7g) or close to the source (HC, Figure 7h); thirdly by considering the center of both façades only (CE, Figure 7i). Moreover, considering that doors and windows are often evenly distributed on a façade, with a vertical and a horizontal alignment, one-dimensional (1D) and two-dimensional (2D) regular diffusors arrangements have also been studied: vertical alignment (1D diffusion, VE, Figure 7k), horizontal alignment (1D diffusion, HO, Figure 7k) and regular arrangement (2D diffusion, RE, Figure 7l). One can consider that the horizontal alignment creates a vertical diffusion (diffusion along the street height), while the vertical alignment creates a horizontal diffusion (diffusion along the street length). Lastly, the random disposition (RA, Figure 7c) has also been studied.

Table III. Effect of the surface ratio of diffusors on the sound propagation in a street, in terms of global sound decay (RT30, EDT) and sound attenuation (m, $\overline{\Delta L}$). Symbol * mentions configurations that have a significant effect of the noise reduction in the street. The relative deviation σ_m and σ_{RT} (in %) by comparison with the reference configuration SP is also given in parenthesis.

Surface ratio	RT30 (s)	EDT (s)
RE10	0.95 (66%)	0.51 (6%)
RE20	0.70 (75%)	0.52 (4%)
RE30	0.73 (74%)	0.53 (2%)
RE40	0.62 (78%)	0.56 (−4%)
RE50*	0.55 (80%)	0.53 (2%)
RE60*	0.53 (81%)	0.53 (2%)
RE70*	0.52 (81%)	0.54 (0%)
RE80*	0.52 (81%)	0.53 (2%)
RE90*	0.51 (82%)	0.53 (2%)
Surface ratio	**m (dB/m)**	**$\overline{\Delta L}$ (dB)**
RE10	0.29 (−16%)	0.54
RE20	0.31 (−24%)	0.66
RE30	0.33 (−32%)	0.77
RE40	0.35 (−40%)	0.81
RE50*	0.37 (−48%)	0.87
RE60*	0.37 (−48%)	0.93
RE70*	0.39 (−56%)	0.91
RE80*	0.40 (−60%)	0.98
RE90*	0.41 (−64%)	1.01

Diffusors and building façades are characterized by a perfectly uniform reflection law ($\delta_d = 1$, $\alpha_d = 0$) and a perfectly specular law ($\delta_f = 0$, $\alpha_f = 0$) respectively.

Results are given at Figure 8 and Table IV.

3.3.1. Effect of diffusors located on one façade only

As expected, configurations LF and RF give almost the same sound attenuation (Figure 8a). The small difference that can be observed for the coefficient of sound attenuation m (Table IV) is mainly due to the fact that simulations are based on random number generations for the sound emission as well as for the sound reflection by building façades and diffusors. Then, even for the same configuration, two numerical simulations do not give exactly the same results. Thus, for the LF and RF configurations, even if the sound source is not accurately at the same distance from the left and the right façades, it was expected that results are similar for the sound attenuation as well for the sound decay.

Moreover, these results show that the difference with the UN configuration, for which the number of diffusors is twice the amount ($p = 100\%$), is not significant. It suggests that it is not necessary to treat entirely both façades (with $p = 100$), but only one (with $p = 50$), to obtain the

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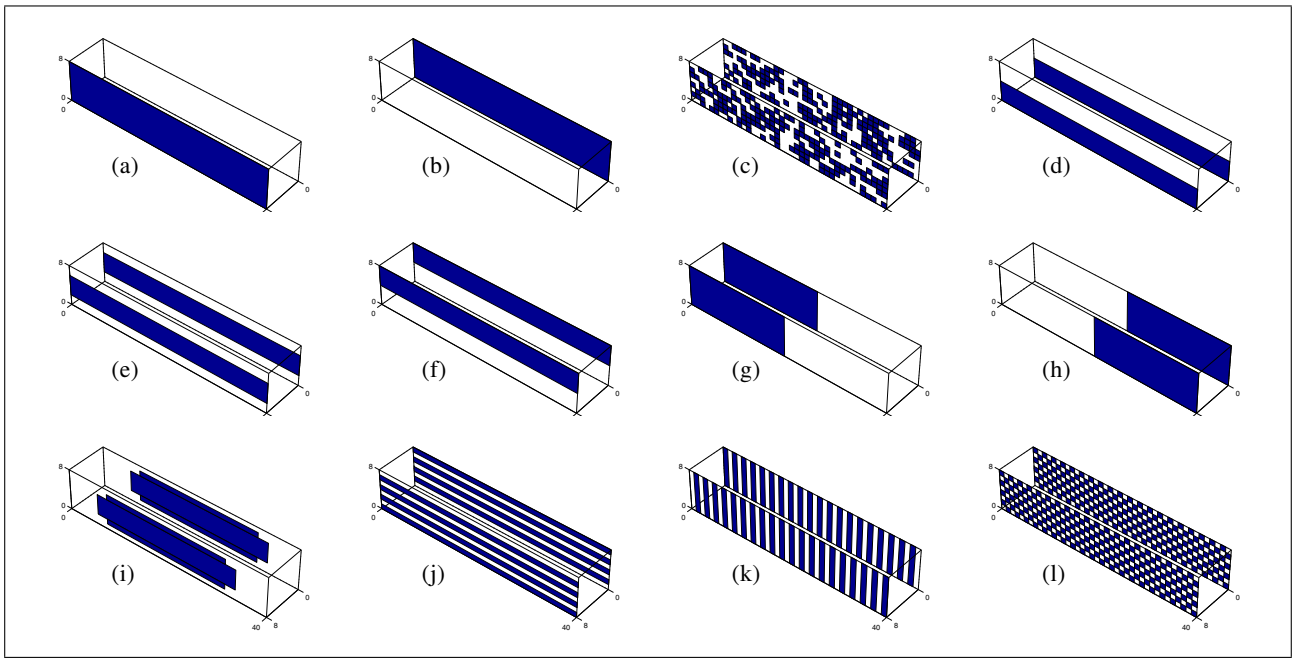

Figure 7. Diffusors arrangement (in blue) on the building façades, with $p = 50\%$: (a) right façade (RF), (b) left façade (LF), (c) random arrangement (RA), (d) lower part of the façade (LO), (e) middle part (MI), (f) upper part (UP), (g) half-part of the façade away from the sound source (HA), (h) half-part of the façade close to the sound source (HC), (i) center of the façade (CE), (j) horizontal arrangement (HO), (k) vertical arrangement (VE), (l) regular arrangement (RE).

