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An angular diffusivity geometrical model to predict urban sound diffusion.

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Abstract

With taking part of an interdisciplinary CNRS research program, we intend to constitute a simulation tool for complex urban soundscapes. For this purpose, we aim to quantify the urban diffusion factor, related to the surface roughness distribution of the urban frontages, taking into account its volume location and its specular surface distribution. Characterization of this distribution leads us to use a fractal technique for modeling the complexity of urban surfaces, through developing a unique method based on Minkowski's operators. The generalization of this measurement technique through the three dimensions of the urban shape provides an angle-dependent diffusive polar response for urban frontages. In order to perform an experimental validation of this angle dependent scattering characterization model, we attempt to define an MLS multisensor method of measurement, applied to the 19th frontage morphology of the « rue d'Orléans » in Nantes. Scattering experimental results will then be compared to the described scattering pressure function at each incidence angle. Another comparison to a 1/5th scale model measurement will provide the acoustical scattering effect of the frontage components, in order to define their qualitative contribution for diffusion. Developed in the aim of architectural design tools for urban acoustics, this frontal angular diffusivity factor allows a good evaluation of the acoustical local reaction of an urban surface. With discerning the morphological attributes of main types of architectures, we will then be able to compute their specific acoustical behavior at every frequency, from the numerical 3-D data of their geometry.

1 Introduction

The exterior frontage of a typical urban building does not reflect noise in a purely specular manner. Because the dimensions of the irregularities (decorative elements, windows, balconies) are comparable to the sound wavelengths, the major type of reflexions on the buildings is scattering, inducing a global diffusion behavior of sound in an urban street. Consequently, irregular surfaces like urban frontages produces an anomalous back-scattered region, with the creation of an acoustic interference field in its neighborhood. Thus, in order to be able to detect that scattered energy's minima and maxima, we have to take into account both incidence angle and multiscale characterization for fractal evaluation of urban surfaces through mathematical morphology techniques. Validation of this geometrical evaluation model is provided through the development of an acoustic measurement method of scattering, both on scale model and on site, in order to confirm the acoustical pertinence of this methodology for the urban frontage characterization.

2 Geometrical diffusivity characterization

The built urban structure is considered as a non-entire dimensional network, taking the volume structure and the multiscale distribution of specular surfaces within the urban space into account. For this distribution, acoustical diffusion is considered. Its multiscale characterization leads us to use a fractal technique for modeling the complexity of urban surfaces. To do so, we develop a method to quantify scaling morphology of the town with a capture procedure based on Minkowski's operators. The generalization of this measurement technique through the three dimensions of the urban shape provides an angle-dependent diffusive polar response for urban frontages, through computation of the diffusion volume of the structure. This new multiscale analysis tool of urban structure has been applied to a 19th urban morphology.

2.1 The urban frontage model

The spatial configuration we analyze here is a numerical 3-D model of a neoclassical frontage of an urban street of Nantes, France, *the rue d'Orléans*, belonging to a 19th urban morphology type, with windows, doors, and freestone casting off. One of the main characteristics of this type of architecture is the relative exuberance of its frontage structure, following neo-classical composition. This frontage is considered as a tridimensional object situated in an ortho-normed space, rotating around the Z-axis (figure 1).

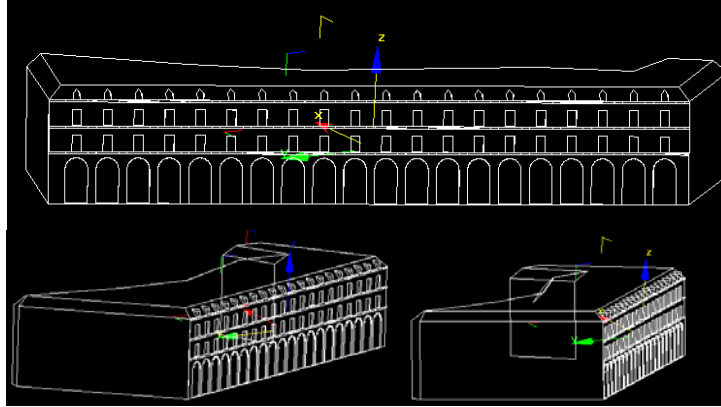


Figure 1 : Orthographical rotative analyze of a frontage.

