A NUMERICAL STUDY OF THE USE OF ACOUSTIC DIFFUSERS TO REDUCE NOISE IN URBAN AREAS

J Picaut Laboratoire Central des Ponts et Chaussées, Nantes, France
D Scouarnec Valeo Engine Cooling, La Verrière, France

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, 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 inside 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 suggests 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, Kang shows that both sound attenuation and sound decay increases with absorption, but non trivial results are also obtained: for example, 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 investigates the use of oriented patches (absorption and diffusion) as a façade treatment to reduce noise in shielded canyons. As an interesting result, they show that vertical diffusion yields lower levels at the shielded side compared to horizontal diffusion.[3.]

In the present paper, the two last studies are extended to investigate the use of acoustic diffusers, as a façade treatment, to reduce the noise propagation in urban areas. The main objective is to determine the optimum parameters of diffusers, in terms of diffusion pattern, relative surface and arrangement on the façades, and 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. The second objective is to propose a prototype of diffusers that verify the previous optimum parameters and that could be used in urban areas to reduce noise.

This paper begins with a presentation of the numerical code used to study the effect of diffusers in a street (Section 2.1), following by a description of the numerical simulations (Section 2.2), and by the main results (Section 2.3). A prototype of urban acoustic diffuser is then proposed in Section 3.1 and is experimentally characterized in Section 3.2. Lastly, Section 4 concludes this paper.

2 NUMERICAL SIMULATIONS

2.1 SPPS numerical code

Numerical simulations have been carried out with the numerical code SPPS 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 and velocity (whose norm is equal to the sound velocity). 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. The numerical simulations present in this paper have been performed using a Monte Carlo method to model sound emission by the sound source and reflection, diffusion and absorption by the building façade. It consists in generating series of random numbers that respect the density of 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. In the present study, calculations have been carried out with one million of sound particles emitted from an omnidirectional sound source defined by a sound power level of 0 dB, and considering 500 time increments with a time step of 2 ms, leading to a total time of propagation of 1 s. Moreover, atmospheric absorption has been neglected.

2.2 Numerical simulations

The main objective of the following numerical simulations is to determine the properties of urban acoustic diffusers, 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 diffuser area to the façade area) on a building façade, that optimize the noise reduction in a street. It means that acoustic diffusers 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 criteria do not involve that the absolute sound pressure level inside the street is the lowest.

To minimize the number of numerical simulations, a sequential approach has been followed. The first step of the study focuses only on the reflection properties of diffusers. To evaluate the effect of the diffusers only, the scattering coefficient of the diffusers is fixed to 1 (i.e. perfectly diffuse reflection), while the scattering coefficient of the façade is chosen as 0 (i.e. perfectly specular reflection). Firstly, numerical simulations has been realized to determine the more appropriate reflection law for the diffusers (Section 2.3.1). Using the obtained reflection law, the following two simulations have been carried out in order to optimize the relative surface of diffusers (Section 2.3.2), as well as the diffusers arrangement on the façade (Section 2.3.3). Then, a new set of simulations is realized to determine the effect of the size of diffusers (Section 2.3.4). Finally, the combined effect of absorption and diffusion is studied at Section 2.3.5. In all simulations, an empty canyon street of size 8 m x 40 m x 8 m (width x length x height) has been considered, with a omnidirectional sound source located at position (6.5, 30.5, 1.5). Street pavement is considered as a perfectly specular reflecting surface.

Three acoustic parameters have been studied to evaluate the effect of diffusers. Firstly, the absolute sound pressure level in the street has been considered. Since an experimental study has already shown that the sound energy is quite uniform on a narrow street section,[5.] the sound pressure level has been estimated by averaging the sound energy on each street section. Secondly, to qualify the sound attenuation for each configuration of diffusers, an attenuation coefficient (in dB per meter) has also been introduced. To avoid the effect of the direct field close to the sound source, the attenuation coefficient has been obtained through a linear interpolation of the sound levels from 5 m from the sound source. Finally, the decay of sound energy in the whole street was also estimated, in terms of early decay time (EDT) and reverberation time (RT30) using the backward integration method.

