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COHERENT AND INCOHERENT REFLECTIONS AT BUILDING FACADES

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1 INTRODUCTION

Differing from free field situations, sound propagation in an urban environment is usually strongly influenced by reflections and possible shielding effects. Reflections do occur at building façades which are often acoustically hard with no or little absorption. Typically such façades show more or less pronounced structures with a depth stepping in the order of decimeters up to meters in case of balconies. For low frequencies the resulting sound reflections are more likely specular or coherent, for higher frequencies they tend to become more and more diffuse or incoherent.

In the following a simple method will be presented to quantify the degree of incoherence. In a next step the degree of incoherence is estimated for typical façades by numerical simulations and finally a calculation model[1] is proposed to handle coherent and incoherent reflections.

2 QUANTIFICATION OF THE DEGREE OF INCOHERENCE FOR A FACADE

In room acoustical applications two measures are in use to quantify the diffusivity of surfaces. The scattering coefficient measures the amount of sound scattered away from the specular reflection direction. The diffusion coefficient on the other hand describes the spatial uniformity of reflections[2]. For the evaluation of these quantities different methods have been proposed. They all have to solve the problem of separation of the specular and the diffuse portion of a reflection. In a very brief overview the fundamental separation principles are described and finally a new method is introduced based on coherence considerations.

2.1 Directivity characteristics

For specular reflections the directivity pattern shows a narrow peak in the outgoing direction that corresponds to an incident direction with equal angle. A diffuse reflection on the other hand produces a much broader directivity pattern which can have the form of a Lambert characteristics with an outgoing intensity in direction ϕ that is proportional to the cosine of the angle ϕ. By collecting the power in the non-specular direction and relating it to the total reflected power the degree of diffusivity can be evaluated. Mommertz[3] proposed a method to relate the scattering coefficient to the correlation of the reflection directivity of the surface of interest and a flat reference surface of equal size.

2.2 Temporal aspects for impulse excitation

The degree of diffusivity of a reflector can alternatively be identified as temporal smearing of the reflection of an impulse. While a specular reflection seems to originate from a single point (the mirror source position) which produces just one sharp and short pulse, the origin of a diffuse

reflection is distributed over the whole reflecting surface. Due to varying path lengths to a receiver point the response of an impulse is thus a broad temporal pattern with decaying amplitude for increasing traveling time. Such an impulse response has a certain similarity to room impulse responses.
A numerical frequency dependent evaluation of the degree of diffusivity can be based on early/late energy ratios of the band pass filtered and squared impulse response functions. However a difficulty is the setting of the transition time to distinguish between early and late energy.

2.3 Separation of correlated and uncorrelated reflection contributions of a rotating reflector

The diffusivity of smaller reflectors can be investigated in the diffuse field of a reverberation chamber. For that purpose the test sample is mounted on a rotating table. The measurement is performed with a correlation technique (e.g. maximum length sequence stimulus) that is sensitive to the time variance of the system under investigation. By rotating the sample, the uncorrelated contribution of the reflection is suppressed. Once the uncorrelated and correlated parts are separated, the diffusivity can easily be calculated as the fraction of the two portions[4].

2.4 Conservation of interference

In the following a different approach is described to evaluate the degree of diffusivity or – more precisely – the incoherence of a façade reflection. The essential characteristic of a specular reflection is the distinct phase relationship of the surface pressure at different locations on the reflecting surface. It is postulated that a specular reflection can be regarded as fully coherent while on the other hand a perfectly diffuse reflection is totally incoherent.
Coherence is here understood as the capability of a façade to conserve interference in the reflection pattern of two sources located at different positions. A way of investigating this in an experiment is to place two sources S_0 and S_1 in front of the façade of interest (Figure 1) and looking at the frequency response of the reflected sound at different receiver locations M_i on a line symmetrical to the two sources.
The amplitudes of the two sources are assumed to be equal but the phase of source S_1 is shifted by 180° relative to S_0 which leads to a canceling of the reflected contributions in case of a fully coherent reflection. For decreasing coherence the reflected contribution becomes larger.

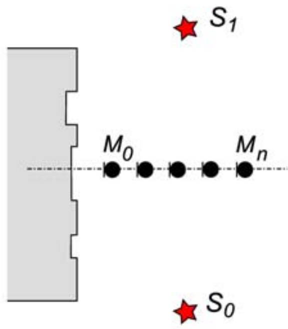

Figure 1: Experiment with two sources S_0 and S_1 in front of the façade under investigation and evaluation of the sound pressure at the receiver positions M_0 .. M_n**.**

For each receiver position M_0 .. M_n the sound pressure stemming from the reflection of source S_0 is composed of a coherent part with squared pressure $p_{S0,c}^2$ and an incoherent part $p_{S0,i}^2$. Similarly for the source S_1 the two contributions are $p_{S1,c}^2$ and $p_{S1,i}^2$.