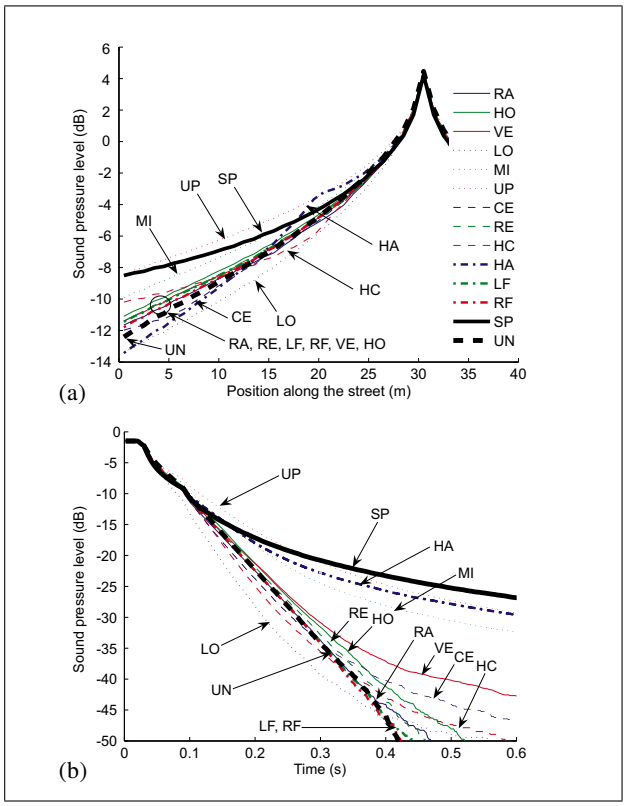

Figure 8. Effect of the diffusors arrangement on the sound propagation along the street (see Figure 7): (a) sound attenuation and (b) sound decay in the street.

same effect. Since the results for the LF and RF configurations are very close to the one obtained with the RA configuration, it also suggests that the diffusors can be shared out on both façades with similar results.

3.3.2. Effect of a regular diffusors arrangement

The results for the configurations VE (horizontal diffusion), HO (vertical diffusion) and RE (two-dimensional diffusion) are quite equivalent. For the sound decay, the vertical arrangement gives a little bit longer RT30 (0.63 s) than for the horizontal and regular alignment (0.57 s and 0.55 s respectively). This result is coherent with those obtained by Hornikx and Forssén [3], showing that vertical diffusion gives a longer sound decay than horizontal diffusion, since more energy is scattered out of the street in the case of diffusion elements oriented horizontally. More accurately, the sound decay is also a little bit more linear and shorter for the RE configuration, than for the HO and the VE configurations. It suggests that it is more efficient to use a 2D-regular diffusors arrangements like RE, instead a 1D-regular arrangement. This results is also confirmed by the RA configuration (2D random) that gives similar results to the RE configuration. For the sound attenuation, the difference is also very low, as already shown by Hornikx and Forssén [3], for the vertical and the horizontal diffusion. However, it slightly seems more efficient to use a vertical arrangement of diffusors to reduce the noise level in the street ($\overline{\Delta L} = 0.92$ dB), instead a horizontal one ($\overline{\Delta L} = 0.71$ dB), but also instead a regular one, although this last configuration produces the best sound decay. It confirms that the best sound attenuation is not correlated with the best sound decay systematically.

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Table IV. Effect of the diffusor arrangement on the sound propagation in a street, in terms of global sound decay (RT30, EDT) and sound attenuation (m, $\overline{\Delta L}$). Symbol * mentions configurations that have a significant effect of the noise reduction in the street. The relative deviation σ_m and σ_{RT} (in %) by comparison with the reference configuration SP is also given in parenthesis.

Arrangement	RT30 (s)	EDT (s)
Full façades (RF)	0.52 (81%)	0.53 (2%)
Full façades (LF)	0.52 (81%)	0.53 (2%)
Random (RA)	0.54 (81%)	0.45 (17%)
Horizontal bands (LO*)	0.42 (85%)	0.46 (15%)
Horizontal bands (MI)	1.96 (30%)	0.61 (−13%)
Horizontal bands (UP)	2.30 (18%)	0.73 (−35%)
Half façade (HA)	2.43 (13%)	0.57 (−6%)
Half façade (HC)	0.47 (83%)	0.53 (2%)
Façade center (CE)	0.53 (81%)	0.52 (4%)
Regular (HO)	0.57 (80%)	0.59 (−9%)
Regular (VE)	0.63 (78%)	0.53 (2%)
Regular (RE)	0.55 (80%)	0.56 (−4%)
Arrangement	m (dB/m)	$\overline{\Delta L}$ (dB)
Full façades (RF)	0.36 (−44%)	0.90
Full façades (LF)	0.38 (−52%)	0.99
Random (RA)	0.36 (−44%)	1.05
Horizontal bands (LO*)	0.43 (−72%)	1.93
Horizontal bands (MI)	0.32 (−28%)	0.12
Horizontal bands (UP)	0.28 (−12%)	−0.58
Half façade (HA)	0.50 (−100%)	0.99
Half façade (HC)	0.31 (−2%)	0.91
Façade center (CE)	0.40 (−60%)	1.20
Regular (HO)	0.36 (−44%)	0.71
Regular (VE)	0.36 (−44%)	0.92
Regular (RE)	0.36 (−44%)	0.88

3.3.3. Effect of horizontal arrangement of diffusors

The discussion is now carried on the LO, MI, and UP configurations. Figure 8 shows that the effect of diffusors is better when they are located close to the pavement, then closer to the sound source (LO configuration): both UP and MI configurations give a lower sound attenuation and smaller sound decay, while the LO configuration gives the larger sound attenuation and the faster sound decay simultaneously. In comparison with the reference configuration (SP), the decrease of RT30 is almost 85% for the LO configuration, while it is only 30% and 18% for the MI and UP configurations respectively. The sound level difference is around 2 dB for the LO configuration, while it is quite null for the MI configuration. Conversely the UP configuration produces an increase of the sound pressure level ($\overline{\Delta L} = -0.58$ dB).