2.3 Numerical results

2.3.1 Effect of the reflection laws

In order to evaluate the optimal reflection laws of acoustic diffusers, the entire façade has firstly been treated as a single acoustic diffuser. Several reflection laws has been considered among them the specular (SP) one is considered as the reference one. The uniform reflection law (UN), for which the sound energy is reflected in all directions with the same probability, and the classical Lambert's law (LA) have also been considered. For the last reflection law, which is widely used to model diffuse sound field in room acoustics,[7.] as well as in urban acoustics,[2.] the angular distribution

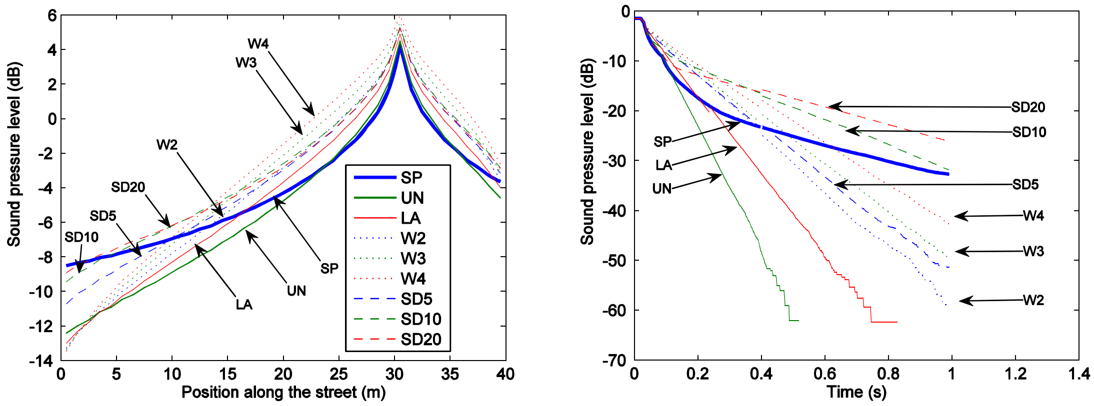

Figure 1. Effect of the façade reflection laws on the sound propagation along the street. Left: sound attenuation. Right sound decay in the street.

of the reflected sound energy is proportional to the cosine of the reflecting angle with respect to the normal to the façade. The last reflection laws (called normal laws on the following) can also be generalized on the form of the *n*-power of the cosine function (with *n*=2, 3, 4 noted W2, W3 and W4 respectively). 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.[7.] A reflection around the specular direction (called semi-diffuse reflection, SD) is probably more in agreement with reality than uniform and Lambert's laws. Thus, in this study, semi-diffuse reflections have also been investigated,[8.] depending on the normal distribution of the perpendicular roughness, with a given variance and a correlation distance (SD5, SD10, SD20).

At first, considering all results, and as already shown by several authors, by adding diffusion on the building façades, the sound decay and the sound attenuation increase (Figure 2). 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 UN reflection law seems to have the most significant effect on the absolute sound pressure level, as well as on the sound attenuation. Near to the sound source, the sound attenuation is very close to the specular one. On average, the sound level difference between the UN reflection and the SP reflection is almost 1 dB. However, this difference increases along the street, to reach 4 dB at the first street extremity. As mentioned above, the absolute sound pressure level and the sound attenuation coefficient are not systematically correlated: although the absolute sound pressure level is low for the UN law, the sound attenuation is not the greatest one. The sound decay for the UN law is also very important, with a 80% RT30 decrease in comparison with the SP reflection. Except with the LA law, RT30 for all other reflection laws are more than twice with respect to the UN reflection. In conclusion, the UN reflection law seems to have the most significant effects, both in terms of absolute sound pressure level, sound attenuation and sound decay. However, close to the sound source, the specular reflection seems to produce the same effects.

2.3.2 Effect of the relative surface of diffusers

The evaluation of the effect of the relative surface of building façades covered by diffusers was studied by considering a regular arrangement of diffusers (similar to RE configuration on Figure 2l)), and increasing the relative surface from 0 (specular façade) to 100% (100% diffusely reflecting façade). When the relative surface of acoustic diffusers is greater than 50%, the sound decay and the sound attenuation are mainly similar: discrepancies with the configuration for which the building façade is entirely diffusing are less than 8% for RT30 and 10% for the sound attenuation coefficient.

