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Masoumeh Shafieian, Farokh Hodjat Kashani

Electrical Engineering Dep., Iran University of Science and Technology, Tehran, Iran
e-mails: shafieian@iust.ac.ir, kashani@iust.ac.ir

Effect of sound source directionality and surface diffusivity on sound diffusion

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Sound diffusion is a well known and desired subject in room acoustics; however it is hardly achievable especially in small rooms and low frequencies. Going toward that goal has been the subject of many researches. This paper try to investigate sound source directionality effects on room frequency response, by considering source directivity and surface diffusivity in a model based on Boundary Element Method. Evaluations of the predictions from the room acoustic modeling program have been run using two source types with the same sound power: (a) an omni-directional source; (b) a realistically-directional source with different directionalities together with different combination of diffusive surfaces on room's walls. Analyses have been run for three source/receiver combinations in two rooms on relative sound pressure level (SPL) at low frequencies. Diffusive surfaces are implemented on different rooms' walls and applied to the model. The results also confirm the relation of sound diffusion to surface diffusivity and show what combinations of surface diffusivity and source directivity could lead to a more smooth frequency response.

Keywords: room acoustics, source directivity, sound diffusion, diffusive surface, boundary element method.

INTRODUCTION

Room acoustic is an important and interesting subject in science and technology; and its role in industry, entertainment and everyday life has been proven widely and is going to be more established. Low frequency band has an important role in sound conception and music but the most difficult part to deal in room acoustic. Small rooms, like recording/broadcast studios, home theatres and conference rooms, usually suffer from problems due to low frequency modes. At low frequencies, the standing wave modes of the room are separated in frequency. The frequency response is uneven meaning that some frequencies are emphasized, where mode(s) are strong, and some suppressed, where mode(s) are weak, leading to colouration of received sound. Kuttruff has emphasized in his book the surprising fact that the acoustics of small rooms are in a way more complicated than those of large ones [1]. Common solutions include choosing appropriate room dimensions, loudspeaker locations and listening positions, to flatten the frequency response of the room as much as possible and avoid degenerate modes. Even when the room dimensions have been carefully chosen, however, the frequency response of the room will still be uneven and acoustic treatment is needed [2]. This problem is a very demanding issue for research and finding solution. Applying absorbers to the room to absorb number of these low frequencies will result a pretty dead room which is not pleasing for acousticians. Finding a way not to excite some of these resonance frequencies might be a desired solution.

Adequate diffusion is critical for obtaining an even distribution of reverberant sound in a listening space. Diffusion, by scattering sound, helps absorptive materials be more effective. Where there is inadequate diffusion, acoustical defects such as flutter echo or coplanar reflection patterns can develop. Lack of diffusion can produce irregularities in the slope of the reverberant decay in a room. In concert halls and other critical listening environments the listener gains a sense of envelopment, of being surrounded by the sound, from reflections that come from the side. Lateral reflections are enhanced by materials or objects that increase diffusion.

The ideal tradeoff between diffuse and specular reflection is one of the more interesting design problems. Too little diffusion can result in inadequate envelopment, glare, and other undesirable characteristics. Excessive diffusion can also pose a problem. Too much diffusion is also expensive and may not work well with the desired architecture. Surfaces providing both specular and diffuse reflections are ideal. Although there is general agreement that diffusion is good, there is less certainty about the amount or type, and how to measure it [3].

In addition to diffusion, another question is investigated in this research: what is the influence of sound source directivity on room acoustics; how greatly does the source directivity affect the modeling results? Too often, sound sources in room acoustic are modeled as having omnidirectional characteristics at all frequencies. But is it necessary to utilize directional characteristics for sources?

Previous work examined the subjective and objective affects of changing the directivity of sound sources in acoustic parameters and auralizations [4]. Research by Prince and Talaske [5] confirmed that source directivities are important to consider when modeling a space, as they took measurements in a hall using both an omnidirectional and a directional source and found large differences in the resulting clarity values. The study of directional sources has been further explored by Otondo and Rindel [6]. They showed that source directivity does have a direct effect on the distribution of objective parameters in a room, including sound pressure level (SPL), clarity index (C80), lateral energy fraction (LF80) and early decay time (EDT).

This paper deals specifically with studying the effects of the directional characteristics of sound sources and surface diffusivity on sound diffusion. The main investigation discussed, extends the work on effects of source directivity on room acoustic modeling predictions by comparing results from inputting two different source types with the same power: (a) an omnidirectional source; (b) sources with realistically-directional characteristics. Surface diffusion is also applied to some rooms' walls. Room frequency responses calculated from the model using these two categories of sources, have been compared. The goal is to obtain considerable results that demonstrate the extent to which directional sources and surface diffusivity pattern make a difference in smoothness of room frequency response prediction.