As in section 3.1.1, this results can be explained by the back-diffusion effect described by Figure 9, for a vertical diffusion. Without acoustic diffusors (Figure 9a), only specular reflection occurs. When these reflections are located above of a given height on the façade, the sound energy quickly disappears from the propagation domain through the top aperture. Conversely, if these reflections occur on acoustic diffusors (Figure 9b), a part of the sound energy comes back to the street floor due to vertical back-diffusion. It explains particularly why the UP configuration produces an increase of the sound pressure level. However, when the diffusors are located at the source height (Figure 9c), many diffuse reflections occur, instead of specular reflection, increasing the amount of sound energy that disappears from the street through the openings.

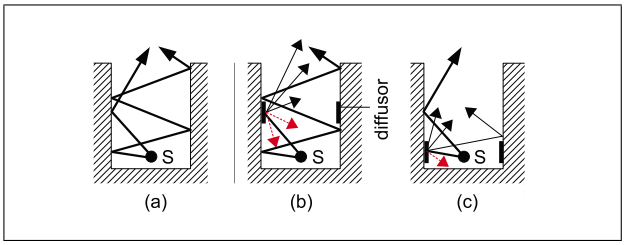

Figure 9. Illustration of the vertical back-diffusion effects: (a) perfectly specular reflection on façades; (b) façades with acoustic diffusors high up (MI and UP configurations); (b) façades with acoustic diffusors close to the pavement (LO configuration). The vertical back-diffusion is represented by red arrows with dashed lines.

For the same reason, the LO configuration is also better than the LF or the RF configurations, both for the sound pressure level and the sound attenuation. It seems more interesting to treat only the lower part of the façades than entirely one side, whereas the number of acoustics diffusors is exactly the same in the street. Moreover, the LO configuration ($RT30 = 0.42$ s and $\overline{\Delta L} = 1.93$ dB with $p = 50\%$) also gives better results than the UN configuration ($RT30 = 0.51$ s and $\overline{\Delta L} = 1.03$ dB with $p = 100\%$), whereas the number of diffusors is the half.

3.3.4. Effect of diffusors on the half of the façades

When diffusors are located close to the sound source (HC configuration), the sound decay is very large due to the multiple diffuse reflections that increase the loss of sound energy through the openings. The sound attenuation is also very large close to the sound source, but decreases in the second half of the street (without diffusors).

Conversely, for the HA configuration, the sound decay is very close to the one obtained with the specular reflection, since there is no diffusors close to the source. The behavior of the sound attenuation for the HA configuration is however a little bit more complicated: the sound attenuation is first very low close to the source, although there is no diffusors, but increases considerably when passing from the part of the street without diffusors to the part with diffusors. Here again, this increase of the sound pressure level close to the source is due to the back-diffusion effect. The last result is then in contradiction with the suggestion presented in section 3.1, which proposes to not treat the building façades close to the sound source, since the sound attenuation curve for the specular reflection was equivalent to the one obtained with the uniform reflection. Indeed, due to the back-diffusion effect, the sound pressure level in the second part of the street (where the sound source is

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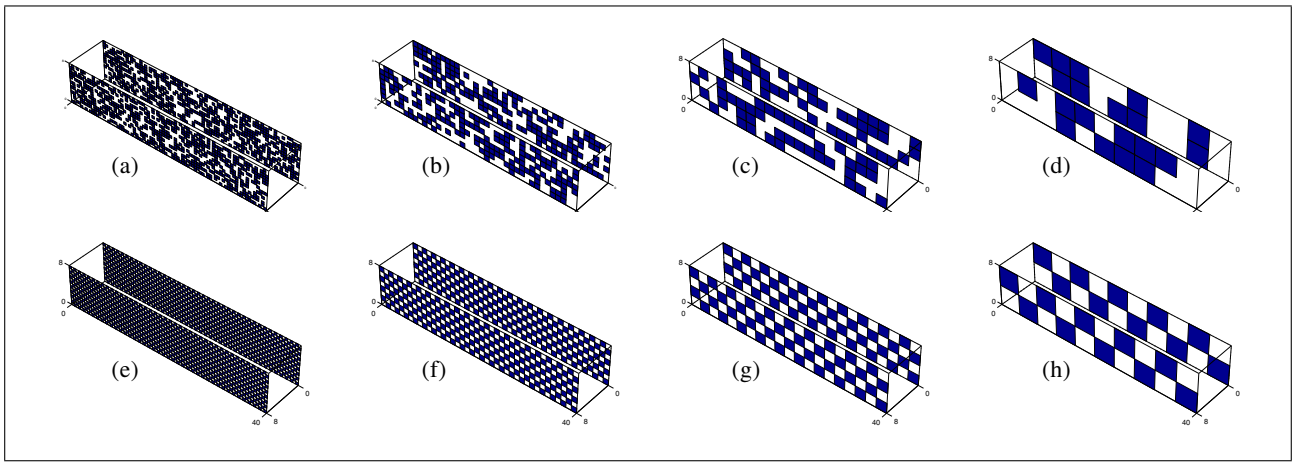

Figure 10. Random and regular arrangement of acoustic diffusors of different sizes. Random arrangement of diffusors of size: (a) 0.5 m×0.5 m (RA05), (b) 1 m×1 m (RA1), (c) 2 m×2 m (RA2), (d) 4 m×4 m (RA4). Regular arrangement of diffusors of size: (e) 0.5 m×0.5 m (RE05), (f) 1 m×1 m (RE1), (g) 2 m×2 m (RE2), (h) 4 m×4 m (RE4). 50% of the building façades is covered by diffusors.

located) is increased by the sound field that is diffused by the diffusors on the first part of the street (Figure 3).

3.3.5. Conclusion

In conclusion, the diffusors arrangement can have an significant effect of the sound propagation in the street. Best results are obtained for the sound attenuation and the sound decay simultaneously, by arranging acoustic diffusors close to the source, and if possible at the same height (LO configuration). Conversely, if diffusors are located higher on the building façade, due to the vertical back-diffusion effect, it increases the sound pressure level, as well as the decay, in the street. This result is different from those obtained by Kang [2], where it was shown that the absorber arrangement plays an insignificant role for the sound field. However, in the Kang's study, only vertical and horizontal absorber arrangements (similar to the VE and HO configurations) on one or two façades have been examined.