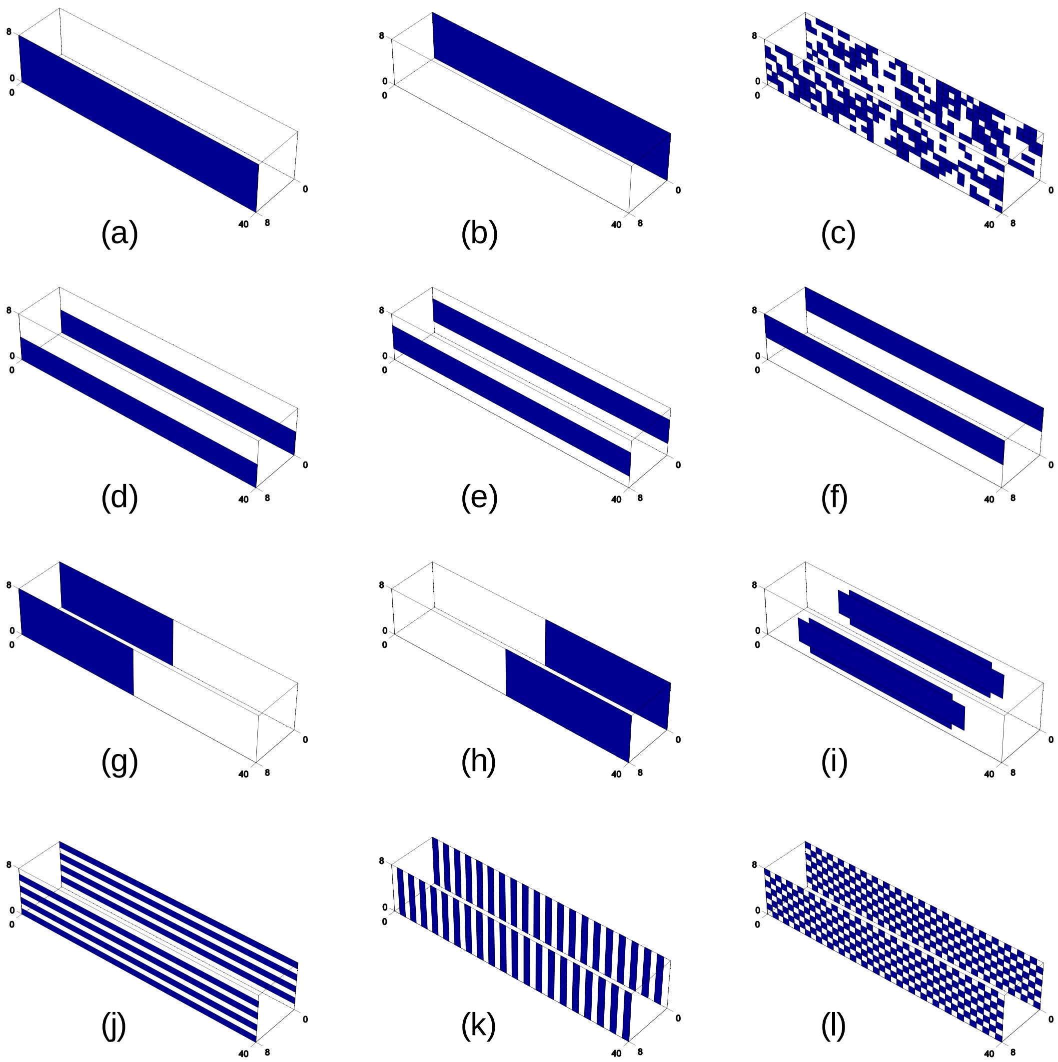

Figure 2. Diffusers arrangement (in blue) on 50% of the building façade areas: (a) right façade (RF), (b) left façade (LF), (c) random arrangement (RA), (d) lower part of the façade (LO), (e) middle part (MI), (f) upper part (UP), (g) half-part of the façade away from the sound source (HA), (h) half-part 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).

As an example, in comparison with the reference configuration (specular), a 80% RT30 decrease of 80 and a 48% sound attenuation increase are obtained for the configuration with 50% of the surface area covered by diffusers. In practice, it would be difficult to treat 50% of the building façades with diffusers). With 20% of the surface, a 75% RT30 decrease and a 24% sound attenuation increase are observed, which is already a significant noise reduction.

2.3.3 Effect of the diffusers arrangement

The sound propagation in a street can also be influenced by the diffusers arrangement on the building façades (Figure 2). Then, several configurations have been studied in this Section, with the same relative surface of diffusers (50%). In particular, the overall coverage of one façade has been considered (LF and RF). Alternative configurations have also been studied, by considering one horizontal arrangement of diffusers at several façade heights (LO, MI, UP), by considering diffusers only on the half of the façades away from the source or close to the source (HA and HC), or by considering the centre of both façades only (CE). 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 diffusers arrangements have also been studied with a vertical alignment (1D diffusion), an horizontal alignment (1D diffusion) and regular arrangement (2D diffusion) (VE, HO, and RE), compared to the random disposition (RA).

