MODELLING AIRBORNE SOUND TRANSMISSION BETWEEN COUPLED ROOMS

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ABSTRACT

A new method has been developed for the calculation of transmission through walls, including auralization in the receiving room. This has been made as an option in the room acoustic simulation software Odeon version 9. Transmission through multiple walls can be investigated; even walls with different materials on either side and with thickness can be handled. The influence of partial areas with different transmission losses, the volumes of the rooms, and the reverberation times of the rooms are included in the simulation results.

1. INTRODUCTION

The room acoustic modeling software Odeon is based on ray tracing in combination with a secondary source radiation method for reflections after a certain transition order, typically 0 – 3 order of reflection. In version 9.0 of this software the option of sound transmission modeling has been introduced [1].

This feature is thought to be useful in projects like schools, offices and industrial halls, where the interesting sound propagation is not limited to a single room. The method may be particularly useful for the prediction of sound insulation between spaces with non-diffuse sound fields like rooms with very uneven distribution of sound absorption and/or special room shape.

Recently, the same idea has been described by Billon et al. [2] but with a different approach. Instead of a ray tracing model they applied a system of two diffusion models, one for each room, and solved the equations numerically with a finite element method.

2. SOUND TRANSMISSION AND RAY TRACING

2.1. Transmission from one room to the next

The possibility of sound transmission between rooms should preferably fulfill the following goals:

- The calculation results in the source room should not be affected
- The calculation time should not be too long
- The sound transmission should be characterized by a frequency dependent reduction index
- The sound pressure level and room impulse response should be accurately calculated in both rooms, taking the absorption in source room and receiver room into account
- Creation of realistically sounding auralization of the sound in both rooms, thus allowing a subjective evaluation of the sound insulation.

The principle is illustrated in Fig. 1. In a two-dimensional section is shown a large number of sound particles (representing the ray tracing of a large number of rays), starting from a point in the source room. When hitting a normal surface the particles are reflected back into the room in accordance with a reflection and scattering model. However, when the particles hit a surface, which has been marked as a transmission surface, a certain fraction of the particles are transmitted, i.e. they jump through the surface into the adjacent room where they continue the propagation. In this way the transmitting surface becomes a sound source that radiates into the receiver room. The transmitting surface may be either a single surface or two parallel surfaces, as the case shown in Fig. 1. This allows the absorption material to be different at the two sides of the surface.

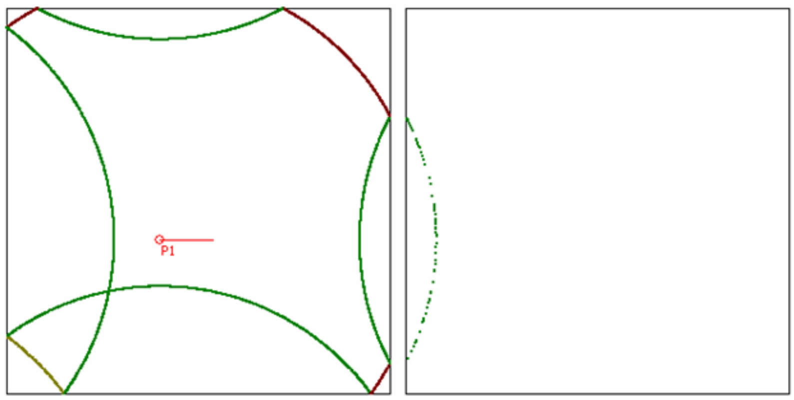

Figure 1. *Illustration of a sound wave being reflected from the boundaries in the source room (left) and partly transmitted into the adjacent room. P1 is the source.*

2.2. Fraction of transmitted rays/particles

In the Odeon model the particles are treated as carriers of sound energy that is reduced after each reflection with the frequency dependent reflection coefficients of the surfaces. So, a straight forward method could be to let the particles split into a reflected part and a transmitted part, the energy of the latter being reduced according to the frequency dependent reduction index of the transmitting surface. However, this would lead to an explosion in number of particles to deal with and thus the calculation time would be unacceptable.