Another interesting results is that increasing the number of acoustic diffusors do not enhance the noise reduction in the street. Indeed simulations for the LO configuration (with $p = 50\%$) gives better results than for the UN configuration (with $p = 100\%$). The location of diffusors is then more important than the number of diffusors.

3.4. Effect of the size of diffusors

In this section, the effect of the size of the diffusors is studied by considering random and regular distribution of diffusors of size 0.5 m×0.5 m, 1 m×1 m, 2 m×2 m, and 4 m×4 m (Figure 10), with the same relative surface of diffusors $p = 50\%$. Diffusors and building façades are still characterized by a perfectly uniform reflection law ($\delta_d = 1$, $\alpha_d = 0$) and a perfectly specular law ($\delta_f = 0$, $\alpha_f = 0$) respectively.

Results are given at Figure 11 and detailed in Table V. As long as the relative surface of diffusors is constant, the effect of the size of diffusors is not significant, neither on the sound attenuation, nor on the sound decay. However, one can barely observed that the RA4 configuration is a little bit better, both for the sound attenuation and the sound decay. This result shows that, in the case of a uniform arrangement of diffusors, the main parameter is the relative surface of diffusors, and not the size of the acoustic diffusors.

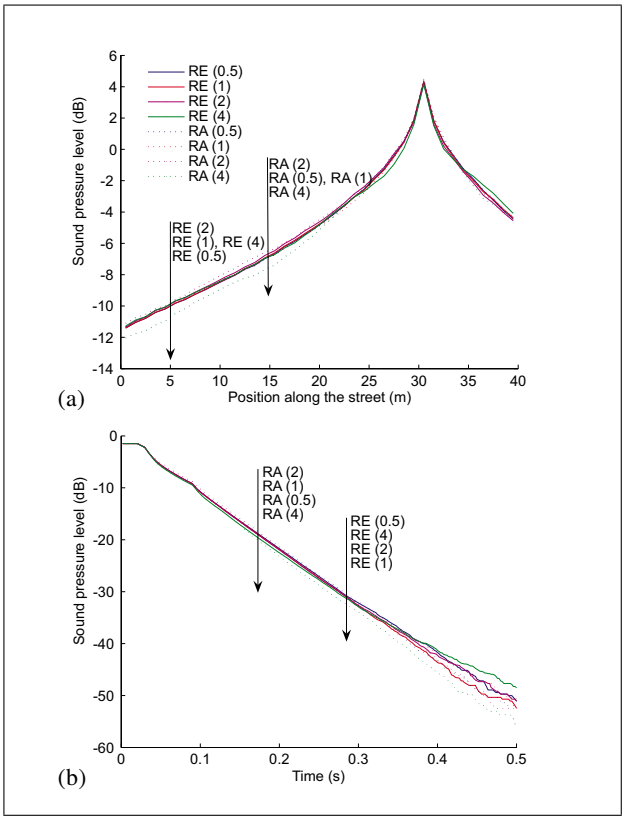

Figure 11. Effect of the size of acoustic diffusors on the sound propagation along the street (see Figure 10 for the abbreviation description): (a) sound attenuation and (b) sound decay in the street. Continuous lines: RE; Dotted lines: RA.

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Table V. Effect of diffusor size on the sound propagation in a street, in terms of global sound decay (RT30, EDT) and sound attenuation (m, $\overline{\Delta L}$). Symbol * mentions configurations that have a significant effect of the noise reduction in the street. The relative deviation σ_m and σ_{RT} (in %) by comparison with the reference configuration SP is also given in parenthesis.

Diffusor size	RT30 (s)	EDT (s)
RE05	0.56 (80%)	0.53 (2%)
RE1	0.55 (80%)	0.56 (−4%)
RE2	0.55 (80%)	0.53 (2%)
RE4*	0.56 (80%)	0.51 (6%)
RA05	0.55 (80%)	0.57 (−6%)
RA1	0.56 (80%)	0.53 (2%)
RA2	0.55 (80%)	0.56 (−4%)
RA4	0.52 (81%)	0.54 (0%)
Diffusor size	m (dB/m)	$\overline{\Delta L}$ (dB)
RE05	0.36 (−44%)	0.89
RE1	0.36 (−44%)	0.89
RE2	0.37 (−48%)	0.83
RE4*	0.35 (−40%)	0.89
RA05	0.36 (−44%)	0.85
RA1	0.35 (−40%)	0.92
RA2	0.36 (−44%)	0.67
RA4	0.39 (−56%)	1.23

3.5. Combined effect of absorption and diffusion by diffusors

In order to evaluate the combined effect of absorption and diffusion by diffusors on the noise reduction in a street, several absorption configurations have been studied on the basis of the LO, LF and RA diffusors configurations, which have been presented in the last sections as the more interesting one. As detailed in Table VI, 9 absorption configurations (A0 to A8) have been considered for each one of the three configurations: 3 configurations (A6, A7 and A8) with the same absorption both on the diffusors and on the façades with $\bar{\alpha} = 0.1$, 0.3 and 0.5; 3 configurations (A1, A3, and A4) with absorption only on the diffusors with $\alpha_d = 0.1$, 0.3 and 0.5 ; and 2 configurations (A2 and A5 with $\alpha_d = 0.2$ and 0.6 respectively) with absorption only on the diffusors but in order to have the same mean absorption as configurations A6 and A7. A reference configuration A0, without absorption ($\alpha_f = \alpha_d = 0$) is also considered. For all configurations, the relative surface of diffusors is fixed to $p = 50\%$ and the size of diffusors is 1 m×1 m. Diffusors are defined by an uniform reflection law ($\delta_d = 1$), while building façades are perfectly specular ($\delta_f = 0$). Results are shown at Figure 12 and detailed in Table VI.