Numerical results have shown that best results are obtained for the sound attenuation and the sound decay simultaneously, by arranging acoustic diffusers close to the source, and if possible at the same height. Conversely, if diffusers are located higher on the building façade, due to the vertical back-diffusion effect, the sound pressure level and the sound decay increases in the street. Another interesting result is that the increase of the number of diffusers does not enhance the noise reduction in the street. Indeed simulations for the configuration with diffusers on the lower part of the façades (with 50%) gives better results than for the configuration with 100% of the surface covered by diffusers. The location of diffusers is then more important than the number of diffusers.

2.3.4 Effect of the size of diffusers

The effect of the diffuser size has also been studied by considering random (RA) and regular (RE) distribution of square diffusers of length 0.5 m, 1 m, 2 m, and 4 m, with the same relative surface 50%. Numerical results show that, as long as the relative surface of diffusers is constant, the effect of the size of diffusers is not significant. However, one can barely observe that the configuration with the larger diffuser size is a little bit better, both for the sound attenuation and the sound decay. This result shows that the main parameter is the relative surface of diffusers, and not the size.

2.3.5 Combined effect of absorption and diffusion

In order to evaluate the combined effect of absorption and diffusion by diffusers on the noise reduction in a street, several configurations have been studied on the basis of the LO, LF and RA configurations. Nine absorption configurations have been considered for each one of the last three configurations: 3 configurations with the same absorption both on the diffusers and on the façades (mean absorption coefficient 0.1, 0.3 and 0.5); 3 configurations with absorption only on the diffusers (mean absorption coefficient 0.1/2, 0.3/2 and 0.5/2); and 2 configurations with absorption on the diffusers only (0.2 and 0.6) but in order to have the same mean absorption as previous configurations (0.1 and 0.3). A reference configuration A0, without absorption (SP) was also considered. For all configurations, the relative surface of diffusers was fixed to 50% and the length of diffusers was 1 m. Diffusers have been defined by an UN law, while building façades were perfectly specular.

As expected for the first 3 configurations, 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 a mean absorption of 0.05 and 0.5 respectively. For the mean sound level difference, the increase is on the order of 0.3 dB to 3 dB. The most important result is obtained by comparing absorption configurations with the same mean absorption coefficient, but with different absorption repartition between the diffusers and the façades. Indeed, the configuration with absorption 0.6 on diffusers only gives better results than the configuration with uniform absorption 0.3 on the diffusers and on the building façades, although they have exactly the same mean absorption coefficient 0.3. This last result suggests that it is more efficient to locate absorption on diffusers instead of on the façades, for the same mean absorption coefficient.

3 A PROTOTYPE OF URBAN ACOUSTICS DIFFUSERS

3.1 Designing an urban quadratic residue diffuser

When talking about acoustic diffuser, one can cite the well-known phase grating diffuser developed by Schroeder,[10.] consisting of a sequence (noted s) of wells of the same size (noted w) and different depths (noted d). Such diffuser allows producing optimum diffusion, either into a hemi-disc (1D diffuser) or into a hemisphere (2D diffuser). In the present study, since it was shown that diffusers with uniform diffusion (UN) seem to produce a significant noise reduction, the choice was done to consider a 2D Schroeder's diffuser based on quadratic residue sequence $s_{n,m}$, of length N, such as:

$$s_{n,m} = \left(n^2 + m^2\right) \mod N \,, \tag{1}$$

where n and m are integers giving the relative depth $d_{n,m}$ of the (n,m) well of the 2D diffuser. The choice of the length N, the size w and the maximum depth d is defined by the frequency range for which an optimum diffusion is required.[1.] The upper frequency (i.e. the minimum wave length $\lambda_{\min}$) is first obtained in order to respect the hypothesis of plane wave propagation within the wells, leading to:

$$w = \frac{\lambda_{\min}}{2} \,. \tag{2}$$

The lower frequency (also called design frequency) is defined by the largest sequence number $s_{\max}$, for a given length sequence N and a maximum depth $d_{\max}$, as:

$$f_0 = \frac{s_{\max}}{N} \frac{c}{2d_{\max}} \,, \tag{3}$$

with c the speed of sound. Quadratic residue diffuser generates also critical frequency, for which the diffuser works as a plane surface because all the wells radiate in phase, i.e. when all the depths are multiple of half of the wavelength. To avoid critical frequency, it is then necessary that the first critical frequency is larger than the upper frequency limit, which leads to:

$$N > \frac{c}{2wf_0} \,. \tag{4}$$

In this study, considering that optimum noise reduction is required for road traffic noise, the frequency range of interest can be assumed as [100, 5000] Hz with a maximum energy around 1000 Hz. This can be obtained by choosing a sequence length N=7, with a maximum depth $d_{\max}$ of 18 cm and a size w of 10 cm. The exact corresponding upper frequency and design frequency are then 1700 Hz and 810 Hz respectively. With these parameters, the condition of equation (4) is verified. It must be pointed out, as mentioned in reference 1., that these frequencies are just limits of applicability of the plane wave propagation theory and not for the diffusion quality. In fact, diffusion still occurs above the upper limit, and below the lower frequency.