As the coherent contributions cancel each other due to the 180° phase shift, the resulting sound pressure square p_{tot}^2 corresponds to the sum of $p_{S0,i}^2$ and $p_{S1,i}^2$.

$$p_{tot}^2 = p_{S0,i}^2 + p_{S1,i}^2 \approx 2p_{S0,i}^2 \approx 2p_{S1,i}^2 \tag{1}$$

An incoherence factor ICF can be introduced which measures the fraction of p_{tot}^2 relative to $p_{ref,i}^2$ for a totally incoherent reflection.

$$ICF = \frac{p_{tot}^2}{p_{ref,i}^2} \tag{2}$$

$p_{ref,i}^2$ is not easily accessible, however it is no problem to find $p_{ref,c}^2$ in case of a perfectly flat reflector. Compared to $p_{ref,i}^2$, $p_{ref,c}^2$ is twice as large due to the coherent superposition or amplitude summation. Finally the ICF can be written as

$$ICF = 2\frac{p_{tot}^2}{p_{ref,c}^2} \tag{3}$$

A value of $ICF = 0.5$ can be interpreted as a limit to distinguish between the two reflection types. $ICF < 0.5$ stands for predominately coherent reflections while in cases of $ICF > 0.5$ the incoherent character is dominating.

3 NUMERICAL INVESTIGATIONS FOR EXEMPLARY FACADES

It is impossible to establish a general façade classification due to the large variety. However two fundamental variants that are often encountered can be identified (Figure 2). The first type consists of a flat surface with small depressions in the order of decimeters at the positions of the windows. The second type shows a more pronounced structuring in depth in the order of 1 or 2 meters. This is typical for façades with balconies.

3.1 Simulations

For four different façade types numerical investigations on the ICF were performed with a two dimensional FDTD computer model. In all cases the façade had a height of 18 m. The two sources S_0 and S_1 were placed 10 m in front and at the bottom and top end of the façade. The 10 receiver positions were at half height of the façade in distances from 4 to 14 m. The ICF was evaluated for all receivers and then averaged by taking the arithmetic mean over the receiver specific values (Figure 3 to Figure 6).

3.2 Discussion

The evaluation of the frequency response curves of the ICF shows in all four cases very low values at the lower end of the frequency range. It is no surprise that for wave lengths much larger than the structure depth dimensions, the reflections behave coherent or specular – the structure is simply not recognized by the very long wavelengths. With increasing frequency the ICF becomes larger. The limit of $ICF > 0.5$ (dominating incoherent reflections) is reached for 500 Hz, 250 Hz, 160 Hz and 160 Hz for the structures 1, 2, 3 and 4. In case of the structures 1, 2 and 3 the corresponding sound wavelengths equal about 6 times the structure depth. Structure 4 differs from the others in its general behavior. Here the ICF reaches a value of almost 0.5 already at a frequency of 80 Hz. The incoherence factor then remains almost constant till 125 Hz before it rises above the level of 0.5. At higher frequencies all structures show a dip in the *ICF*. For structures 1, 2 and 3 the dip frequencies correspond to wavelengths that equal 2 times the structure depth. This is plausible as in this case the way back and forth results in a phase turn of 360 degrees. For these frequencies the structure resembles a plane surface.

Figure 2: Typical examples of façades with varying depth structure.