1. ROOM ACOUSTIC MODELING

This paper utilizes a Boundary Element Method (BEM) to solve interior acoustics of rooms. The major advantage of this method is the reduction of the dimension of the problem being solved. The three dimensional problem is solved using two dimensional treatment because only the surface of the body is of concern, whereas in the domain methods such as finite element the whole three dimensional object is needed to solve the problem.

Helmholtz-Kirchhoff integral equation forms the core of many of the prediction models used including BEM. This integral equation formulates the pressure at a point, as a combination of the pressure direct from the sources, and a surface integral of the pressure and its derivative over the reflecting surfaces. The single frequency form of the integral equation gives the pressure $p(r)$ at a position r as [7, 8, 9]:

$$\left\{\begin{matrix} r\in E & -p(r) \\ r\in S & -\frac{1}{2}p(r) \\ r\in D & 0 \end{matrix}\right\} = -p_i(r,r_0)+\int_s p(r_s)\frac{\partial G(r,r_s)}{\partial n(r_s)} - G(r,r_s)\frac{\partial p(r_s)}{\partial n(r_s)}ds, \quad (1)$$

where $r=\{x,y,z\}$ is the vector describing the receiver location, $r_0=\{x_0,y_0,z_0\}$ is the vector describing the source location, $r_s=\{x_s,y_s,z_s\}$ is the vector for a point on the surface, $p(r_s)$ is the surface pressure at r_s, $p_i(r,r_0)$ is the direct pressure radiated from the source at r_0 to the receiver at r, G is the green's function, n is the normal to the surface pointing out the surface, E is the external region, S is the surface and D is the interior of the surface.

By single frequency, it is meant that the system is in steady state conditions so that the time variation, $e^{j\omega t}$, can be neglected. G is the Green's function which gives how the pressure and its derivative propagate from one point in space to another point. Consequently, in 3D the Green's function is simply a point source radiation equation 2:

$$G(r)=\frac{e^{-jkr}}{4\pi r}, \quad (2)$$

where $r=|r-r_0|$ and k is the wave number.

If the surface is taken to be local reacting, the derivative of the surface pressure will be related to the surface pressure by the surface admittance. In terms of equations:

$$jkp(r_s)\beta'(r_s)=\frac{\partial p(r_s)}{\partial n(r_s)}, \quad (3)$$

where β' is the surface admittance. In BEM modeling, it is normal to define quantities in terms of an outward pointing normal. Surface admittances would normally be defined with an inward pointing normal. The prime is used to signify this difference, where $\beta'=-\beta$, where β is the more usual surface admittance [7].

1.1. Sound Source Directivity Considerations

The strength of a pulsating sound source (monopole) can be expressed by the volume flow it generates. The sound pressure is proportional to the volume rate at which fluid is introduced or withdrawn by the source; it is given by [10]:

$$\tilde{p} = \frac{jk\rho c\bar{Q}e^{-jkr+j\omega t}}{4\pi r}. \quad (4)$$

The sound pressure of a small spherical source is determined by its volume flow, and by nothing else. It is obvious that the shape of a small source will not influence the pressure it generates at a sufficiently great distance from it and that sources producing equal volume flow will generate the same sound pressure and the same sound energy.

If the sound source is at the apex of a conical horn and generates the volume flow Q in a space angle Ω, 4π has to be replaced by Ω and the sound pressure becomes [10]:

$$\tilde{p} = \frac{jk\rho c\bar{Q}e^{-jkr+j\omega t}}{\Omega r}. \quad (5)$$

Assuming a cone with apex angle 2θ, the solid angle is the area of a spherical cap on a unit sphere:

$$\Omega = 2\pi\left(1-\cos\theta\right). \quad (6)$$

1.2. Surface Diffusion

Since sound can be described by its phase and amplitude, it is possible to modify the directionality of scattered sound by modifying the phase and amplitude of the scattered wavelets. Change of phase and angle of reflected wave causes diffuse reflection and that's directly related to surface admittance value and its variations. Therefore to apply the diffusive surface on any part of room's wall in the model, the changes of surface admittance can be considered, when sound is scattered from a surface. So the model applies constant values for admittance of nondiffusive parts, while changing values are considered for diffusive parts. Since the BEM model uses boundary elements to less than 1/6 wavelength, it assumes a randomly selected value for admittance of that element which differs from neighboring elements. The admittance value assignment for each element on any diffusive surface is stochastic. Since admittance of a diffusive surface is a complex number, to apply diffusive surface to the model, its admittance is randomized between 0.007 and (0.2, 0.2j); 0.007 approximately corresponds to a random incidence absorption coefficient of 0.056 and (0.2, 0.2j) corresponds to an estimated random incidence absorption coefficient of about 0.7.