As expected for the 3 configurations LO, LF and RA, both the sound decay and the sound attenuation increase with the mean absorption coefficient. On average for all configurations, the RT30 decreases on the order of 7% to 38% for $\bar{\alpha} = 0.05$ to 0.50 respectively. For the mean sound level difference $\overline{\Delta L}$, the increase is on the order of 0.3 dB to 3 dB. There is however one exception for the A7 ($\bar{\alpha} = 0.30$) and A4 ($\bar{\alpha} = 0.25$) absorption configurations, applied to the LO configurations. Indeed, the results are switched for the sound attenuation (Figure 12a) and for

Table VI. Effect of absorption of the sound propagation in a street, in terms of global sound decay (RT30, EDT) and sound attenuation (m, $\overline{\Delta L}$), for 9 absorption configurations A0 to A8, for each of the LO, LF and RA configurations. $\bar{\alpha}$ is the mean absorption of the façades. Absorption configurations have been sorted by the mean absorption coefficient. The relative deviations σ_m and σ_{RT} (in %) with the reference configuration A0 is also given in parenthesis.

	α_f	α_d	$\bar{\alpha}$	
A0	0.00	0.00	0.00	
A1	0.00	0.10	0.05	
A6	0.10	0.10	0.10	
A2	0.00	0.20	0.10	
A3	0.00	0.30	0.15	
A4	0.00	0.50	0.25	
A7	0.30	0.30	0.30	
A5	0.00	0.60	0.30	
A8	0.50	0.50	0.50	
Results for LO configuration				
	RT30 (s)	EDT (s)	m (dB/m)	$\overline{\Delta L}$ (dB)
A0	0.42	0.46	0.43	—
A1	0.39 (7.1%)	0.43 (6.5%)	0.43 (0.0%)	0.39
A6	0.36 (14.3%)	0.43 (6.5%)	0.43 (0.0%)	0.49
A2	0.37 (11.9%)	0.41 (10.9%)	0.43 (0.0%)	0.78
A3	0.35 (16.7%)	0.38 (17.4%)	0.44 (−2.3%)	1.18
A4	0.31 (26.2%)	0.33 (28.3%)	0.45 (−4.7%)	1.99
A7	0.31 (26.2%)	0.36 (21.7%)	0.45 (−4.7%)	1.45
A5	0.28 (33.3%)	0.31 (32.6%)	0.45 (−4.7%)	2.40
A8	0.26 (38.1%)	0.31 (32.6%)	0.46 (−7.0%)	2.41
Results for LF configuration				
	RT30 (s)	EDT (s)	m (dB/m)	$\overline{\Delta L}$ (dB)
A0	0.52	0.53	0.38	—
A1	0.49 (5.8%)	0.50 (5.7%)	0.39 (−2.6%)	0.32
A6	0.46 (11.5%)	0.51 (3.8%)	0.40 (−5.3%)	0.64
A2	0.46 (11.5%)	0.47 (11.3%)	0.40 (−5.3%)	0.63
A3	0.43 (17.3%)	0.44 (17.0%)	0.41 (−7.9%)	0.96
A4	0.37 (28.8%)	0.37 (30.2%)	0.42 (−10.5%)	1.62
A7	0.37 (28.8%)	0.41 (22.6%)	0.42 (−10.5%)	1.84
A5	0.34 (34.6%)	0.33 (37.7%)	0.43 (−13.2%)	1.96
A8	0.30 (42.3%)	0.33 (37.2%)	0.44 (−15.8%)	2.99
Results for RA configuration				
	RT30 (s)	EDT (s)	m (dB/m)	$\overline{\Delta L}$ (dB)
A0	0.53	0.50	0.37	—
A1	0.53 (0.0%)	0.54 (8.0%)	0.37 (0.0%)	0.16
A6	0.49 (7.5%)	0.52 (−4.0%)	0.39 (−5.4%)	0.54
A2	0.49 (7.5%)	0.48 (4.0%)	0.36 (−2.7%)	0.66
A3	0.46 (13.2%)	0.47 (6.0%)	0.40 (−8.1%)	0.82
A4	0.41 (22.6%)	0.41 (18.0%)	0.40 (−8.1%)	1.40
A7	0.37 (30.2%)	0.41 (18.0%)	0.42 (−3.5%)	1.56
A5	0.37 (30.2%)	0.37 (26.0%)	0.39 (−5.4%)	2.06
A8	0.29 (45.3%)	0.32 (36.0%)	0.43 (−16.1%)	2.94

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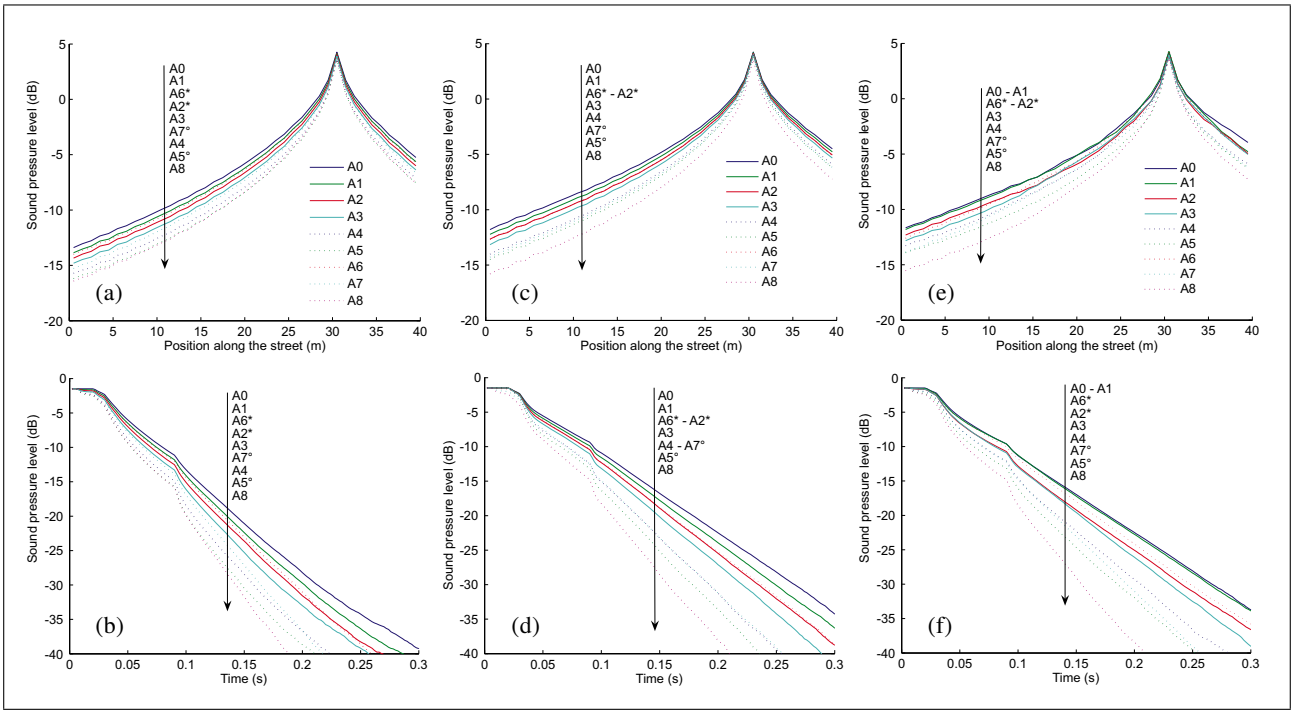