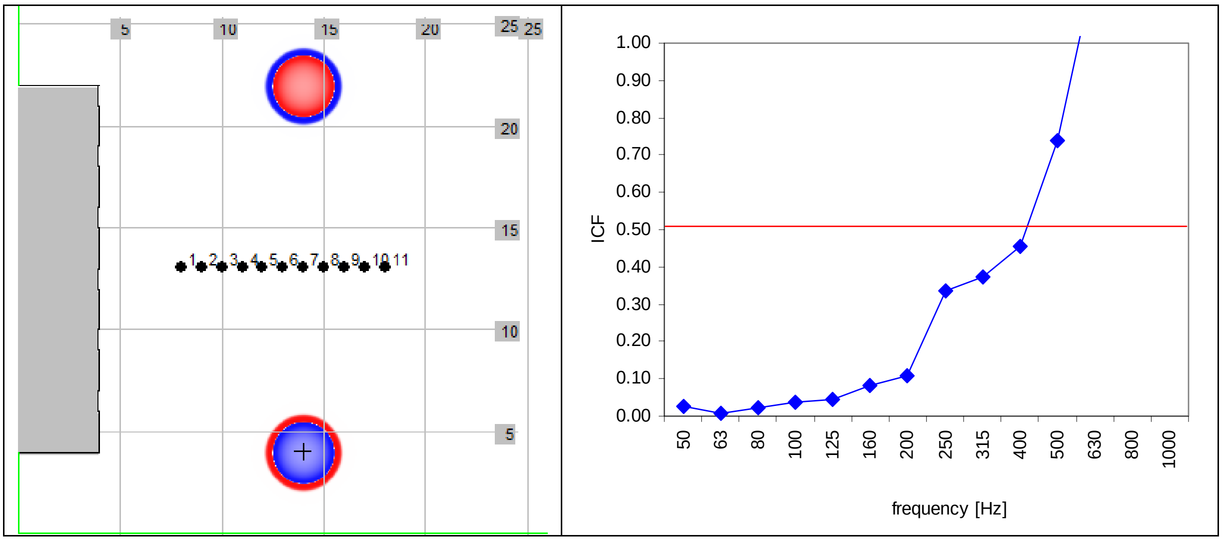

Figure 3: Left: 2D situation of a façade (structure 1) with depressions of 10 cm. The two circles represent the sound pressure distribution around the sources S_0 and S_1 approximately 5 ms after the emission of the impulse. Dark red stands for high positive sound pressure, dark blue marks high negative pressure. Right: resulting average *ICF* as a function frequency.

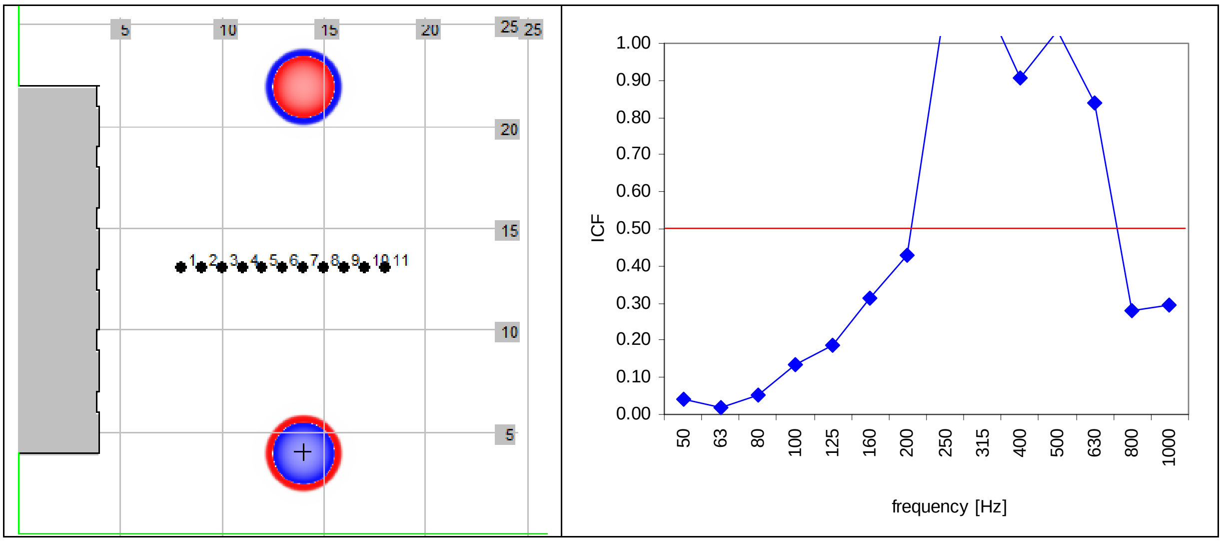

Figure 4: Left: 2D situation of a façade (structure 2) with depressions of 20 cm. Right: resulting average *ICF* as a function frequency.