In stead, in Odeon version 9.0 a method was introduced in which the fraction of transmitted particles was set to 50%, so statistically an equal number of particles would be either reflected or transmitted. In this way the total number of particles in the calculation would remain the same, and in order to compensate for the reduced number of particles, the energy of both reflected and transmitted particles was adjusted by a factor of 2 (i.e. + 3 dB). However, in some cases this method could give problems calculating the correct decay curve due to a high fraction of particles being transmitted back from the adjacent room to the source room.

Decreasing the fraction of transmitted particles can solve the problems in the source room, but in the receiver room it may then be difficult to reach a sufficient reflection density. There doesn't seem to be a well defined optimum fraction of transmitted particles. However, if only 1% is transmitted it is clear that a very large number of initial rays/particles would be required (at least 100 times more rays would be needed in order to get a sufficient reflection density in the receiver room). Thus, in the most recent Odeon version 9.2 the fraction of transmitted particles has been set to 10%. This means that transmitted particles have the energy increased by a factor of 10 (i.e. + 10 dB) before the values of the reduction index are subtracted, and the reflected particles have the energy increased by a factor of 10/9 = 1.1111 (i.e. + 0.5 dB). This is the model that has been examined below.

2.3. Testing with different reduction index

In the following tests the decay curves and the integrated squared impulse responses (the Schroeder curves) have been investigated at the 1 kHz octave band in the source room as well as in the receiver room. The room dimensions are 5 m * 5 m * 5 m and the transmitting surface is 25 m^2. All surfaces have the absorption coefficient of 0.10. Fig. 2 shows the results for R = 40 dB, 10 dB, and 6 dB.