2.2 The Minkowski measurement technique

In order to characterize the volumic multiscale behavior of the frontage, we apply a fractal Minkowski operator to evaluate the vertex multiscale densitometry distribution at each incidence angle. This operator consists into replacing each point of the vertexes of the urban geometry with an increasing radius sphere, as seen figure 2.

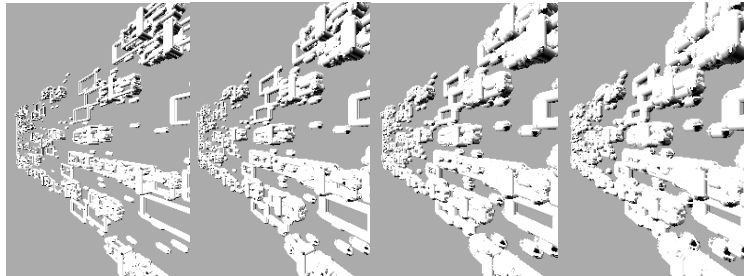


Figure 2 : Tridimensional dilation of the urban scene vertexes (perspective views).

This transformation of the urban geometry corresponds to the *dilation* operation in the morpho-mathematical context [1]. The union of all spheres is called the *3-D Minkowski sausage*. The variation of their diameter gives us successive approached perimeter/surface ratios at each vision angle, which regression evaluates the fractal dimension of the structure, in a specified validity domain [2].

2.2.1 Frontage shape spectrum

The spatial multiscale evolution of the perimeter-surface ratio P/S defines the profile's *Shape spectrum* of the frontage [2]. This spectrum defines

the multiscale relationship between the radius evolution of the spherical structuring element and the “mass” of the structure, for each the angular evaluation. As readable in the following figure, the specular domain is illustrated with a strong decrease of the P/S ratio, which corresponds to localization length limit Λ for the radius of the structuring element. For this domain, the Euclidean dimension d and the fractal dimension D reach the same value. This break in the frontage indentations shape spectrum behavior occurs for the structuring element value $\Lambda_{max} = 100\text{cm}$ (figure 3).

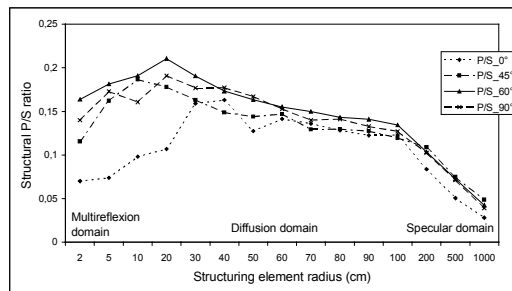


Figure 3 : “ Shape spectrums ” of the urban frontages with a spherical recovering element, at different incident angles.

2.2.2 Angular vertex densitometry

This method allows the computation of the vertex densitometry for every incidence angle of the surface, with an increment of 5 degrees for localisation lengths Λ from 0.05 to 10 m, which corresponding acoustical frequency domain is 25 Hz to 8 kHz. Those densitometries correspond to the characteristic directions of scattering, through the vertex density distribution for each incidence angle.

This spatial evaluation of the vertexes distribution shows azimuthal densitometries due to interreflexions of the corners and the freestone casting along four windows depth, corresponding to the lateral active diffraction zone. The geometry of our configuration defines an active area (Fresnel zone [3]), which represents the part of the frontage which will majoritary send back the scattered energy (figure 4).

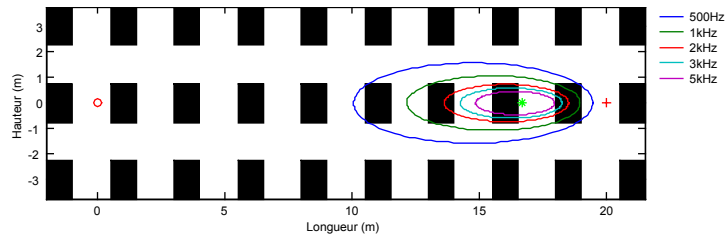


Figure 4 : Active Fresnel diffraction zone for grazing incidence angles.