This research assumes that the admittance of reflecting, nondiffusive or hard surface is real and is acceptable when the surface impedance is high. The admittance values are assumed to stay constant within the considered frequency range unless otherwise stated. In this text ‘‘admittance’’ refers to normalized admittance value. The admittance of reflecting surfaces is assumed to be 0.009, which approximately corresponds to a random incidence absorption coefficient of 0.07.

2. STRUCTURE OF THE RESEARCH

The main study discussed in this paper involves changes in source directivity and surface diffusion only within the program, which is developed by the authors for this research, and studying the magnitude of differences in the relative SPL results. The purpose is to study the effect of source orientation and surface diffusion on smoothness of room frequency response. In this study BEM is used to model acoustic of the room. Element dimension is set below λ/6, where λ is the wavelength of the acoustic wave. For keeping the numerical errors small, at corners elements are considered smaller than λ/6. Fig. 1 illustrates the room geometry selected: a rectangular room. It is obvious from the figure and *xyz* coordination, that the *xz* planes located at $y = 0$ and $y = LY$ are floor and roof of the room, respectively.

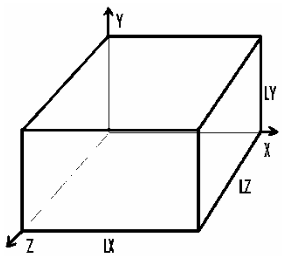

Figure 1.

3D of rooms modeled according to *xyz* coordinates

Two different rooms have been used for the modeling. The dimensions of room 1 are 4 m in length, 3 m in width and 2.8 m in height, which in *xyz* coordination are represented as (4×2.8×3 m). In this room three different source-receiver locations are considered, they are listed in table 1. To approach a more comprehensive conclusion and to study the effect of surface diffusion and source directivity on a medium to large room's frequency response, room 2 is considered. Room 2's dimensions are (6.9×2.8×4.6 m) according to *xyz* coordination. Again three different source-receiver locations are assumed as seen on table 2.

Table 1. Source-Receiver locations for room 1

Source-Receiver Pair	Source location	Receiver location
First	(0.2, 1, 0.2)	(1, 1.5, 1)
Second	(2, 1, 0.5)	(2, 1.5, 2.5)
Third	(2, 1, 0.5)	(0.2, 1.5, 2.8)

Table 2. Source-Receiver locations for room 2

Source-Receiver Pair	Source location	Receiver location
First	(0.3, 1, 0.3)	(3, 1.5, 2)
Second	(3.4, 1, 0.5)	(3.4, 1.5, 3.5)
Third	(3.4, 1, 0.5)	(0.3, 1.5, 4.3)

To validate that our modeling program's results are reliable and accurate, relative SPL in some frequencies (20…100 Hz with 1 Hz resolution) has been measured in room 1 with hard walls. Wall surfaces are very hard with an approximate normalized admittance value of only 0.007, which corresponds approximately to a random incidence absorption coefficient α_{ran} of 0.056. Fig. 2 shows measured and calculated (using numerical BEM model) relative SPL in room 1. In this practice, source was located at (0.2, 1, 0.2) and the receiving point was (1, 1.5, 1).

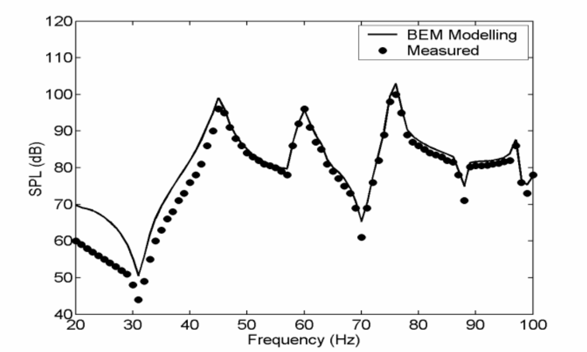

Figure 2.

Comparison of BEM model with measurements in room 1

The discrepancy at frequencies below 40 Hz is due to measurement errors caused by the low signal strength of the loudspeaker at such low frequencies. The accuracy of the developed BEM model is confirmed to be very good.

2.1. Source modeling

As mentioned already, two different types of sources were used in the study: (a) an omnidirectional source; (b) sources with realistically-directional characteristics. For each directional source in all source-receiver pairs, three source orientations are considered and applied to the model. To show directivity of the source, a vector is used. In both rooms, the source directivity vectors which were assumed for the source in first source-receiver pair are: (1, 0, 0) facing left toward *x*-axis direction; (0, 0, 1) facing front toward *z*-axis direction; and (1, 0, 1) facing left with 45º in respect to *x* axis. For the second and third source-receiver combinations, source directivity vectors are: (0, 0, 1) facing front toward *z*-axis direction; (1, 0, 1) facing left with 45º in respect to *x* axis; and (–1, 0, 1) facing right with 135º in respect to *x* axis. The sound power level of each source was set to be the same across all frequencies. The directional source type that was assumed was an artificial one simulated to have a directional radiation pattern. Wang and Vigeant [11] in their study about source directionality and its effect on subjective and objective acoustic parameters in a hall created an artificial sixteenth-tant source, a one-sixteenth slice of the spherical radiation pattern, which has an extremely directional radiation pattern. An extreme case, such as that, was desirable to examine the effects of applying distinct source directivity at all octave bands into the computer model (ODEON). Such extremely directional source is not practical, so a more real one was used in current study. A one-twelfth slice of the spherical radiation pattern was made to beam at a level 10 dB higher than the rest of the source's directivity pattern. The same beaming source directivity pattern was applied to all 1/3 octave bands.

