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Sound insulation auralization filters design for outdoor moving sources

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ABSTRACT

Auralization techniques are rapidly attaining importance, mostly due to their applications in building acoustics and virtual reality. As an application, sound insulation auralization has become a valuable tool to assess the sound insulation of buildings in terms of investigating how the indoor and outdoor noise sources are influencing the daily work and live routine of humans. The airborne sound insulation prediction standards have several simplifications that are implicit in the formulation on which they are based. Therefore, it is necessary to develop a model to build up an auralization chain of the sound insulation by taking into account the complex wave fields on the surfaces of the building elements and the spatial and temporal variation of the sound pressure field inside arbitrarily shaped rooms. We investigate the bending (flexural) wave patterns on the extended walls of buildings, the directionality of the outdoor moving sound sources to construct perceptually correct binaural filters. Additionally, we address the problem of synthesizing the room impulse response from the one-third octave band values of the reverberation times. Our proposed approach increases acoustic interaction with the virtual environments creating a deeper, more realistic and immersive scene and leading to more accurate perceptual evaluations of sound insulation.

Keywords: Sound Insulation, Bending Waves, Auralization, Noise, Perception

1. INTRODUCTION

The ability to predict sound and vibration transmissions in built-up structures such as buildings, trains and automobiles is important for human comfort, health and safety. There is a high concern about steadily growing annoyance due to the noise in private dwellings and the background speech in commercial work sites that leads towards reduced power of concentration during physical or mental work (1). In this context, in residential and worksite premises, especially in urban area, the international standards provided by ISO (International Standards Organization) have reflected the trend mentioned above, increasing both in number and covering broader aspects (2). However, these guidelines do not provide the optimal acoustic satisfaction when specific sounds (e.g. conversation varying in intelligibility) originate from the adjacent office and cause the dissatisfaction in job performance in one hand and on the other hand, when transient moving sound source from outdoor are creating annoyance in daily life's physical or mental work. Therefore, measurement procedures applied in the laboratory or in the field is just one part of the story. There exist several guidelines and standards that describe the performance of buildings elements in terms of noise reduction and sound level reduction indices in the form of a single number value and/or frequency dependent curves. However, it can be assumed that these quantities are insufficient to describe the real situation for the perception of noise, therefore, it is desirable to have a simulation tool which simulates the sound field at the ears of the listener from predicted or measured data using auralization of these noises, which, better consider the subjective impressions of subjects, and psychoacoustic and psychological factors. The basic principle of building acoustic auralization is to simulate the alteration of a sound signal from its source to the receiver via transmission through the building structures. The auralization of a situation, whether it is an office-to-office situation or against the outdoor sounds, where either the speech spoken in one office or the noise produced by an outdoor source, is transmitted through building structures, requires the source signal modelling sound propagation, i.e. its generation and transmission form walls and the insulation characteristics of the direct and flanking elements of dwelling. Both level and spectral characteristics of sources highly depend on the insulation curve of the building construction separating the source and receiver.

Most of the auralization methods of sound insulation are available in compliance with standardized data formats (ISO 12354-1 (3), ISO 12354-3 (4), ISO 3382-2 (5)) of sound insulation by calculating point to point transfer functions from source to the listener. However, due to certain limitations that are rooted in ISO derivations, it is necessary to address certain important wave phenomenon (such as bending wave patterns on the building elements) to design these transfer functions accurately for auralization and plausible reproduction of level and coloration. Therefore, there is an opportunity in developing a building acoustic auralization framework based on detailed models of ISO standards and available up-to-date research (2) and (6-9), to accurately realize the perception and evaluation of noise and its influences on the humans. Hence, we develop an auralization framework dealing with noise producing sources located both inside and/or outside the dwellings. However, in this paper, we present a part of our model that deals with sound sources against outdoor situations.