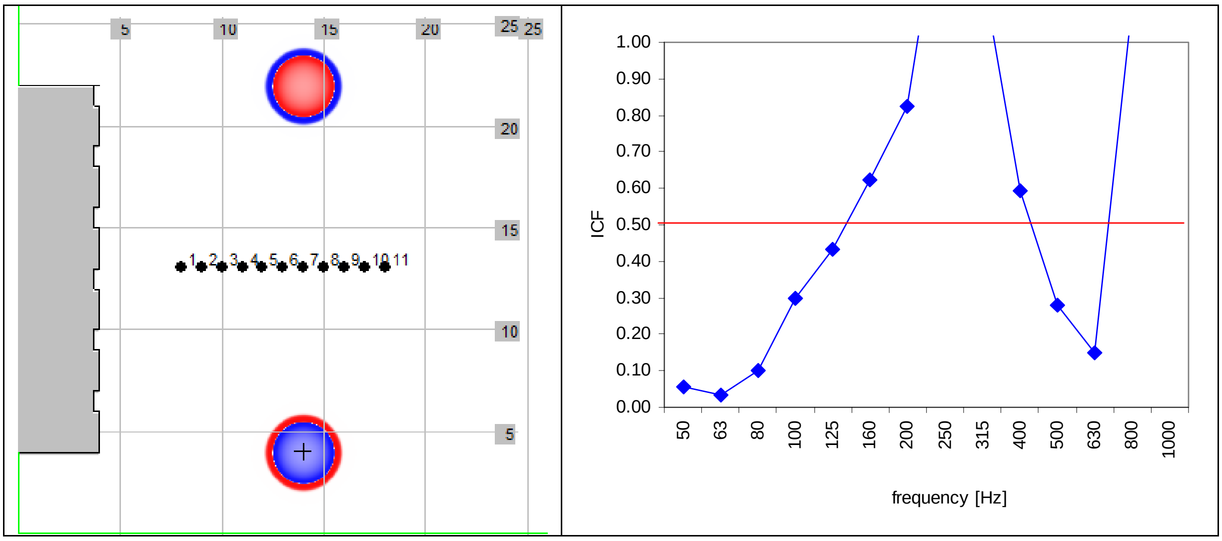

Figure 5: Left: 2D situation of a façade (structure 3) with depressions of 30 cm. Right: resulting average *ICF* as a function frequency.

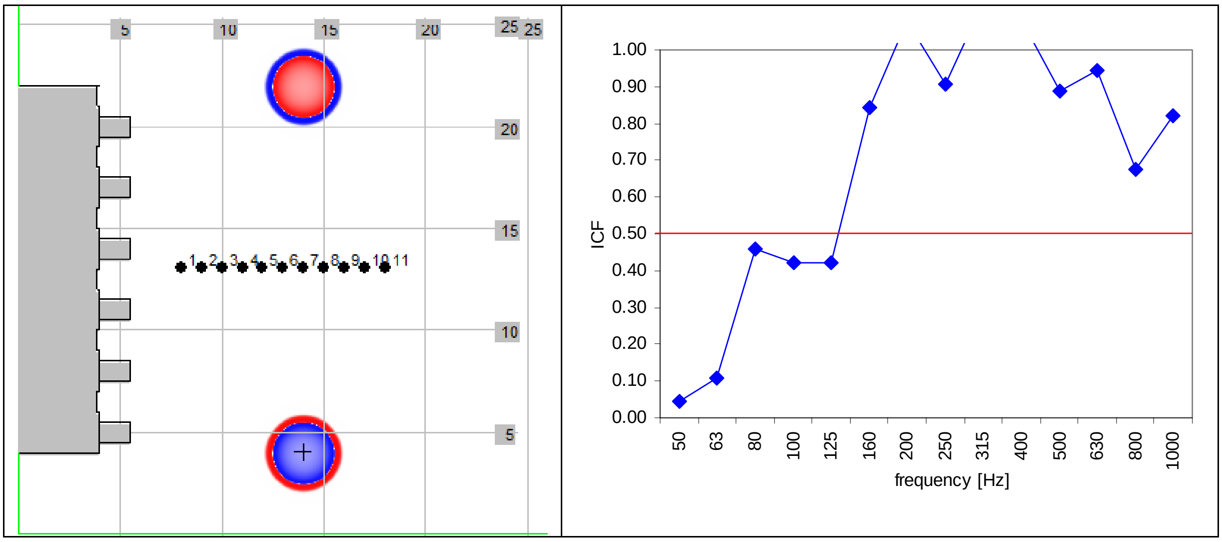

Figure 6: Left: 2D situation of a façade (structure 4) with balconies of 150 cm. Right: resulting average *ICF* as a function frequency.

4 CALCULATION MODEL

As mentioned in the introduction a calculation model for reflections in an urban environment has to distinguish between coherent and incoherent reflections. The above introduced incoherence factor ICF can be used to decide which reflection type is dominating. In the following, the basic principles for a calculation model are presented to handle coherent and incoherent reflections[1].