2.2. Room Surfaces Modeling

To evaluate the influence of surface diffusion in presence of different source types and orientations, different cases are considered for each source-receiver pair in both rooms. In the first case all room's side walls and roof are diffusive; in table 3 this case is referred to as "fully diffusive". In this case floor remains reflective. In second case all side walls, roof, and floor are reflecting, this case is named "fully reflective". Four other cases are assumed in the study. In each one, the roof and one of room's side walls are diffusive while other walls and floor are reflective. For clear referring to side walls, in this study they are referred to by numbers. Therefore in followings, mentioned cases are referred to as "roof and wall #(1 to 4) are diffusive". According to the room's shape shown in Fig. 1, wall #1 is on $z = 0$ plane; wall #2 is on $x = LX$ plane; wall #3 is on $z = LZ$ plane; and wall #4 is on $x = 0$ plane.

3. MODELING RESULTS

Relative sound pressure levels are calculated using the program. Each case is applied to the model and modeling is carried out for each source-receiver pair, with the two sources: omnidirectional, and realistically directional with three different orientations.

The goal for a good-sounding room is to achieve a fairly flat room frequency response. We would want the line to be as flat as possible, with few peaks and valleys. Where frequency response peaks and valleys did exist, we would want them to be as shallow as possible. Hence statistical mean (M) and standard deviation (SD) of predicted SPLs for each source-receiver pair for the considered frequency range are calculated and compared. Besides, the source location in second and third source-receiver pair in both rooms is identical. Therefore in addition to examine the evenness of frequency response we could investigate (approximately) whether the sound field in these cases is diffused or not.

The calculated results across all source-receiver pairs for each of the source orientations are tabulated as mean and standard deviation of relative SPL. In following tables, M stands for mean of relative sound pressure levels and SD, in percent, represents standard deviation of sound pressure levels versus mean level.

3.1. Room 1

Tables 3 to 5 show the calculated results of applying all mentioned cases together with different source-receiver locations and specifications for room 1. The considered frequency range is 20…100 Hz. All predictions are calculated at a 1 Hz frequency resolution. It was seen that some numerical results in following tables are very close, to represent the tiny difference in these cases single digit precision is used; even if it doesn't seem necessary.

Table 3. Results of different source directionalities for first source-receiver pair in room 1

	Directional Source Source Directivity Vector						Omnidirectional Source	
	(1, 0, 0)		(0, 0, 1)		(1, 0, 1)			
	M	SD	M	SD	M	SD	M	SD
Fully diffusive	84.9	5.7	86.1	5.0	95.6	5.9	78.7	8.5
Fully reflective	88.5	8.9	87.8	10.7	95.7	6.7	79.4	13.2
Roof and wall #1 diffusive	86.8	7.3	87.6	7.2	95.6	6.2	79.0	10.7
Roof and wall #2 diffusive	86.3	7.4	87.7	8.0	95.6	6.1	79.7	10.3
Roof and wall #3 diffusive	87.3	6.9	86.6	7.6	95.7	6.0	79.8	10.3
Roof and wall #4 diffusive	87.6	7.2	86.5	8.9	95.6	6.3	79.1	11.0

By comparing the results in table 3, it has been shown that in all cases, using directional source results a more flat frequency response. The best result is obtained when source is oriented left with 45º in respect to x axis which the source directivity vector is (1, 0, 1). It is apparent that, the results improve when the walls which source is directed to, are diffusive. Comparison between the results of omnidirectional and directional sources show the undesirable effect of omnidirectional one; so in first source-receiver pair, utilizing omnidirectional source is not recommended at all.