2. AIRBORNE SOUND INSULATION AGAINST OUTDOOR SOUND

Sound transmission from an outdoor source, (e.g. a moving vehicles), into a building is a complex process. The moving sources are directional sound sources with strong low frequency sound characteristics. There exist multiple propagation paths from these sources to several parts of a building including reflections from the ground and other surround buildings. Sound transmission through exterior walls of a building becomes more complicated because of the varying angles of incidence of the source, the multiple transmission paths within the building and the fact that these phenomena all vary greatly with the frequency of the sound source. In this paper, we introduce a procedure for estimating indoor sound levels from outdoor noise sources. The procedure for the filter designs of sound levels should cover sound transmission loss of exterior walls, roof constructions, windows, and some doors.

2.1 Sound Insulation Model

Our first model for outdoor sound insulation prediction is based on the filter design techniques described in the previous work (10, 14, 16, 17). However, the procedures of filter design for sound levels should cover sound transmission loss of exterior walls, roof constructions and windows. Therefore, we begin with a new idea of segmenting the building elements into finite size patches known as secondary sound sources (SS), because generally the exterior walls of common buildings are consist of an assembly of two or more parts or surfaces (e.g. windows etc.). ISO 12354-3, provides basic guidelines for airborne sound insulation against outdoor sound source, which are based on diffuse field theory. The diffuse sound field approximations are very advantageous for the indoor cases where the adjacent rooms are assumed to be diffuse. This is not the case for outdoor environments. Hence, we take into account only the direct part of the sound filed hitting the surfaces of the building elements exposed. We consider direct sound transmission paths Dd, through each small part of the element (secondary sources) because it is assumed that the transmission for each secondary source is independent from the transmission of the other (4, 6). Therefore, for a direct sound field the sound transmission coefficient of a plane wave depends on the angle of incidence θ, between the direction of propagation of the incident plane wave and the normal to the plane of the exterior elements (i.e. walls). Furthermore, there are certain building acoustics parameters for which, normally, the spatially averaged values are used for indoor cases such as; vibration velocities on the surface of elements, radiation efficiencies and bending wave transmission across the junctions. However, we consider the angle of incidence dependent radiation efficiencies $\sigma(\theta)$, to get angle dependent transmission coefficients. The angle dependent transmission coefficient is denoted as $\tau(\theta)$ and is given by,

$$\tau(\theta) = \left| \frac{1}{1 + \frac{Z(\theta)\cos\theta}{2Z_0}} \right|^2 \quad (1)$$

Z_0 is impedance of free medium (i.e. air). The bending wave impedance of the wall $Z(\theta)$, is given by Equation 2.

$$Z(\theta) = j\omega \left[1 - \left(\frac{f}{f_c}\right)^2 . (1 + j\eta_{tot}) \sin^4 \phi \right] \quad (2)$$

Here, f_c is the critical frequency and η_{tot} is the loss factor of element. The single sided radiation efficiency $\sigma(\theta)$, for infinite plate is given by Equation 2 (for $f > f_c$).

$$\sigma(\theta) = \frac{1}{\cos\theta} \quad (3)$$

Therefore, Equation 1 can be rewritten as,

$$\tau(\theta) = \left| \frac{1}{1 + \frac{Z(\theta)}{2\rho c.\sigma(\theta)}} \right|^2 \quad (4)$$

After simplifications, we finally get the angle dependent transmission coefficient given by,

$$\tau(\theta) = \frac{1}{\left(1 + \frac{mf\pi}{\rho c}.\frac{\eta_{tot}r^2\sin^4\theta}{\sigma(\theta)}\right)^2 + \left(\frac{mf\pi}{\rho c.\sigma(\theta)}\right)^2\left(1 - \left(\frac{f}{f_c}\sin^2\theta\right)^2\right)^2} \quad (5)$$

We now calculate this angle dependent transmission coefficient (Equation 5) for the small segments (finite patch), which is a function of angle dependent radiation efficiency $\sigma(\theta)$. However, due to the assumption of infinite size plates, important discrepancies may be found between predicted and experimental data (18). To remove these discrepancies, we adopted spatial windowing technique which is introduced by Villot et al. in (8), where, he showed that the results are much closer to measurement results than other simple procedures. Hence, we implement this technique for finite size secondary sources (SS) and hence calculate the corresponding transmission coefficients. In spatial windowing technique, the idea behind is to compute the radiated power where only a small area S_S (of length L_x and width L_y) of an infinite structure contributes to the sound radiation, as shown in Figure 1.