Figure 12. Effect of adding absorption on acoustic diffusors and on façades for 3 configurations of acoustic diffusors: (a) and (b) for LO; (c) and (d) for LF; (e) and (f) for RA. Upper figures: sound attenuation along the street. Lower figures: global sound decay in the street. Configurations marked with symbols $*$ and $\circ$ are characterized by the same mean absorption $\bar{\alpha} = 0.10$ and $\bar{\alpha} = 0.30$ respectively, but with different absorption coefficients on the diffusors and on the façades.

the mean sound level difference (Table VI): the A4 configuration gives a better result than the A7 configuration, although the mean absorption is lower. This is probably due to the presence of higher absorption close to the sound source (i.e. the presence of diffusors with $\alpha_d = 0.5$ close to the source), for the A4 absorption configuration, in comparison with the A7 absorption configuration ($\alpha_d = 0.3$).

The most important result is obtained by comparing absorption configurations with the same mean absorption coefficient, but with different absorption repartition between the diffusors and the façades. Indeed, the A5 absorption configuration gives better results than the A7 configurations for all configurations, for the sound attenuation as well for the sound decay, although they have exactly the same mean absorption coefficient ($\bar{\alpha} = 0.3$). This effect is also visible by comparing the sound attenuation and the sound decay curves presented at Figure 12 for the A6 and A2 configurations with $\bar{\alpha} = 0.3$. This result suggests that it is more efficient to localise absorption on diffusors instead of on the façades, for the same mean absorption coefficient.

3.6. Application to realistic streets

In the last sections, basic configurations have been studied in order to evaluate the effect of several diffusors parameters on the sound propagation in a street. Most of times, these basic configurations do not correspond to a realistic street. For example, due to the presence of façade irregularities, the sound reflection by a building façade is probably not fully specular but partially diffusing with absorption. Then, the set of values ($\alpha_f = 0, \delta_f = 0$) that has been considered in the last simulations, does not correspond to a realistic configuration. In this Section, diffusors are then applied to more realistic streets in order to evaluate their effects in a "real" situation.

3.6.1. Street geometry

Although there are numerous studies of sound propagation in urban areas, there is still very little information about the real values of the absorption and scattering coefficients of real building façades. Using a physical scale model, Ismail and Oldham have shown that the scattering coefficient could be on the order of 0.09-0.13 for façades with surface irregularities similar to those found in real building façades, that is comparable in magnitude to the absorption coefficient used most of time for the modeling of sound propagation in urban areas [7]. On the basis of numerical simulations and experimental data, Onaga and Rindel have found that the sum of the absorption and the scattering coefficients of building façades could be on the range $[0.1, 0.25]$, for small height/width street ratio [8]. Considering all these recent results, arbitrary but plausible values have been considered in the present paper, using $\alpha_f = 0.1$ for the absorption coefficient and $\delta_f = 0.3$ for the scattering coefficient (30% of uniform reflection and 70% of specular reflection), such as $\alpha_f + \delta_f = 0.4$.

Moreover, in a practical point of view, due to the presence of doors and windows, but also for technical, economical or, even, for aesthetical reasons, it would probably not be possible to arrange all acoustic diffusors on the

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lower part of a façade, and let-alone, with a relative surface of diffusors on the order of $p = 50\%$. In the present study, diffusors of size 1 m × 1 m with $p = 20\%$ have then been considered. In addition, in order to evaluate the effects of the façades length and height, 3 street sizes have been considered: S1 ($8 \times 40 \times 8\,\mathrm{m}^3$), S2 ($8 \times 60 \times 8\,\mathrm{m}^3$) and S3 ($8 \times 60 \times 12\,\mathrm{m}^3$).

Since the last numerical simulations have shown that the lower part of a building façade seems the best position for the diffusors, 3 configurations have been studied here (Figure 13). Firstly, diffusors have been located on the lower part of the façades, between $z = 0$ and $z = H/4$ (H being the façade height), by means of 4 m pieces long with 1 m of separation. This configuration is noted L1 (Figure 13a), L2 and L3 for the streets S1, S2 and S3 respectively. Secondly, a succession of vertical bands has been considered, with diffusors located from $z = 0$ to $z = H/2$, each 2 m along the street length axis y (between $y = 4$ and $y = 36$ m for the street of 40 m long, and $y = 6$ and $y = 53$ m for the street of 60 m long). This configuration is noted V1 (Figure 13b), V2 and V3 for the streets S1, S2 and S3 respectively. Thirdly, a configuration with a single block of diffusors, centered on the façade length (between $z = 1$ and $z = 3$ for S1, and between $z = 1$ and $z = 4$ for S2 and S3), from $y = 4$ to $y = 36$ m for S1 and S2, and $y = 6$ to $y = 54$ m for S3. This configuration is noted C1 (Figure 13c), C2 and C3 for the streets S1, S2 and S3 respectively. Lastly, in order to compare the results with a basic configuration, a regular diffusors arrangement was also considered, noted R1 (Figure 13d), R2 and R3 for the streets S1, S2 and S3 respectively, with the same relative surface of diffusors $p = 20\%$.