Finally, an arbitrary N=7 quadratic residue diffuser can be built by considering the first 7 rows and 7 columns of the sequence beginning by (0,0) (see Figure 3). In order to make the diffuser symmetric, the 8th row and 8th column are added, which gives a diffuser size of 80 cm x 80 cm. It must be noted that is probably not the best solution, since by extending the diffuser size arbitrarily, it is not able to obtain the correct sequence by placing side by side the same proposed diffuser. Indeed, as suggested in reference 1. (figure 9.32 page 261), it would be more pertinent to consider a sequence beginning by (2,2) since it produces a symmetric 7x7 quadratic residue diffuser directly, with the 0 in the middle of the diffuser, without adding a new column and a new row arbitrarily (see Figure 3 in green). However, about periodicity, one can assume that for practical reason, it is easier to locate a single diffuser of such size on a building façade, due the limited "free" surface area on real frontages, than using a periodic arrangement of diffusers needing a larger surface area. Moreover, the scattering from a single diffuser is often more uniform than a periodic arrangement of diffusers.[1.]

3.2 Experimental characterization

In order to evaluate the acoustic diffusion produced by the proposed diffuser, and its effective frequency range, an experimental investigation has been carried out. For practical reasons, measurements have been realized on ½ QRD scale models (40 cm x 40 cm) instead of full scale models (left of Figure 4), with $d_{\max}$=9 cm and w of 4.5 cm (instead of 5 cm). The corresponding

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	1	4	2	2	4	1	0	1	4	2	2	4	1
2	1	2	5	3	3	5	2	1	2	5	3	3	5	2
3	4	5	1	6	6	1	5	4	5	1	6	6	1	5
4	2	3	6	4	4	6	3	2	3	6	4	4	6	3
5	2	3	6	4	4	6	3	2	3	6	4	4	6	3
6	4	5	1	6	6	1	5	4	5	1	6	6	1	5
7	1	2	5	3	3	5	2	1	2	5	3	3	5	2
8	0	1	4	2	2	4	1	0	1	4	2	2	4	1
9	1	2	5	3	3	5	2	1	2	5	3	3	5	2
10	4	5	1	6	6	1	5	4	5	1	6	6	1	5
11	2	3	6	4	4	6	3	2	3	6	4	4	6	3
12	2	3	6	4	4	6	3	2	3	6	4	4	6	3
13	4	5	1	6	6	1	5	4	5	1	6	6	1	5
14	1	2	5	3	3	5	2	1	2	5	3	3	5	2

Figure 3. Array sequence of N=7 quadratic residue diffuser (two periods). Selection of a periodic pattern (in yellow) by adding adding the 8th row and 8th column. A true periodic N=7 QRD is also shown in green.

Figure 4. ½ scale model of N=7 QRDs (with 8x8 elements) with (left) and without (right) thin fins.

design frequency of the ½ QRD scale model is then 1619 Hz (i.e. 810 Hz equivalent full scale (FS)). Moreover, since it is easier and cheaper to built diffusers without thin fins, a second diffuser of size 36 cm x 36 cm was also investigated (right of Figure 4). Lastly, for comparison, a plane panel of size 40 cm x 40 cm has also been investigated. Measurements of the scattered polar responses have been carried out using an equivalent procedure as proposed in reference 9., except that the diffuser size is larger than the recommended one (a 1/5 scale model could be more appropriate). The diffuser was located in a semi-anechoic chamber, with a sound source at 2 m in front of the diffuser centre (Figure 5). A ¼-inch microphone is moved with an equal angular spacing of 5°, at several locations on a quarter of the sphere centred on the diffuser, with a radius of 1 m. Scattered impulse responses are then obtained by subtracting the full impulse responses measured both with and without the diffuser. The smooth hemispherical polar response surface is obtained firstly by symmetrizing the data obtained on the "measurement" quarter (639 data), and secondly by interpolating the 2x639 resulting data using a cubic interpolation (Figure 5). The polar responses as well as the diffusion coefficient are then evaluated in third octave bands and in the full frequency range up to 10000 Hz (i.e. 5000 Hz FS).