Table 4. Results of different source directionalities for second source-receiver pair in room 1

	Directional Source Source Directivity Vector						Omnidirectional Source	
	(0, 0, 1)		(1, 0, 1)		(-1, 0, 1)			
	M	SD	M	SD	M	SD	M	SD
Fully diffusive	92.9	5.1	87.1	9.7	87.2	9.4	79.5	5.3
Fully reflective	92.9	6.7	88.0	13.2	88.3	12.4	82.9	8.9
Roof and wall #1 diffusive	93.2	5.8	88.4	11.2	88.7	10.5	81.6	7.4
Roof and wall #2 diffusive	93.1	6.0	87.0	12.6	88.5	11.1	81.8	7.4
Roof and wall #3 diffusive	92.7	5.7	88.4	11.2	88.7	10.5	81.8	7.4
Roof and wall #4 diffusive	93.1	6.0	88.4	11.2	88.7	10.5	81.8	7.4

In second source-receiver pair the directional source provides an improvement in flatness of frequency response, but not in all source orientations; this can be deduced from presented results in table 4. The most flat response, in all cases, results from a directional source with (0, 0, 1) source directivity vector, when source is directed front toward *z* axis direction. Otherwise using an omnidirectional source leads to a more smooth response, over using a directional source.

Table 5. Results of different source directionalities for third source-receiver pair in room 1

	Directional Source Source Directivity Vector						Omnidirectional Source	
	(0, 0, 1)		(1, 0, 1)		(-1, 0, 1)			
	M	SD	M	SD	M	SD	M	SD
Fully diffusive	84.4	9.7	91.7	5.1	98.1	5.1	79.9	6.4
Fully reflective	86.4	12.1	96.6	8.0	98.6	7.2	81.2	11.3
Roof and wall #1 diffusive	86.0	10.1	95.0	6.7	98.8	6.0	80.4	9.5
Roof and wall #2 diffusive	86.8	10.6	94.8	6.3	98.7	6.0	81.5	8.3
Roof and wall #3 diffusive	85.2	10.3	94.4	6.4	98.4	5.9	80.7	9.2
Roof and wall #4 diffusive	86.1	10.8	95.3	6.4	98.3	5.9	80.6	9.6

It is obvious from table 5 that the first and second best resulting source directivity vectors are (–1, 0, 1) and (1, 0, 1), respectively. Except utilizing these two source orientations, using an omnidirectional source is preferable.

For better perceiving, Figs 3, 4 and 5 show the results which were calculated for 1/3 octave band center frequencies up to 315 Hz for some cases with first, second and third source-receiver pairs in room 1.

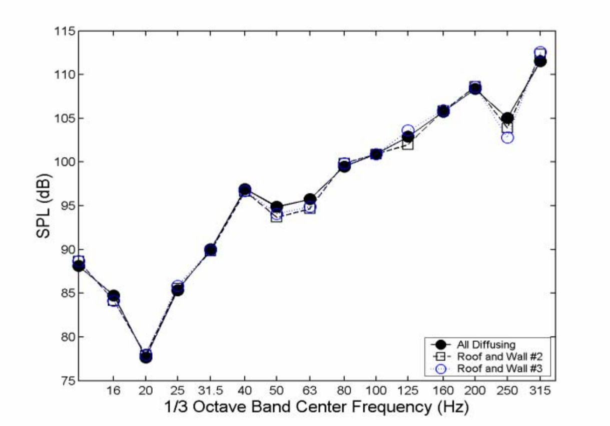

Figure 3.

1/3 octave bands SPL of first source-receiver pair for directional source with directivity vector of (1, 0, 1) in room 1

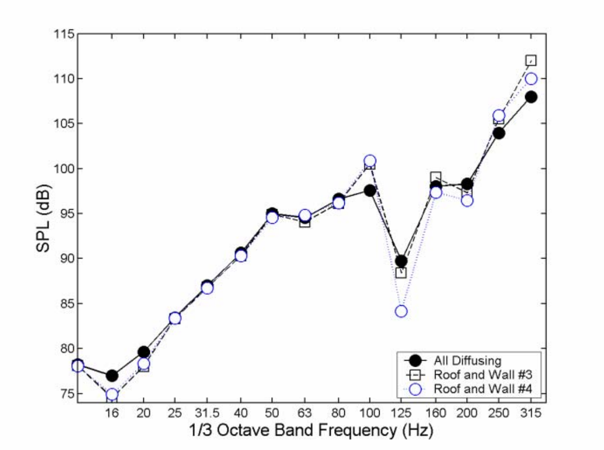

Figure 4.

1/3 octave band SPL of second source-receiver pair for directional source with directivity vector of (0, 0, 1) in room 1

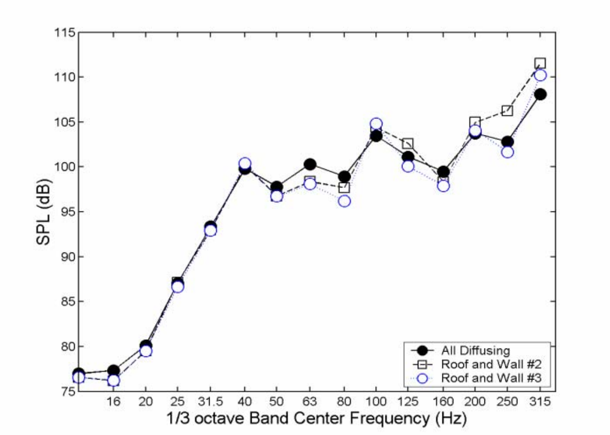

Figure 5.