3.6.2. Results

Results are presented at Figure 14 and detailed in Table VII. As, presented at Figures 14a and 14b for the street S1, results are similar for configurations L1, V1 and C1, both for the global sound attenuation and the sound decay. In accordance with the results of section 3.3, all these configurations, which are characterized by a location of diffusors on the lower part of the building façades, give better results than an uniform random distribution of diffusors on the entire façades (R1). This result is confirmed for the streets S2 and S3, as presented in Figures 14c and 14d. It suggests that the more important is the location of diffusors on the lower part of the façades, whatever their arrangement.

Tables II and VII for the street S1, show that results are better for the street S1 (L1, VI or C1, with $p = 20\%$) than for the UN configuration (street S1 with perfectly diffusing façades, and with $p = 100\%$), for the same street size. This is an interesting results since it shows that, by adding absorption, is not necessary to cover entirely the building façades to have an efficient noise reduction in the street.

In addition, and as already mentioned by Kang [2], as well as observed by Onaga and Rindel [8], Table VII shows that the reverberation times RT30 increases with the street length (+20% on average by from 40 m to 60 m) and the street height (+40% on average from 8 m to 12 m).

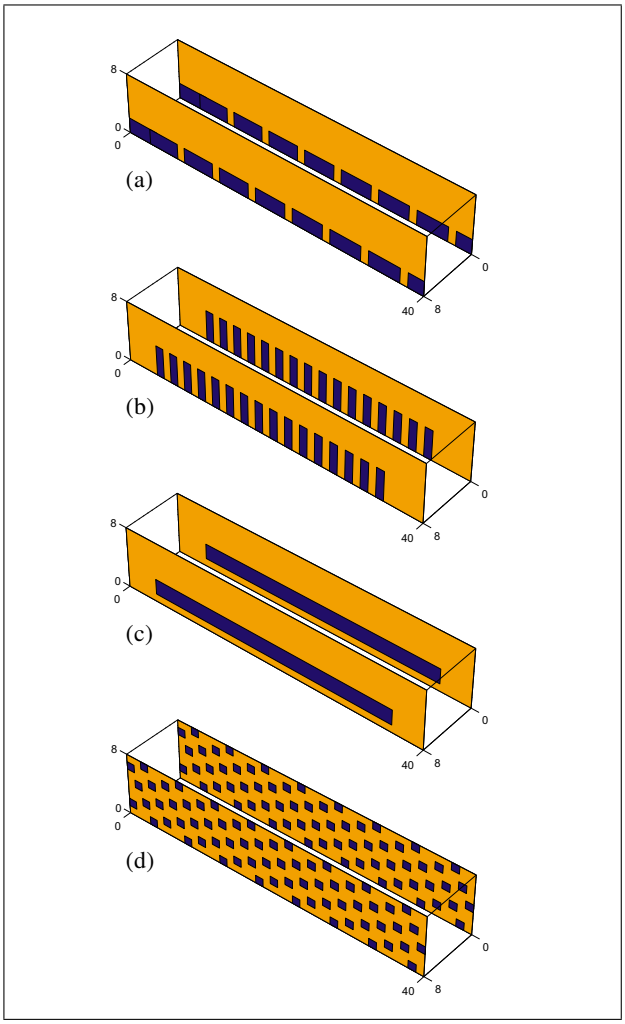

Figure 13. Arrangement of acoustics diffusors (in blue) on 20% of the building façades in a street S1 of size (width × length × height) $8 \times 40 \times 8\,\mathrm{m}^3$: (a) lower part of the façade (L1), (b) vertical arrangement (V1), (c) center of the façade (C1), (d) regular arrangement (R1). Similar configurations were also studied for the streets S2 and S3 of size $8 \times 60 \times 8\,\mathrm{m}^3$ (configurations noted L2, V2, C2 and R2) and $8 \times 60 \times 12\,\mathrm{m}^3$ (configurations noted L3, V3, C3 and R3).

4. Conclusion

Numerical simulations have been carried out in order to evaluate the effects of acoustic diffusors on the sound propagation in a street, then to determine if such device can be used to reduce noise in urban areas. At first, several parameters have been studied, among which, the reflection law (specular, uniform, Lambert, etc.), the relative surface of diffusors on building façades (from 0%, i.e. without diffusors, to 100%, i.e. entirely covered by diffusors), the diffusors arrangement (random, regular, etc.), the size of diffusors (from 0.5 m×0.5 m to 4 m×4 m), and finally by adding absorption on diffusors. Secondly, in order to evaluate the effects in real configuration, numerical simulations have also been carried out for more realistic streets, with mixed diffuse and specular reflection on façades ($\delta_f = 0.3$), a relative surface of diffusors on

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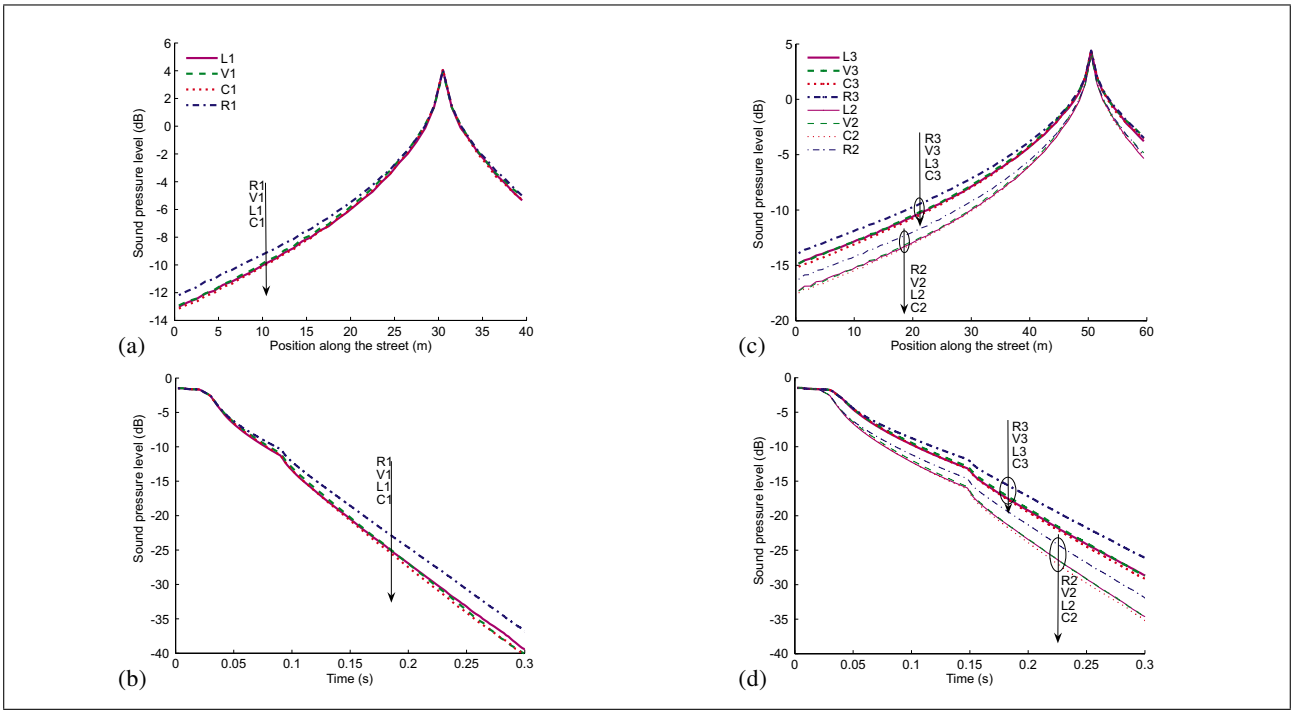