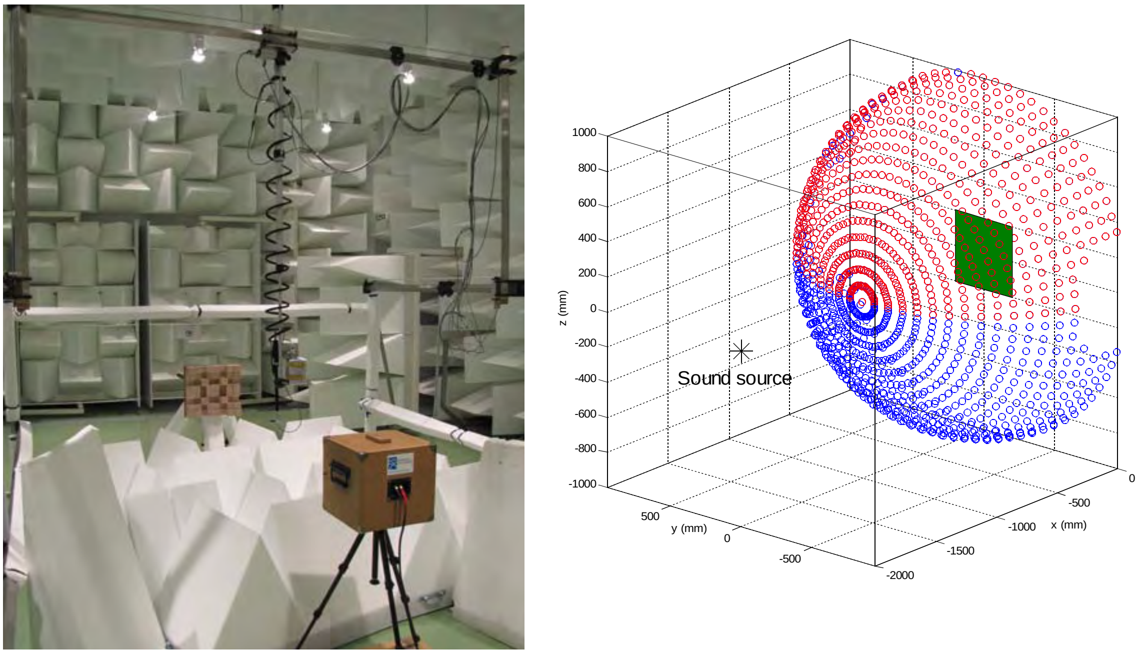

Figure 5. Experimental setup for the evaluation of the polar responses of diffusers (left). Measurements have been carried out on a quarter of the sphere centered on the diffuser (639 observation points, right figure, in red). The polar response over an hemisphere is obtained by symmetrizing data (in blue) and by fitting the resulting “surface”.

3.3 Experimental results

As an example, Figure 6 shows the scattered polar responses for the third octave bands 500 Fz FS and 1600 Hz FS, for both diffusers and the plane panel. As expected the polar responses for the diffusers present lobes with specific locations and directions, for which the reflected sound field is maximum. For the plane panel, the main lobe is oriented in the normal direction, which is expected for a specular reflection with a normal incidence. In order to evaluate the uniformity of the reflected sound field (i.e. the diffuser quality), the diffusion coefficients have been calculated for each diffuser, according to section 4.4 of reference 1., and are presented in Figure 7. As expected, the diffusion coefficient for the diffuser with thin fins presents maximum at multiple of a given frequency. However, this frequency, which can be estimated around 612 Hz FS (following peaks at 1224 Hz FS and 1736 Hz FS), is lower than the fixed design frequency (810 Hz FS). This can be due to the fact that the proposed diffuser is not really a N=7 QRD, but a mixed between a N=7 QRD and a N=8 QRD, since the diffuser length has been extended arbitrarily. For the N=8 QRD, the corresponding design frequency with the same sequence as the N=7 QRD, is around 700 Hz that is closer than the experimental one.

The diffusion coefficient is about 0.4-0.5 on the frequency range [500-1400] Hz FS for the first diffuser, while the diffuser without thin fins gives complementary results with a diffusion coefficient around 0.4 below 500 Hz FS and above 1400 Hz FS. For both cases, an upper limit of diffusion can be estimated around 2000 Hz FS, i.e. about the predicted upper frequency, although diffusion still occurs between 2700 Hz FS and 3700 Hz FS with a diffusion coefficient around 0.3. In conclusion, in the background of this study about the use of diffusion effects to reduce urban noise, the diffuser with thin fins produces an expected diffusion pattern between 500 Hz and 1400 Hz and seems well adapted to reduce noise in this frequency range. For noise outside this frequency range (i.e. mainly for lower frequencies and within the limit of the upper frequency), the diffuser without thin fins could give interesting results.