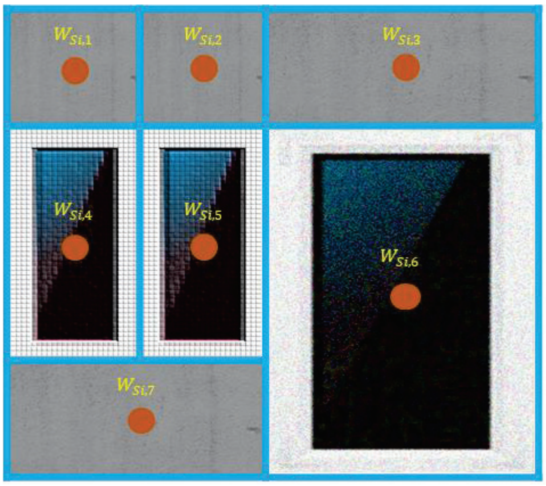

Figure 1 – Exterior wall between source and receiver, segmented into patches (SS)

Assuming a propagating structural wave of wave number k_p, the velocity field in the wave number domain is defined by taking the spatial Fourier transform, giving,

$$\hat{v}(k_x, k_y) = \hat{v}.L_z L_y \frac{\sin\left(\left(k_x - k_p\cos\psi\right)\frac{L_x}{2}\right).\sin\left(\left(k_y - k_p\sin\psi\right)\frac{L_y}{2}\right)}{\left(\left(k_x - k_p\cos\psi\right)\frac{L_x}{2}\right).\left(\left(k_y - k_p\sin\psi\right)\frac{L_y}{2}\right)} \quad (6)$$

Where, ψ is the azimuth angle for k_p. This result is used to calculate the radiated power (with reference to Fahy (15)) and is giving,

$$W(k_p,\psi) = \frac{\rho_0 c_0}{8\pi^2}\int_0^{k_0}\int_0^{2\pi}\frac{\left|\hat{v}(k_x,k_y)\right|^2}{\sqrt{k_0^2-k_r^2}}k_0 k_r d\phi\, dk_r \quad (7)$$

With $k_x = k_r\cos(\phi)$ and $k_y = k_r\sin(\phi)$. The radiation factor (8, 15) is then calculated by double integral, which may be written as,

$$\sigma(k_p,\psi) = \frac{S}{\pi^2}\int_0^{k_0}\int_0^{2\pi}\frac{\sin^2\left((k_r\cos\phi - k_p\cos\psi)L_x\right).\sin^2\left((k_r\sin\phi - k_p\sin\psi)L_y\right)}{\left[(k_r\cos\phi - k_p\cos\psi)L_x\right]^2\left[(k_r\sin\phi - k_p\sin\psi)L_y\right]^2} \times \frac{k_0 k_r}{\sqrt{k_0^2-k_r^2}}\; d\phi dk_r \quad (8)$$

Villot (8), found that the dependence of the radiation efficiency (Equation 7) on the angle ψ is slight. Therefore, in order to condense the results and present the variation of the radiation efficiency as a function frequency and angle of incidence θ, the radiation efficiency is averaged over ψ.

$$\langle\sigma(k_p)\rangle_\psi = \frac{S}{2\pi^3}\int_0^{2\pi}\int_0^{k_0}\int_0^{2\pi}\frac{\sin^2\left((k_r\cos\phi - k_p\cos\psi)L_x\right).\sin^2\left((k_r\sin\phi - k_p\sin\psi)L_y\right)}{\left[(k_r\cos\phi - k_p\cos\psi)L_x\right]^2\left[(k_r\sin\phi - k_p\sin\psi)L_y\right]^2} \times \frac{k_0 k_r}{\sqrt{k_0^2-k_r^2}}\; d\phi dk_r d\psi \quad (9)$$