Those densitometries corresponds to the characteristic directions of scattering, which has to be calculated using the *scattering pressure function* [4] along the lateral active diffraction zone. Global polar responses for growing localisation lengths shows globally a decreasing diffusivity, revealing a bilobe distribution structure of the biggest scatterers, a cardioid for middle-sized ones and very characteristic peaks for high frequency roughness (figure 5).

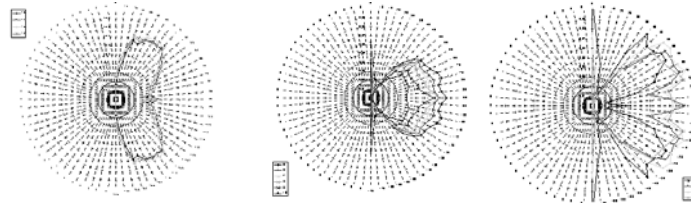


Figure 5 : Polar responses of the urban frontage applied to the urban scene, respectively for 1 to 10 m, 0.5 to 0.5 m, and 0.05 to 0.5 m.

2.3 Experimental validations

In order to validate this geometrical scattering characterization model, we attempt to define a new method of measurement, applied both *in situ* and to a 1/5th scale model of the frontage previous example. Scattering experimental results will then be compared to the geometrical angular estimation of diffusivity. This will allow the generalization of this diffusive characterization method to any complex urban configuration, structurally considered as an acoustic diffusive system.

Scattering geometrical characterisation are here compared to experimental results at each incidence angle, with using an MLS multisensor method of measurement, in order to perform an experimental validation of this angle dependent scattering fractal-characterization model. For this aim, we will have two approaches to measure the angular response of the frontage. The first is applied to a 1/5th scale model and the second will take a real neoclassical frontage in Nantes into account. Both have in common the same impulse response measurement technique.

2.3.1 Common instrumental Methodology

This measurements procedures of the back-scattered region of the real and scale-modeled frontage consists in emitting an impulse sound wave, and then to record incident wave (time t) and the back-scattered wave (time $t+dt$). This signal, constituting the frontage impulse response, is analyzed to pull the incident wave away from the rest of the signal by time windowing. The content of this window is then analyzed in frequency domain applying Fourier transform and provides the frontage's Frequency Transfer Function. Several positions of source and microphone

give the reflection law of the frontage, according to microphone position and for a given source incidence.

3 First experimental validation : 1/5th scale model

As our geometrical approach uses a 3-D numerical model of those frontage configurations, acoustical measurements have first being done on a 1/5th scale model for the flat and windowed configurations by the Laboratoire d'Acoustique de l'Université du Maine and the Laboratoire Central des Ponts et Chaussées [5]. The measurements technique based on impulse response provides the frontage's Frequency Transfer Function for each incidence angle of reception.

3.1 Measurement method

The 1/5th scale model, dimensioned as follow : 2.80 m × 1.50 m × 0.07 m represents a three-storied, seven windows width frontage, which real dimensions are : 14 m × 7.50 m × 0.35 m. Measurement has been made with a ¼ inch B&K preamplified microphone on a mobile 72 cm arm allowing a 2,5 degree-step rotation, at 75 cm height. The Burst Chirp source is generated with a Hewlett Packard Dynamic Signal 35665A Analyser, which provides an impulse response through intercorrelation method. The bandwidth analysis imposes a 15.625 ms source signal duration, for a 31.25 ms acquiring time. The Burst Chirp signal is transmitted to an AUDAX HM 17020 loudspeaker through a Brüel & Kjær 2706 typed amplifier. The 2048 points microphonic signal acquiring has been made through a 65.7 kHz sampling frequency. The 1/5th scale model impulse response has been directly calculated from the source-microphonic signals intercorrelation. In order to improve the signal/noise ratio, an averaging of 50 successive acquisitions have been made.

The following figure shows the impulse response provided with a normal positioning of the microphone : the first response on the flat surface presents the direct sound peak A and the reflected sound peak B, clearly emerging despite the ground reflection C. The second response shows the acoustic perturbations due to the windows, particularly through peaks C and D (figure 6).