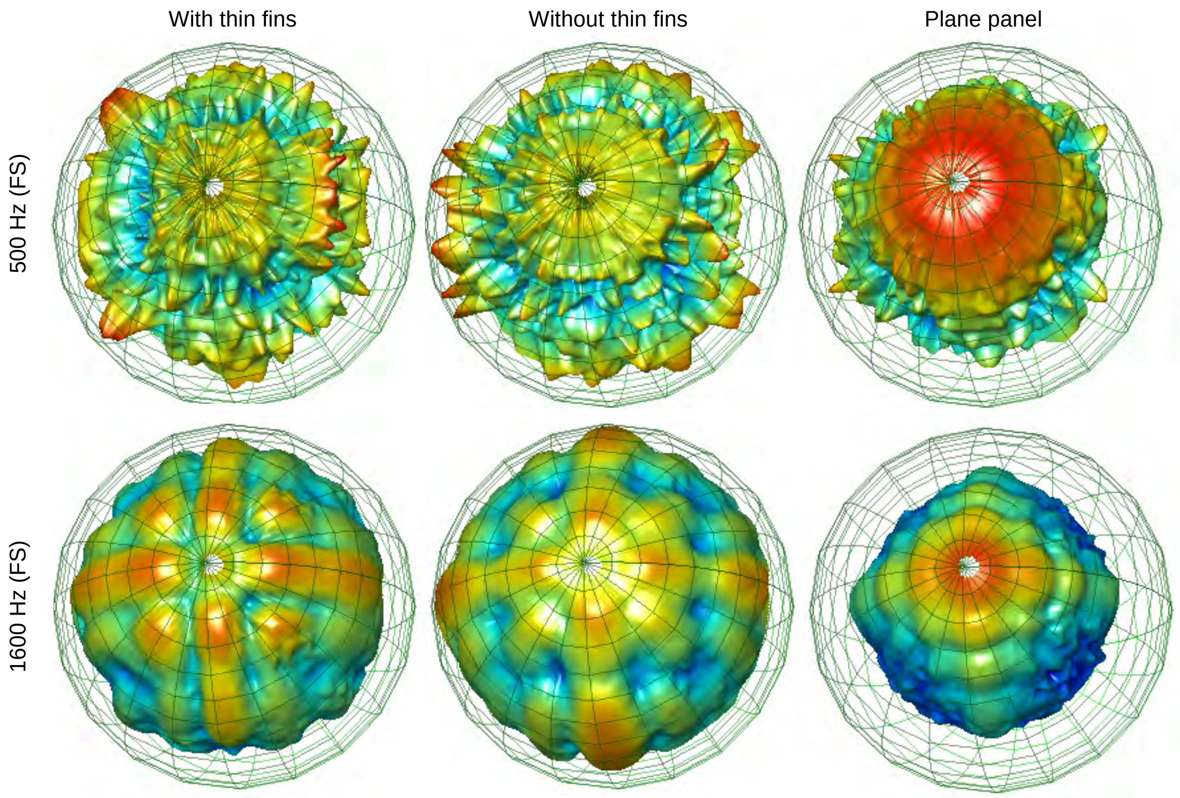

Figure 6. Example of scattered polar responses for the diffuser with (left) and without (right) thin fins, and for the plane panel, for the 1/3 octave band 500 Hz FS -(top) and 1600 Hz FS (bottom).