Furthermore, Fahy (15) and Villot (8) observed that for $k_0 L < 4$, the radiation efficiency of the finite structure (e.g. $1.4 \times 1.1 \; m$) using spatial windowing filtering is lower than that of the infinite system for any angle of incidence and does not significantly vary with the angle of incidence θ, whereas, for $k_0 L > 4$, radiation efficiency of the finite structure increases with the angle of incidence θ, following the radiation efficiency of the infinite system, up to a certain incidence angle and does not significantly vary afterwards. For an acoustic wave, the wave number k_p is related to the incident angle θ, by $k_p = k_0\sin\theta$. Therefore, the transmission coefficient given in Equation 5 can now be determined for small size secondary source (denoted by $\tau_S(\theta)$) by inserting sigma from Equation 9 for frequencies greater than critical frequency. Below the critical frequency, the sound transmission coefficient is calculated using the average diffuse field single sided radiation efficiency approach given in (3), while the bending stiffness is ignored.

The idea is now to apply the spatial windowing to the radiation process and also to find the effect of spatially windowing on the incident pressure field, there by correcting the transmission factor of the infinite structure to obtain the corresponding transmission factor of the finite structure $\tau_S(\theta)$, thus using Equation 9 into Equation 5, we can get the final transmission coefficient for a single secondary source. Another approach proposed by Vigran in (18) to obtain the transmission coefficient $\tau_S(\theta)$, for finite plate (i.e. in our case secondary source), is to calculate the transmission coefficient $\tau_{inf}(\theta)$ for infinite plate and then use Equation 10 to get finite $\tau_S(\theta)$. The term $e^{j\beta(\theta)}$ is the phase of the secondary source radiation, which depends on the incidence angle of the wave and time of arrival of wave at secondary source. In this paper, we are not discussing on the phase part of Equation 10.

$$\tau_S(\theta) = \tau_{inf}(\theta)(\sigma(k_0\sin\theta)\cos\theta)e^{j\beta(\theta)} \quad (10)$$

2.2 Filters Design Technique

Sound insulation filters are designed based on the above presented model, where at the first place, we consider the sound source directivities. Secondly, the sound insulation transfer functions from source to the receiving rooms are calculated for extended walls by using concept of dividing the individual building element into a multitude of secondary sound sources. The elements may be homogeneous (e.g. a single homogeneous wall element) or consisting of an assembly of two or more parts or surfaces (e.g. doors, windows). Thirdly, the receiver room acoustics is implemented in a way that it includes the receiving room reverberation based on room geometry, absorption and binaural transfer functions between secondary sound sources and the receiver. Moreover, the room impulse responses (RIRs) are synthesized from one-third octave band values of the reverberation times of the receiving room.

To proceed for the filters design procedure, let us take a sound source with directivity, Q_S and the acoustics power $P_a = 10^{-12}10^{-0.1L_W}$ (in Watts). Then the mean squared sound pressure at any point at a distance r, from the source in energetic notation is given by Equation 11.

$$p_S^2 = \rho_0 c \cdot \left(\frac{Q_S}{4\pi r^2}\right) \tag{11}$$

The sound power on the external surfaces of the building elements can be calculated with a simple modification to the stationary sound fields in the ordinary room that is to separate the direct sound field and the reverberant part. Therefore, under free field conditions the direct incident sound power on a secondary sound source 'i' of a surface area of S_S, denoted by $W_{S,i}$ is given by Equation 12, where r_i is the distance from the source acoustic centre to the infinitesimal element dS and θ is the incidence angle. The quantities Q_S, r_i and θ depend on the element geometry.

$$W_{S,i} = \frac{P_a}{4\pi}\int_S \frac{Q_S}{4\pi \cdot r_i^2}|\cos\theta| dS \tag{12}$$