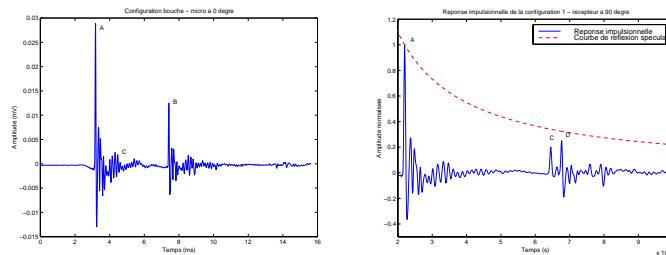


Figure 6 : Flat and windowed surfaces impulse responses.

3.2 Comparative results between the geometrical model and the 1/5th scale model

Results of the geometrical characterization describes the polar response of the urban frontage, with an increment of 5 degrees, and for localization lengths of 0.5 m and 0.1 m. Comparison between acoustical measurements on the 1/5th scale model and the corresponding geometrical characterization provides a good angular agreement for the frequencies 1 kHz and 5 kHz, which corresponds to localization lengths of 0.5 m and 0.1 m (figures 7 and 8). Global polar responses shows a decreasing diffusivity for growing localization lengths.

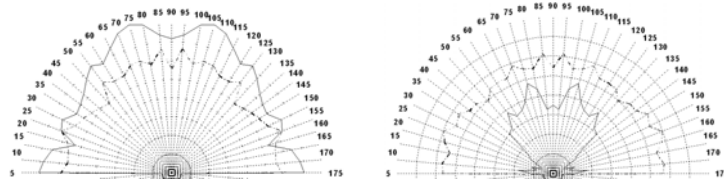


Figure 7 : Geometrical characterization for localisation lengths of 0.5 m and 0.1 m. The flat surface is dashed, the windowed one is continued.

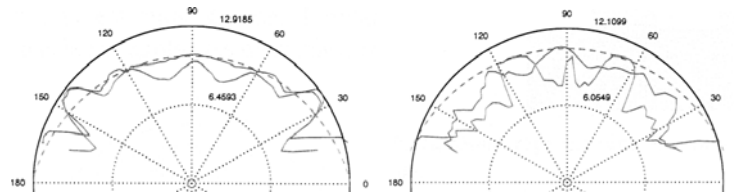


Figure 8 : Acoustical measurements at frequencies of 1 kHz and 5 kHz. The theoretical flat surface is dashed, the measured flat and windowed surfaces are continued.

Figure 8 shows us three diffusivity peaks at 90°, [120-60°], and [145-35°], due to interreflexions between the corners of the three windows of the lateral active diffraction zone, at 1kHz. The geometrical analysis of the frontages Figure 7 shows a setup of 10°, with vertexes distribution peaks at [150-30°], [125-55°] and [105-75°]. Those two last azimuthal densitometries increase at 5 kHz, conserving their peaks till localization length 0.05m (10 kHz), with the apparition of a new 90° tip.

4 Second experimental validation : *in situ* measurements

The first acoustical angular response will be measured on a neoclassical frontage in the historical heart of Nantes, the *Hôtel Deurbrouck*, with windows, free-stone casting off, and finely worked metal guardrail and railing.

4.1 Measurement method

The method we use is maximum-length sequences stimulus (MLS), that means a binary value pseudo random sequence with a period : $L = 2^N - 1$, generated by a N level digital register and supply a loudspeaker. The MLS have a quasi flat spectrum, and autocorrelation provides a Dirac function. Moreover, its significant signal/noise ratio avoid high peak factor and enables urban background noise decorrelation.

This manipulation involves a Supravox broadband 215RTF-bicone 21cm loudspeaker, enclosed with a $\frac{1}{4}$ length wave system, installed at 6,80m height in the front of the building on a mobile system. The 1/2-inch B&K microphone has a similar height and can move on a half-circle with step of 5° , using a laser pointer for precise setup, in order to vary the reception incidence angle. Frontage impulse response is then recorded for each angle, through a microcomputer equipped with a numerical acquisition card and software emitting MLS, and processing data (MLSSA V.10.0).

The microphonic post-treatment data provides the back-scattered reflection law for each frequency. Compared to the same measurement method applied on a specular smooth urban surface, we obtain the scattering effect of the frontage extrusions.