Figure 14. Sound propagation in the streets S1 of size $8 \times 40 \times 8\,\mathrm{m}^3$ (left curves), and S2-S3 of size $8 \times 60 \times 8\,\mathrm{m}^3$ and $8 \times 60 \times 12\,\mathrm{m}^3$ (right curves), for 4 diffusors arrangements (see Figure 13 for details): (a), (c) sound attenuation and (b), (d) sound decay in the street.

Table VII. Effect of acoustic diffusors on the sound propagation in 3 streets S1, S2 and S3 of size (width × length × height) $8\times40\times8\,\mathrm{m}^3$, $8\times60\times8\,\mathrm{m}^3$ and $8\times60\times12\,\mathrm{m}^3$, in terms of global sound decay (RT30, EDT) and sound attenuation (m), in function of the arrangement of 1 m×1 m diffusors on the building façades (see Figure 13).

Street	S1				S2				S3			
Size	$8 \times 40 \times 8\,\mathrm{m}^3$				$8 \times 60 \times 8\,\mathrm{m}^3$				$8 \times 60 \times 12\,\mathrm{m}^3$			
(α_f, δ_f, R)	(0.1, 0.3, UN)				(0.1, 0.3, UN)				(0.1, 0.3, UN)			
(α_d, δ_d, R)	(0.1, 1.0, UN)				(0.1, 1.0, UN)				(0.1, 1.0, UN)			
p (%)	20%				20%				20%			
Arrangement	L1	V1	C1	R1	L2	V2	C2	R2	L3	V3	C3	R3
RT30 (s)	0.45	0.43	0.43	0.49	0.55	0.52	0.52	0.58	0.63	0.62	0.61	0.68
EDT (s)	0.44	0.46	0.45	0.49	0.44	0.47	0.45	0.52	0.61	0.64	0.61	0.72
m (dB/m)	0.40	0.40	0.41	0.37	0.23	0.24	0.24	0.22	0.22	0.23	0.23	0.22

building façades of 20% located on the lower part of the façades, and by considering a classical absorption coefficient of 0.1 both for the façades and the diffusors. The numerical results have shown that, most of the time, the use of acoustic diffusors allows to reduce noise, by increasing the sound attenuation and decreasing the sound decay in the street. More precisely, it has been shown that:

- in comparison with the specular reflection, the effect of diffusion on the sound pressure level appears as an increase at short distances from sources, and as a decrease at larger distances. Moreover, the sound decay is shorter for diffuse reflection law than for specular one. Lastly, it seems that a linear sound decay can be obtained with a minimum of diffusion around the specular reflection. Finally, considering all reflection laws, the uniform reflection law produces the best noise reduction in a street, both for the global reverberation time and the absolute sound pressure level in the street;
- by increasing the relative surface of diffusors (i.e. by increasing the number of diffusors or by increasing the size of diffusors), it improves the sound attenuation and the sound decay in the street;
- the location of diffusors can be more important than the number of diffusors: by arranging diffusors on the lower part of both façades or on only one façade surface ($p = 50\%$ in both cases), it gives better results than by covering entirely both façades ($p = 100\%$). In addition, it also seems more efficient to use a two-dimensional arrangement of diffusors (random or regular) than a one-dimensional arrangement.
- as expected, noise reduction can also be increased by adding absorption on diffusors. Nevertheless, as long as the mean absorption is constant, best results are obtained when absorption is localised on diffusors instead of on building façades.

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In a theoretical point of view, the use of acoustics diffusors to reduce noise in streets seems a possible solution. Considering the last results, to have a significant effect, it requires:

- to develop diffusors producing uniform diffusion on the frequency band of interest, which corresponds in practice to the traffic noise spectrum in urban areas. This can be done for example by considering one-dimensional or two-dimensional Schroeder diffusors, designed for the desired bandwidth [1];
- to consider a relative surface of diffusors larger than 20%;
- to arrange diffusors on the lower part of the building façades, around the sound source height;
- to add absorption on diffusors. By building diffusors with classical noise barrier materials with large sound absorption on the frequency band of interest, it allows either to increase the noise reduction for a constant number of diffusors, or to reduce the number of diffusors for a given noise reduction.

In comparison with building façades producing specular reflections and low absorption, the use of acoustic diffusors can have a significant effect. However, in fact, real façades incorporate many elements (doors, windows, store windows...) and many frontage irregularities, which create a large amount of diffuse reflections. The effect of diffusors in a real street is then probably lower. Moreover, due to the presence of these façade elements, the area available for the application of such devices is limited, particularly on the lower part of a building façades, which is one of the above-suggested configurations. Lastly, in real streets, multiple noise sources are present simultaneously at several locations along the street. The far field effect, which is observed in a street with acoustic diffusors for a single sound source, becomes unimportant in terms of absolute sound pressure level. However, in terms of reverberation, the effect of diffusors would still be significant. In a practical point of view, the effect of diffusors is then probably lower than the one observed in this paper. An experimental study could conclude on the real efficiency of such devices. Besides these acoustic considerations, there are also aesthetic, cost and maintenance reasons that would militate against such treatment.

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