Let the integral in Equation 12 can be written as,

$$F_i = \int_S \frac{Q_S}{4\pi r_i^2}|\cos\theta| dS \tag{13}$$

The, F_i, can be approximated numerically under the conditions that the dS elements are neither very large, nor very close to the sound source position and Q_S is smooth in the direction of interest. This integral is obtained by assuming that Q_S, r_i and θ do not vary significantly along S_S. In this way, Q_S, r and θ can be taken out of the integral and we get

$$F_i \approx \frac{S_S \cdot Q_{S,i}}{4\pi \cdot R_i^2}|\cos\theta_i| \tag{14}$$

Where, R_i is the length of vector that goes from the source to the centre of secondary source i and θ_i, is the angle of incidence of vector, R_i. The $Q_{S,i}$ denotes the mean directivity value for particular value of θ_i. We calculate the integral F_i numerically by the well-known adaptive Simpson's method. Thus the incident power on the each secondary source of an element can be calculated by

$$W_{S,i} = \frac{P_a \cdot F_i}{4\pi} \tag{15}$$

Using Equation 15 and the definition of the transmission coefficient, the sound power transmitted from source to receiver room by one secondary source is given by

$$W_{SS} = P_a \cdot \tau_S(\theta) \cdot \left(\frac{F_i}{4\pi}\right) \tag{16}$$

Using Equation 9 and Equation 5, we get $\tau_S(\theta)$ and hence, W_{SS}. And finally the contribution of the Dd path for the finite size patch to the mean squared pressure in the receiving room is derived as follows by using the expression given by Equation 17 with Q_j, as directivity of secondary source and A_R, as the equivalent absorption area of the room.

$$p_{S,R}^2 = \rho_0 c \cdot W_{SS}\left(\frac{Q_j}{4\pi r_j^2} + \frac{4}{A_R}\right) \tag{17}$$

The time domain representation of the sound pressure for single 'SS' is given by Equation 18, where S_i is the area of the walls and r_j is the distance of receiver from secondary source.

$$p_{S,R}^2 = \frac{\rho c \cdot P_a \cdot \tau_S(\theta) \cdot S_S}{S_i}\left(\frac{Q_j \cdot F_i}{16\pi^2 r_j^2} + \frac{F_i}{\pi A_R}\right) \quad (18)$$

For an input time signal, $s(t)$ and transfer function $\tau_S(\theta)$, the final sound pressure in temporal domain from source to receiver for one secondary source as radiating element is given by,

$$p_{R,SS}(t) = \sqrt{\frac{P_a \cdot \tau_S(\theta) \cdot S_S}{S_i}} \cdot s(t) * \left(\sqrt{\frac{Q_j \cdot F_i}{16\pi^2 r_j^2}} \cdot \delta\left(t - \frac{r_i + r_j}{c}\right) + \sqrt{\frac{F_i}{\pi A_R}} \cdot h_R\left(t - \frac{r_j}{c}\right)\right) \quad (19)$$

2.3 Auralization

Once, the filters for sound insulation are calculated as described in the previous section, auralization makes the sound pressure in the receiving room audible at the ears of the listener by an appropriate equipment using reproduction techniques. From an input time signal $s(t)$ and transfer functions (i.e. filters), the time signal at the output of any LTI system can be calculated by means of convolution techniques. Hence, the time signal at a receiver in a room is calculated from the source signal and the transfer function from all secondary sources to the listener by convolution. However, the filters length is an important parameter for convolution technique. We generally consider the building acoustics frequency range to be defined by one-third-octave-bands from 50 to 5000 Hz. For signal processing, these quantities have to be turned into frequency spectra with a practical number of frequency lines. In case of sound insulation filters, an input with 21 values in one-third octave bands ranging from 50 Hz to 5000 Hz are given. To obtain a frequency spectrum with 4097 lines, these values have to be interpolated. This is done by applying cubic spline interpolation on insulation filters.