1/3 octave band SPL of third source-receiver pair for directional source with directivity vector of (–1, 0, 1) in room 1

Comparison between the best results of three source-receiver locations utilizing omnidirectional source and realistically directional source with different orientations in room 1 shows that although “fully diffusive” case brings smoothness to frequency response in some source directionalities, but this is not true for all of them. Besides since covering whole room’s walls with diffusive surfaces is not nor economic, neither beautiful, this case is not applicable in a real room. It is apparent from the results that in some cases, standard deviation of SPL is very close to “fully diffusive” case. So it can be concluded that half of surface diffusion used in “fully diffusive” case is needed to obtain approximately the same results. However the most important matters which must be considered are the amount, order, and location of surface diffusion, which is the matter of more research.

Consequently, the most smooth frequency response in room 1 is obtained with second source receiver pair, when source is oriented toward *z* axis direction while wall #3 and roof are diffusive. In other words, when source is located in front of a diffusive surface and radiate directly toward it, sound field approaches diffusion.

To investigate existence of a nearly diffuse sound field, predicted SPLs for second and third source receiver pairs (with identical source location) are compared in table 6.

Table 6. Comparison of predicted results of different source directionalities when source location is (2, 1, 0.5), for two receiver locations in room 1

	Directional Source Source Directivity Vector												Omnidirectional Source			
	(0, 0, 1)				(1, 0, 1)				(–1, 0, 1)							
Receiver location	(2,1.5,2.5)		(0.2,1.5,2.8)		(2,1.5,2.5)		(0.2,1.5,2.8)		(2,1.5,2.5)		(0.2,1.5,2.8)		(2,1.5,2.5)		(0.2,1.5,2.8)	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Fully diffusive	92.9	5.1	84.4	9.7	87.1	9.7	91.7	5.1	87.2	9.4	98.1	5.1	79.5	5.3	79.9	6.4
Fully reflective	92.9	6.7	86.4	12.1	88.0	13.2	96.6	8.0	88.3	12.4	98.6	7.2	82.9	8.9	81.2	11.3
Roof and wall #1 diffusive	93.2	5.8	86.0	10.1	88.4	11.2	95.0	6.7	88.7	10.5	98.8	6.0	81.6	7.4	80.4	9.5
Roof and wall #2 diffusive	93.1	6.0	86.8	10.6	87.0	12.6	94.8	6.3	88.5	11.1	98.7	6.0	81.8	7.4	81.5	8.3
Roof and wall #3 diffusive	92.7	5.7	85.2	10.3	88.4	11.2	94.4	6.4	88.7	10.5	98.4	5.9	81.8	7.4	80.7	9.2
Roof and wall #4 diffusive	93.1	6.0	86.1	10.8	88.4	11.2	95.3	6.4	88.7	10.5	98.3	5.9	81.8	7.4	80.6	9.6

Only omnidirectional source's results in two receivers are relatively close. Another examination was done by comparing the predicted SPLs when source is placed at (2, 1, 0.5), for five receiver locations: R1: (2, 1.5, 2.5); R2: (1, 1.5, 1); R3: (0.2, 1.5, 2.8); R4: (3, 1.5, 1); R5: (2, 1.5, 1.5); for 1/3 octave band center frequencies up to 200 Hz. The comparison result is shown in Fig. 6. Source is directional with (0, 0, 1) directivity vector. Floor and wall #3 are considered to be diffusive. Since these assumptions had shown the best results in room 1, they were chosen for this prediction. It can be seen in Fig. 6, when receivers are in a same plane, the SPLs are nearly close.

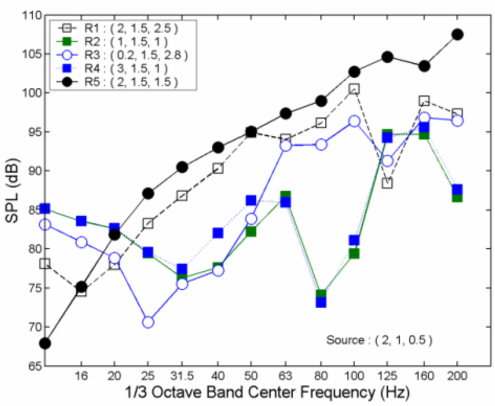

Figure 6.

1/3 octave band SPL when source-receiver pair for directional source with directivity vector of (–1, 0, 1) in room 1

3.2. Room 2

Could room 1's conclusion be extended if room's dimensions are changed? To investigate that room 2 is considered. By applying different mentioned cases, the calculations are carried out using the program and presented in table 7 to 9 for three source-receiver pairs. The predictions are calculated for 1/3 octave band center frequencies up to 200 Hz.