4.1 Coherent reflections

In principle coherent reflections can be calculated with the help of mirror sources. However this concept assumes that the reflector surfaces are infinitely large. In practical situations this assumption is often violated for low frequencies. The incorporation of the true wave nature of sound is possible by numerical evaluation of the Kirchhoff-Helmholtz integral in Eq. 4. It states that the sound pressure $p(x,y,z,\omega)$ at any point $<x,y,z>$ in space for the angular frequency ω can be expressed as a surface integral of sound velocity $v_S(\omega)$ and sound pressure $p_S(\omega)$ evaluated on a closed surface S.

$$p(x,y,z,\omega)=\frac{1}{4\pi}\int_S\left(j\omega\rho v_S(\omega)\frac{e^{-jkr}}{r}+p_S(\omega)\frac{1+jkr}{r^2}\cos(\phi)e^{-jkr}\right)dS \tag{4}$$

In Eq. 4 the variable r is the distance from the point of interest $<x,y,z>$ to the surface point under consideration, ρ is the density, c is the speed of sound, k is the wave number and ϕ is the angle between the normal direction of the surface and the direction to the point $<x,y,z>$. It can be assumed that typical façades are acoustically hard. It then follows that $v_S(\omega)$ equals zero and the only field variable needed is the sound pressure. With a priori knowledge about the build-up of the sound field, the Kirchhoff-Helmholtz integral (Eq. 4) can be solved iteratively for a discretized representation of the reflecting surfaces.

4.2 Incoherent reflections

The physical concepts behind the model for incoherent reflections are Lambert's law and the fundamental principle of energy conservation. The sound power emitted by a sender and received by a reflecting surface is given by the product of surface area and normal component of sound intensity. It is assumed that near field effects can be ignored which means that sound pressure and velocity are in phase and their amplitude ratio equals ρc. The sound intensity vector points in the same direction as sound velocity. This direction depends only on the last sender position. For that reason no memory is needed that stores the history of the geometry of the sound path.

For a surface element dS the normal component of the incoming sound intensity dI is given by:

$$dI=\frac{W}{4\pi r_1^2}\cos(\phi) \tag{5}$$

where W is the sound power of the sender, r_1 is the distance from the sender to the surface element and ϕ is the angle between the direction from the surface element to the sender and the normal vector of the surface. The sound power dW received by the surface element of area dS amounts to $dI \cdot dS$. It is assumed that dW is reflected according to Lambert’s law. In 1 m distance, the reflected intensity $dI(1\text{m},\psi)$ in direction ψ can be written as

$$dI(1m,\psi)=I_0\cos(\psi) \tag{6}$$

The constant I_0 in Eq. 6 has to be adjusted in such a way that the integral over the surface of a half sphere S (to represent all directions) equals the received sound power dW.

$$dW = \int_S dI(1m,\psi) = \int_0^{\pi/2} I_0 \cos(\psi) 2\pi \sin(\psi) d\psi = I_0 2\pi \frac{\sin^2(\psi)}{2}\Big|_0^{\pi/2} = I_0 \pi \tag{7}$$

Finally, the intensity at a receiver point in distance r_2 with angle ψ to the surface normal vector stemming from dS is given by

$$dI(r_2,\psi) = \frac{dW}{\pi}\cos(\psi)\frac{1}{r_2^2} \tag{8}$$

Again as in the case of coherent reflections, the incoherent sound field can be calculated iteratively for discretized surface elements. It turns out that the updating formulas are identical from a formal point of view for both type of reflections[1].

5 CONCLUSIONS

The calculation of sound fields due to reflections in urban environments has to distinguish between coherent and incoherent reflections. For low frequencies coherent reflections dominate while at higher frequencies the reflections are rather incoherent. The calculation of coherent reflections makes it necessary to discretize the situation geometry in elements in the order of a fraction of the wave length. Regarding the computational effort this is only affordable at low frequencies. For higher frequencies the calculation can be performed with the incoherent model which allows for a significantly coarser discretization. In this case the grid cell size can be chosen in the order of one meter.

Based on an incoherence factor ICF it can be decided whether a reflection has to be handled as coherent or incoherent. Investigations regarding the degree of incoherence for typical façades have shown that structure depths in the order of 20 cm yield a surprisingly low transition frequency of about 250 Hz.

As future work, the applicability and limitations of the incoherence factor concept will be further investigated. Of special interest is the fact that in the numerical simulations ICF values were found as high as 1.5 which is not straightaway compatible with the assumption that the coherent parts of the reflection cancel each other. Furthermore, the sensitivity of the source and receiver positioning will be tested.

6 REFERENCES

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