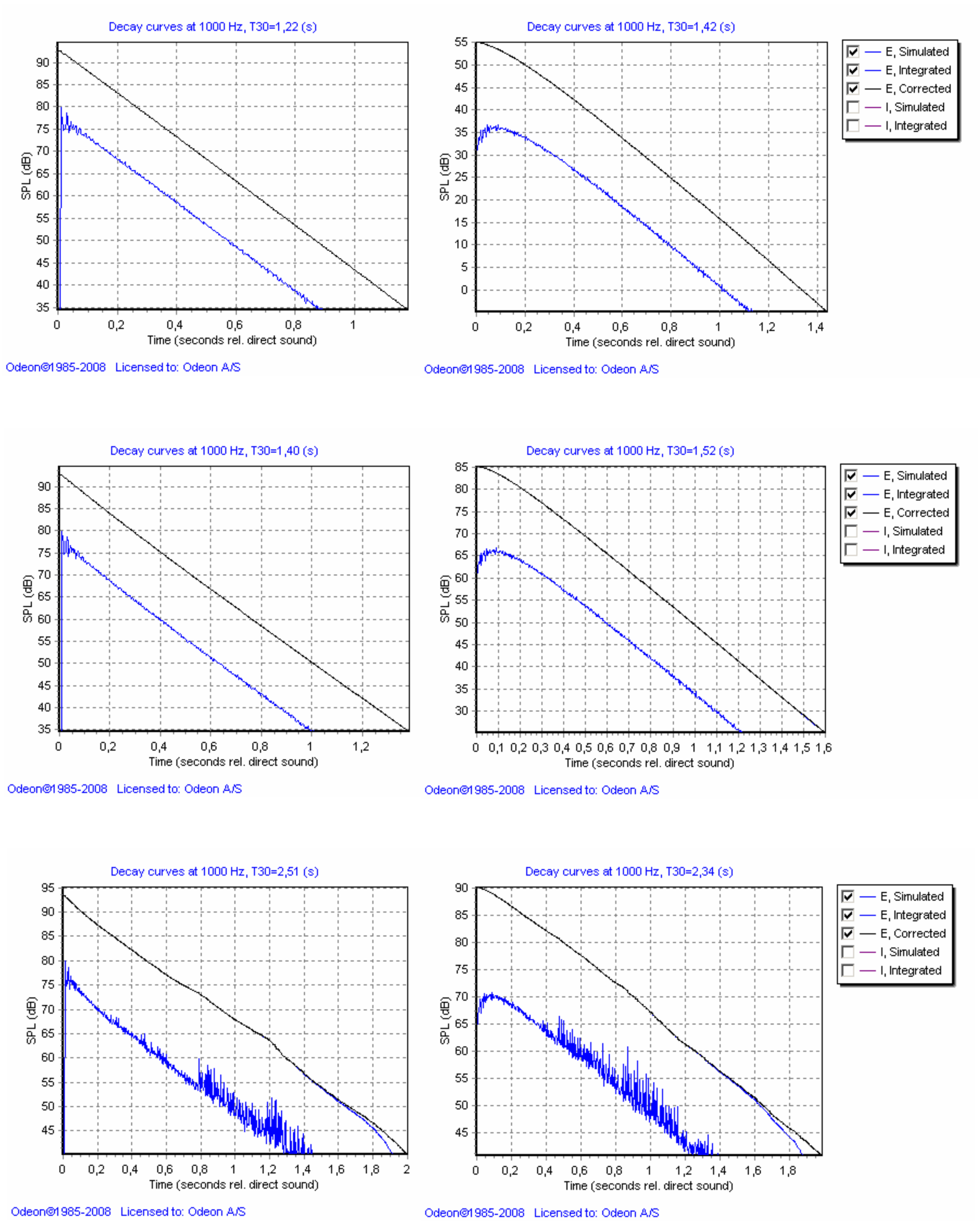

Figure 2. *Calculated decay curves and integrated squared impulse response curves.*
Left column: Source room, Right column: Receiver room.
Top row: R = 40 dB, Middle row: R = 10 dB, Bottom row: R = 6 dB.

It is seen in Fig. 2 that the calculated decay curves are very similar with R = 40 dB and 10 dB, whereas the lower curves for R = 6 dB are clearly infected by strong reflections that appear after approx. 45 ms in the receiver room and after approx. 60 ms in the source room. This means that for R = 6 dB the results are not reliable, e.g. the calculated reverberation time is too long (2.5 s in stead of 1.2 s) and the sound pressure level is too high (95.2 dB in stead of 94.5 dB), see Table 1. The case of infinite reduction index in Table 1 is calculated by setting all surfaces to 'normal', i.e. without any sound transmission to the adjacent room.

Table 1. *Calculated reverberation times and sound pressure levels in the source room at 1 kHz for different values of the reduction index of the transmitting surface.*

R (dB)	3	6	10	20	40	∞
T_{30} (s)	–	2,51	1,40	1,20	1,22	1,19
SPL (dB)	101,8	95,2	94,6	94,5	94,5	94,5

The test results suggest that the transmission model works satisfactorily for transmission losses at 10 dB and above that. For the reduction index less than 10 dB the coupling between the two rooms is too strong with this method and thus the sound decay in the source room is affected by the decay in the adjacent room.

2.4. Testing with different absorption in source room

A series of tests have been made in order to verify the suggested method. The tests are very similar to those in ref. [2]. The reference test case is the same as above, but with R = 20 dB, both rooms 125 m^3 and all surfaces having absorption coefficient $\alpha = 0.10$.

In each simulation the sound pressure levels are calculated in a position in the middle of each room with the source in the source room. The reverberation time in the receiver room is found from a calculation with a source in the receiver room using an evaluation range from -5 dB to -35 dB, and finally the reduction index is calculated from the equation:

$$R = L_1 - L_2 + 10 \cdot \log \frac{S}{A_2} = L_1 - L_2 + 10 \cdot \log \frac{S \cdot T_2}{0.16 \cdot V_2} \text{ , (dB)} \tag{1}$$

where L_1 and L_2 are the sound pressure levels in the source and receiver room, respectively, S is the area of the transmitting surface, A_2 is the equivalent absorption area of the receiver room, and T_2 and V_2 are reverberation time and volume of the receiver room, respectively.