Table 7. Results of different source directionalities for first source-receiver pair in room 2

	Directional Source Source Directivity Vector						Omnidirectional Source	
	(1, 0, 0)		(0, 0, 1)		(1, 0, 1)			
	M	SD	M	SD	M	SD	M	SD
Fully diffusive	85.4	7.5	81.7	6.9	83.4	9.5	73.7	10.4
Fully reflective	91.4	14.6	85.2	13.6	88.9	14.1	79.0	15.2
Roof and wall #1 diffusive	87.7	11.6	83.5	8.2	84.3	11.2	75.7	12.3
Roof and wall #2 diffusive	86.3	11.4	83.3	8.6	84.1	10.8	75.8	12.1
Roof and wall #3 diffusive	88.1	11.1	82.9	8.4	84.3	10.6	75.8	12.0
Roof and wall #4 diffusive	87.1	10.7	82.4	8.3	82.8	13.2	75.1	11.5

Comparison between the room 2's results (see table 7) and room 1's, shows that the standard deviations are greater than their pairs for room 1. As was expected frequency response of room 2 is wavier than room 1's. The best results are obtained when a directional source with source directivity vector of (0, 0, 1) is used. Otherwise an omnidirectional source results a smoother frequency response.

Table 8. Results of different source directionalities for second source-receiver pair in room 2

	Directional Source Source Directivity Vector						Omnidirectional Source	
	(0, 0, 1)		(1, 0, 1)		(–1, 0, 1)			
	M	SD	M	SD	M	SD	M	SD
Fully diffusive	84.4	9.9	80.8	8.0	80.9	8.4	75.3	5.3
Fully reflective	87.4	14.2	86.5	15.3	86.7	14.5	81.6	13.2
Roof and wall #1 diffusive	85.4	11.7	83.7	11.9	84.5	10.0	77.5	9.1
Roof and wall #2 diffusive	85.1	11.7	82.3	12.2	84.2	10.4	77.7	8.8
Roof and wall #3 diffusive	84.8	11.2	82.6	11.3	82.3	11.3	77.6	8.9
Roof and wall #4 diffusive	85.1	11.7	83.4	11.9	82.9	11.4	77.7	8.8

By comparing the data in table 8 it is seen that despite previous results, an omnidirectional source obtains the most flat frequency response for all cases, however this is not the desired frequency response.

By looking at table 9 it is obvious, like the former source receiver pair (table 7), the omnidirectional source have the best frequency response, although it is far from an ideal one.

The same analysis (like room 1) could be done by comparing the results of second and third source-receiver pairs in room 2, because the source locations are identical. The results are tabulated in table 10. It is apparent, the calculated results in two receiver locations of an omnidirectional source and a directional source with (0, 0, 1) directivity vectors are relatively close.

Table 9. Results of different source directionalities for third source-receiver pair in room 2

	Directional Source Source Directivity Vector						Omnidirectional Source	
	(0, 0, 1)		(1, 0, 1)		(-1, 0, 1)			
	M	SD	M	SD	M	SD	M	SD
Fully diffusive	80.1	11.8	86.4	6.6	92.8	9.2	76.9	5.4
Fully reflective	86.7	18.0	95.0	12.6	95.3	12.3	83.4	13.3
Roof and wall #1 diffusive	83.5	13.6	90.6	10.0	94.3	10.6	79.5	8.8
Roof and wall #2 diffusive	84.1	14.4	89.7	9.5	94.2	10.7	79.9	8.8
Roof and wall #3 diffusive	82.1	14.3	89.9	10.0	93.9	10.6	79.7	9.0
Roof and wall #4 diffusive	83.2	14.2	90.5	9.8	93.6	10.3	79.1	9.1

Table 10. Comparison of predicted results of different source directionalities when source location is (3.4, 1, 0.5), for two receiver locations in room 2

	Directional Source Source Directivity Vector												Omnidirectional Source			
	(0, 0, 1)				(1, 0, 1)				(-1, 0, 1)							
Receiver location	(3.4,1.5,3.5)		(0.3,1.5,4.3)		(3.4,1.5,3.5)		(0.3,1.5,4.3)		(3.4,1.5,3.5)		(0.3,1.5,4.3)		(3.4,1.5,3.5)		(0.3,1.5,4.3)	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Fully diffusive	84.4	9.9	80.1	11.8	80.8	8.0	86.4	6.6	80.9	8.4	92.8	9.2	75.3	5.3	76.9	5.4
Fully reflective	87.4	14.2	86.7	18.0	86.5	15.3	95.0	12.6	86.7	14.5	95.3	12.3	81.6	13.2	83.4	13.3
Roof and wall #1 diffusive	85.4	11.7	83.5	13.6	83.7	11.9	90.6	10.0	84.5	10.0	94.3	10.6	77.5	9.1	79.5	8.8
Roof and wall #2 diffusive	85.1	11.7	84.1	14.4	82.3	12.2	89.7	9.5	84.2	10.4	94.2	10.7	77.7	8.8	79.9	8.8
Roof and wall #3 diffusive	84.8	11.2	82.1	14.3	82.6	11.3	89.9	10.0	82.3	11.3	93.9	10.6	77.6	8.9	79.7	9.0
Roof and wall #4 diffusive	85.1	11.7	83.2	14.2	83.4	11.9	90.5	9.8	82.9	11.4	93.6	10.3	77.7	8.8	79.1	9.1