In the receiving room the secondary sources, located at different positions and orientation relative to the listener's ears, are excited by bending waves due to the sound transmission from the source, therefore, they are required to be perceptually localized to create a spatial impression of listening the room. Hence, it is necessary to consider an auralization with measured or individualized binaural signals by head related impulse responses (HRIR) or corresponding head related transfer function. The expression $\delta\left(t - \frac{r_i+r_j}{c}\right)$ in Equation 19 is then replaced with $HRIR(\theta_j, \varphi_j, \frac{r_i+r_j}{c})$ for binaural room impulse response. In our signal processing, the HRTFs of the ITA dummy head are used. Furthermore, to listen the impression of the receiving room, we have simulated impulse response for the receiving room for each secondary source to the listener position. The expression, $h_R(t)$, in Equation 19 is the room impulse response form a secondary source to the receiver and is statistically valid for all points inside the room.

3. RESULTS

3.1 Verification of Sound Reduction Index 'R'

The method presented is tested in a scenario where the receiving room dimensions are taken as $4.8 \times 4 \times 3 \ m$. The external wall of the room is made of concrete material and is taken as homogeneous finite size plate with internal loss factor, $\eta_{int} = 0.005$ and critical frequency, $f_c = 152 \ Hz$. To verify the results for the direct sound transmission it is segmented into small patches (SS) as shown in Figure 1, and for each patch the transmission coefficients are calculated after applying spatial windowing technique. Here it is necessary to mention that each patch is concrete with same material properties so that we can verify the results of model with ISO standard. After computing sound reduction index R_S for each SS the total reduction index is obtained by using Equation 20, from Vigran (8), and comparison with ISO standards is shown in Figure 2.

$$R_{total} = 10 \log\left[\frac{1}{S_i}\sum_{i=1}^{n} S_S . 10^{\frac{R_S}{10}}\right] \quad (20)$$

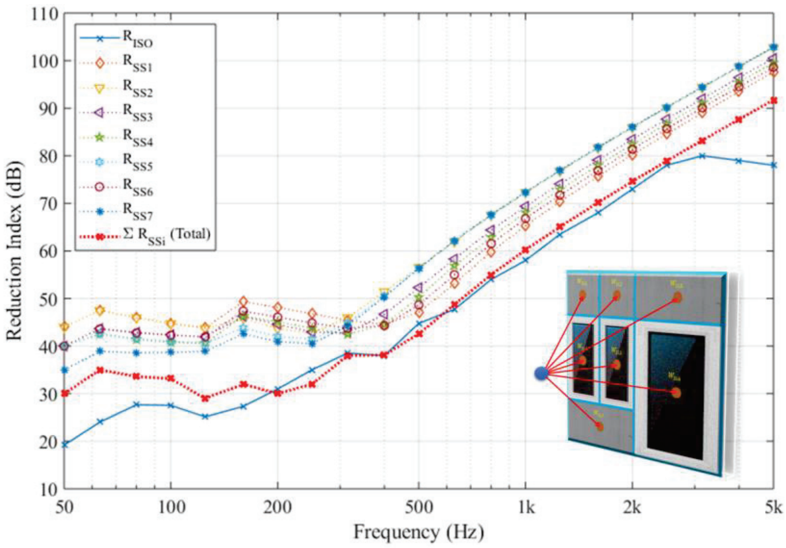

Figure 2 – Comparison of Sound Reduction Index (R)

3.2 Visualization of Sound Filed

A sound source is placed at three positions in the vicinity of the building and sound pressures level is calculated at the exterior surfaces and in the receiving room for these positions as shown.