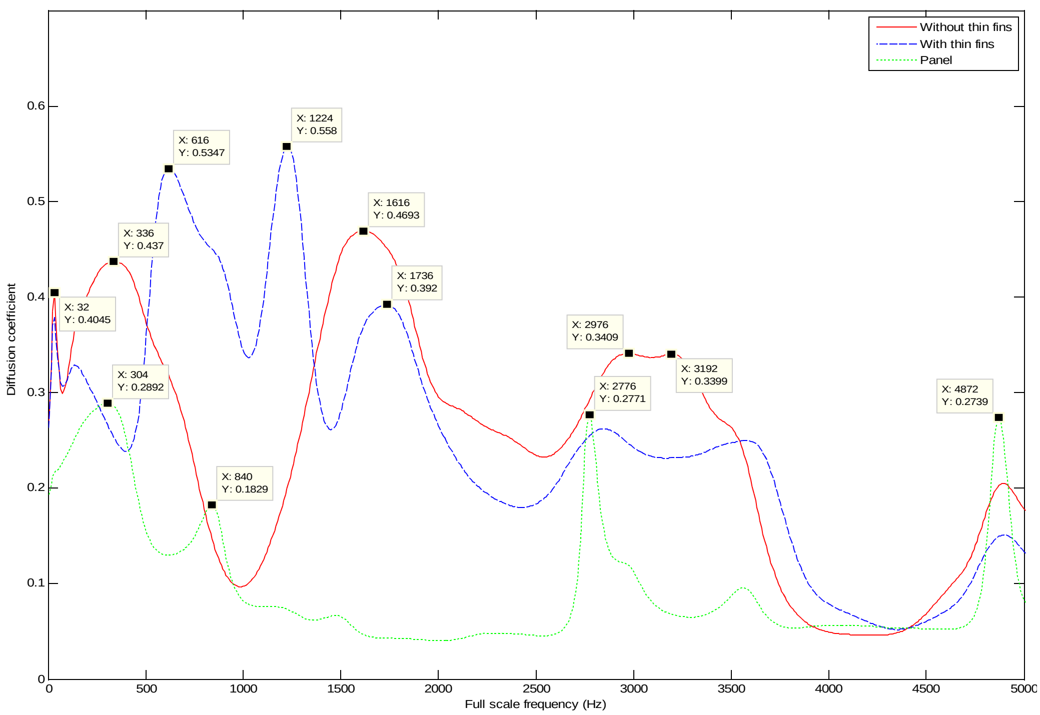

Figure 7. Measured diffusion coefficient. Positions X (frequency) and Y (value) are indicated for the main peaks.

4 CONCLUSION

Numerical simulations have been carried out in order to evaluate the effects of acoustic diffusers on the sound propagation in a street, then to determine if such device can be used to reduce noise in urban areas. To have a significant effect, it requires (1) to develop diffusers producing uniform diffusion on the frequency band of interest (i.e. in practice to the traffic noise spectrum in urban areas), (2) to consider a relative surface of diffusers larger than 20%, (3) to arrange diffusers on the lower part of the building façades, around the sound source height, and (4) to add absorption on diffusers. By building diffusers 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 diffusers, or to reduce the number of diffusers for a given noise reduction.

In this study, two prototype of urban diffusers, based on a quadratic residue diffuser, have been proposed (with and without thin fins). An experimental characterization of the diffusion coefficient has shown that the diffuser with thin fines produces an expected diffusion pattern in the frequency range [500-1400] Hz and seems well adapted to reduce noise in this frequency range, while the diffuser without thin fins could give interesting results for noise outside the previous frequency range.

In comparison with building façades producing specular reflections and low absorption, the use of acoustic diffusers 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 diffusers in a real street is then probably lower. Moreover, 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 diffusers for a single sound source, becomes less important in terms of absolute sound pressure level. However, in terms of reverberation, the effect of diffusers would still be significant. In a practical point of view, the effect of diffusers is then probably lower than the one observed in this paper. An experimental study could conclude on the real efficiency of such devices.

5 REFERENCES

1. T.J. Cox and P. D'Antonio. Acoustics Absorbers and Diffusers: Theory, Design and Application, Spon Press, Taylor & Francis Group. (2004).
2. J. Kang. Urban sound environment. Spon Press, Taylor & Francis Group. (2007).
3. M. Hornikx and J. Forssén, 'A scale model study of parallel urban canyons', Acta Acustica united with Acustica 94(2) 265–281.(2008).
4. J. Picaut, 'Numerical application of the concept of sound particles to modeling sound fields in architectural acoustics'. Bulletin des Laboratoires des Ponts et Chaussées 258-259 59–88. (2005).
5. J. Picaut, T. Le Pollès, P. L'Hermite and V. Gary, 'Experimental study of sound propagation in a street'. Applied Acoustics 66 149–173. (2005).
6. H. Kuttruff, Room acoustics, Fourth ed., Spon Press, Taylor & Francis Group. (2000).
7. J. Picaut and M. Bérengier, Qualitative evaluation of sound reflection by a building façade, Proc. Internoise 2001. The Hague, The Netherlands (2001).
8. J. Picaut, Effects of diffusion on the sound propagation in a street. Proc. Internoise 2004. Prague, Czech Republic (2004).
9. AES, AES information document for room acoustics and sound reinforcement systems - characterisation and measurement of surface scattering uniformity, J. Audio Eng. Soc. 49(3) 149-165. (2001).
10. M.R. Schroeder, 'Diffuse sound reflection by maximum-length sequences', J. Acoust. Soc. Am. 57(1) 149-150. (1975).