CONCLUSIONS

A validation study has shown that the objective results from our room acoustic computer modeling program based on BEM, matched quite well to those measured in an existing room. Consequently, the program was used to carry out the main study. The main investigation evaluated changes in the calculated room frequency response using two types of sources with the same sound power: (a) an omnidirectional source; (b) sources with realistically-directional characteristics and different orientations. Surface diffusion was also applied in different parts of the room.

The main analysis was carried out using two rooms; room 1 which is a pretty small room, and room 2 which is a medium room. Results demonstrate that using directional sources and surface diffusion may cause a smoother frequency response in some cases, but in others an omnidirectional source gives somewhat a smoother frequency response.

It was seen in all source-receiver pairs in room 1, realistically directional source leads to a smoother frequency response, while omnidirectional source's results were not preferable most of the time. In contrast the SD of SPL calculated for a directional source for most of source-receiver pairs with different directionalities was pretty high in room 2, which means this type of source is not desired to approach sound diffusion in such rooms. In both rooms, the smoothness of room response apparently improved when the realistically directional source was directed to a wall covered with diffusive surfaces.

Although different patterns of surface diffusion affect flatness of the response, but it was seen that in four last cases for a specific source directivity vector, changes in surface diffusion pattern have not a significant effect on the room sound diffusion. As mentioned earlier, in these cases one wall and the roof are diffusive while other surfaces remain reflective. Therefore it can be concluded that in each orientation of source, the diffuseness of the wall which source is directed to, does not affect much the smoothness of frequency response in compare to the diffuseness of another room's wall. This is true in both rooms for all source-receiver pairs and all source directivity vectors, except few cases.

Comparing the results of one source in two receiver locations show: the omnidirectional source in room 1 results a nearly diffuse sound field while the omnidirectional and directional source with (0, 0, 1) directivity vector yields such field.

The conclusions may be no comprehensive because of limited frequency ranges and room dimensions; that is due to computational burden on BEM based program.

Future work could expand this research by completing similar analyses under different combinations of real diffusers that could influence the degree to which source directivity can influence the flatness of frequency response, and also in rooms of varying dimensions and geometries. Another idea is to test other directional traits of sources, such as sources in motion. Besides utilizing some absorption together with former assumptions is also the matter of further research. These additional investigations will continue to lead to better understanding of the effect of source directivity and characteristics of room's surfaces on room acoustic modeling.

REFERENCES

1. Kuttruff H. Room Acoustics, fourth edition, ISBN 0-419-24580-4, Spon Press, 2000.
2. Cox T. J., D'Antonio P. Acoustic Absorbers and Diffusers, Theory, design and application, ISBN 0-415-29649-8, Spon Press, 2004.
3. M. Long. Architectural Acoustics, ISBN 13: 978-0-12-455551-8, Elsevier Academic Press, 2006.
4. Dalenback B. I., Kleiner M, Svensson P. Audibility of changes in geometric shape, source directivity, and absorptive treatment — experiments in auralization. J Audio Eng Soc 1993, 41(11), 905–13.
5. Prince D., Talaske R., Variation of room acoustic measurements as a function of source location and directivity. Wallace Clement Sabine centennial symposium, 1994, p. 211–14.
6. Otondo F., Rindel J. H., The influence of the directivity of musical instruments in a room. Acta Acust Unit Acust, 2004, 90(6), 1178–84.
7. Burton A. J. The solution of Helmholtz equation in exterior domain using integral equations, NPL Report NAC30, 1973.
8. Schenck H. A. Improved integral formulation for acoustic radiation problems, J. Acous. Soc. Am. 44, pp. 41–58, 1968.
9. Lam Y. W. Issues of computer modeling of room acoustics in non-concert hall settings. J. Acoust. Sci. & Tech. 26, 2, 2005.
10. Skudrzyk E. The Foundations of Acoustics, Basic Mathematics and Basic Acoustics. ISBN 3-211-80988-0, Springer-Verlag, Wien, 1971.
11. Wang L. M., Vigeant M. C. Evaluations of output from room acoustic computer modeling and auralization due to different sound source directionalities. Applied Acoustics, December 2008, volume 69, issue 12, pp. 1281–93.