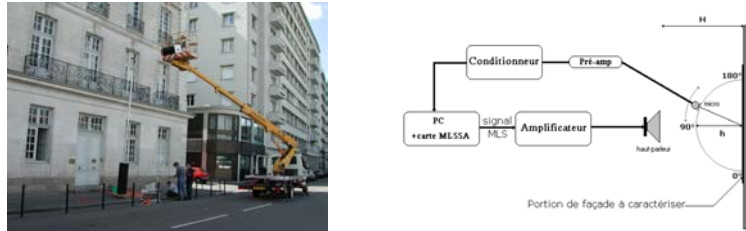


Figure 9 : *In Situ* experimental system

We can note that all measured reflection laws verify the specular mode at low frequencies, in complementation with diffuse reflexion behaviour for high frequencies. An accurate impulse response observation shows the efficiency of this measurement for the scattering description, confirming a sharp correlation between the fractal geometrical analysis of the frontages and the pure acoustical diffractive behaviour [6]. The following figure shows the impulse response provided with a normal positioning of the microphone successively in front of the flat and the neoclassical surfaces. As the direct and specular peaks A and D are clearly readable as in the scale model, the different parts of the frontage response are more detailed in this in situ measurement, so we can discriminate the stonework (B), the windows (C) and the guardrail (E) contributions.

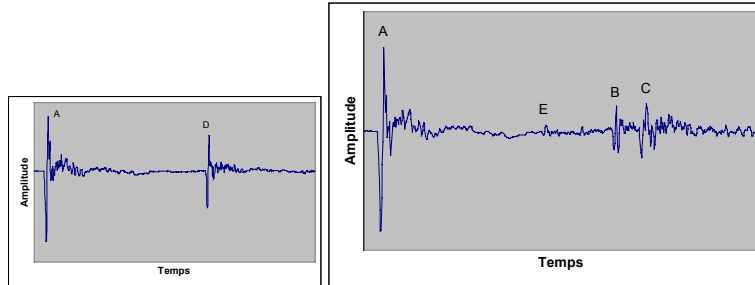


Figure 10 : Comparative impulse responses : flat and neoclassical frontages.

4.2 Comparison between geometrical and experimental results

The following results represent the measured polar reflection laws for each specified frequency band. Values describe the early reflected sound energy level (the first 10 milliseconds backscattered signal) for each reception angle varying from 15° to 165° .

Correspondance between geometrical and metrological results is clearly visible through the « bilobe » behaviour of the low frequencies, evolving towards a cardioïd figure for the medium acoustical domain, including three reflection lobes in the incidence direction and at angles 30° - 140° (consequence from sound reflection on windows). Results for high frequencies confirm the acoustical validity of the fractal geometry evaluation model too, as we can read on both results the diffusivity peaks in the incidence direction and at characteristic angles from 60° to 75° (105 - 170°), and for grazing angles from 15° to 35° (145 - 165°).

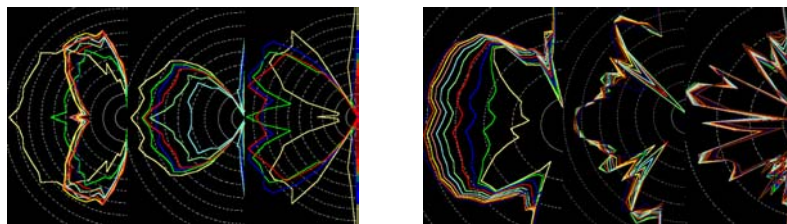


Figure 11 : Comparison of geometrical and measured result data around 100 Hz, 1 kHz and 4 kHz.

5 Conclusion

Comparison between experimental results and morphological characterization shows a good agreement between the results for frequencies from 15 Hz to 6 kHz, for non-grazing incidence angles: specified behavior is discerned for eight frequency bandwidths, readable on both morphological and experimental result data. Therefore, the Minkowski sausage technique provides a quantification of the scatter distribution function of the indented surface of a specified urban neo-classical frontage at each incidence angle.

Developed in the aim of architectural design tools for urban acoustics, this method allows a good evaluation of the acoustical reaction of an urban surface with using morphological attributes of an architecture. Through those morphological treatment of architectural shapes, this research work will confirm the definition of the diffusion process as a geometrical-dependant phenomenon, influenced by the built structure on urban acoustics.

6 References

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