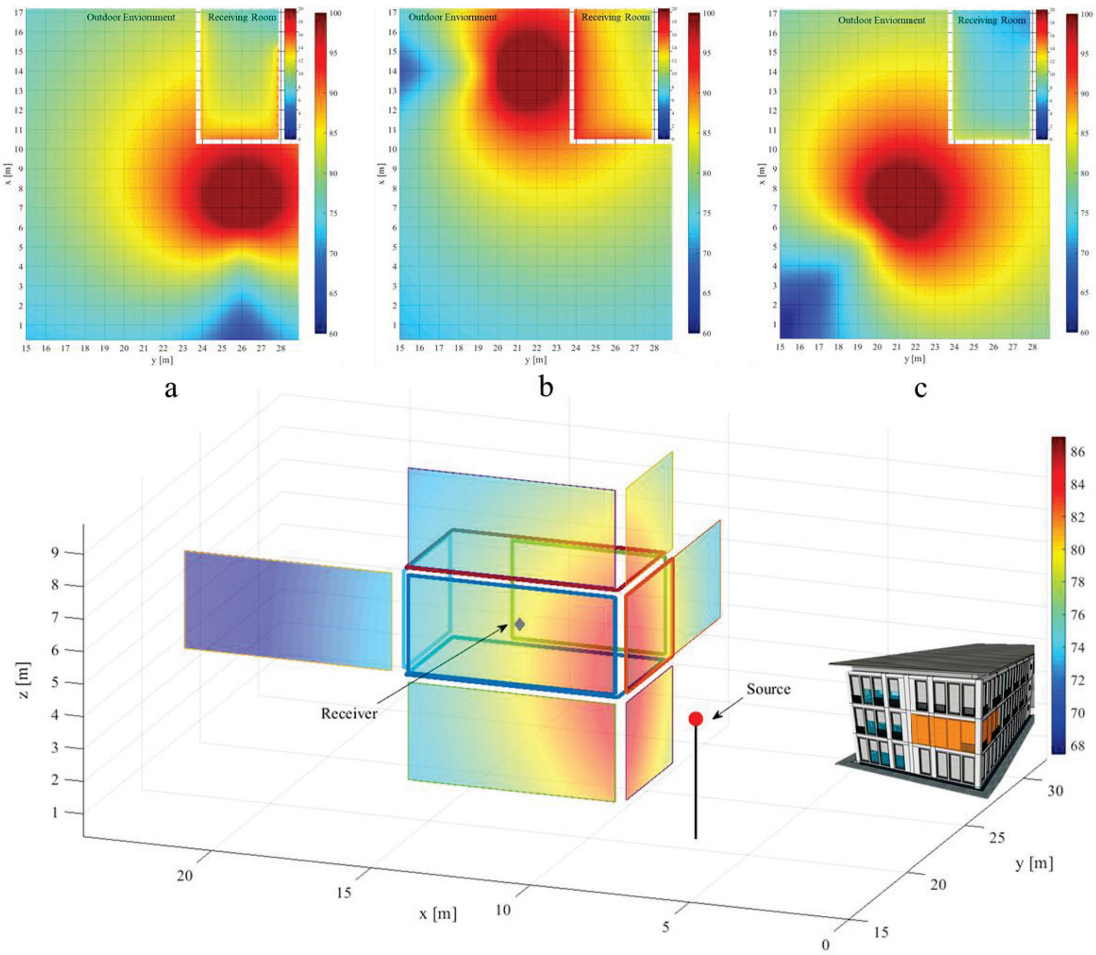

Figure 3 – Sound pressure level at the exterior boundaries of the building. And a, b and c are the sound pressure level at $z = 1.5 \ m$, height from floor in receiving rooms for three source positions

4. CONCLUSIONS

We presented a sound insulation model for filter design in the context of outdoor sources. The findings of this work are analogous to the results of ISO standards. From the results we can conclude that the spatial windowing techniques is quite advantageous for segmenting the building elements into finite size small patches as multitude secondary sources. Hence, it is possible to treat each secondary sources as a sound radiating element for the auralization with its specific phase rather than taking the whole wall as a single point source radiator located at its centre. Furthermore, since the authors assume that the moving outdoor sound source can be perceptually localized within the dwellings and are one of the major reasons for distraction and annoyance, therefore, the next step is to conduct listening experiments to auralise a building scene where the outdoor source would be placed at any location in the vicinity of the building to analyse the localization capabilities of the listeners.

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