Table 2. *Results of calculated transmission using different absorption in the source room.*

α (1)	L_1 (dB)	L_2 (dB)	L_1-L_2 (dB)	T_2 (s)	Corr.	R (dB)	Diff.(dB)
0,05	96,06	77,95	18,11	1,2	1,76	19,9	-0,1
0,1	93,25	75,11	18,14	1,2	1,76	19,9	-0,1
0,2	90,42	72,18	18,24	1,2	1,76	20,0	0,0
0,3	88,46	70,15	18,31	1,2	1,76	20,1	0,1
0,4	87,29	68,83	18,46	1,2	1,76	20,2	0,2
0,5	86,42	67,77	18,65	1,2	1,76	20,4	0,4

In Table 2 is seen the results of the tests when the absorption coefficient of all surfaces in the source room is varied from 0.05 to 0.5. The difference between the simulated reduction index and the true value (R = 20 dB) is within a narrow range from -0.1 dB to +0.4 dB.

2.5. Testing with different absorption in receiver room

Next the absorption coefficient in the source room is kept constant at 0.1, and the absorption in the receiver room is varied. In Table 3 is seen the results of the tests when the absorption coefficient of all surfaces in the receiver room is varied from 0.05 to 0.5. The difference between the simulated reduction index and the true value (R = 20 dB) is within a narrow range from -0.1 dB to -0.4 dB.

Table 3. *Results of calculated transmission using different absorption in the receiver room.*

α (2)	L_1 (dB)	L_2 (dB)	L_1-L_2 (dB)	T_2 (s)	Corr.	R (dB)	Diff.(dB)
0,05	93,25	78,04	15,21	2,34	4,66	19,9	-0,1
0,1	93,25	75,11	18,14	1,2	1,76	19,9	-0,1
0,2	93,25	72,08	21,17	0,6	-1,25	19,9	-0,1
0,3	93,25	70,21	23,04	0,38	-3,23	19,8	-0,2
0,4	93,25	68,9	24,35	0,27	-4,72	19,6	-0,4
0,5	93,25	67,87	25,38	0,21	-5,81	19,6	-0,4

2.6. Testing with different volume of receiver room

In this test the absorption coefficient in both rooms is kept constant at 0.1, and the volume of the receiver room is varied from 50 m^3 to 1000 m^3 by changing the length of the room. In this test the sound pressure levels are determined as the average over nine equally distributed receiver positions in each room, except in the shortest room (length 2 m), where only three positions were used. In the very long rooms the sound field is far from being diffuse, and the sound pressure levels drop with the distance from the transmitting wall, see Fig 3. In the 40 m long room the sound pressure level drops 3 dB from one end of the room to the other.

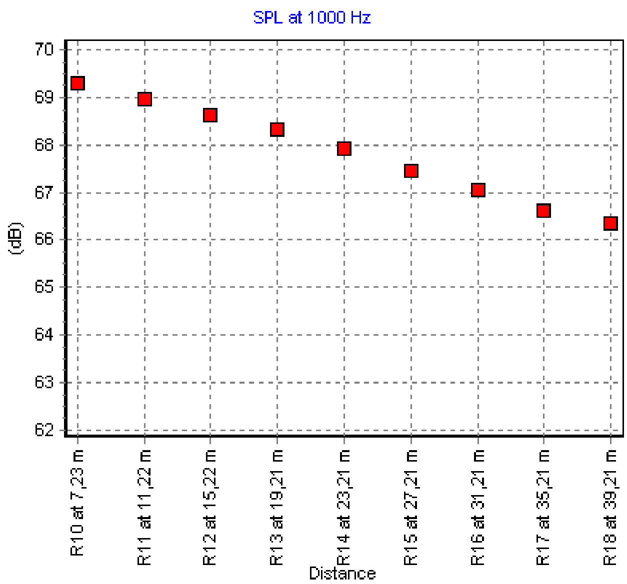

Figure 3. *The sound pressure levels in nine positions covering the length of the 40 m long receiver room*

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In Table 4 is seen the results of the test with different volume of the receiver room. The difference between the simulated reduction index and the true value (R = 20 dB) is within a narrow range from -0.4 dB to +0.3 dB.

Table 4. *Results of calculated transmission using different volume of the receiver room.*

Length (m)	L_1 (dB)	L_2 (dB)	L_1-L_2 (dB)	T_2 (s)	Corr.	R (dB)	Diff.(dB)
2	93,92	78,28	15,64	0,8	3,98	19,6	-0,4
5	93,92	75,45	18,47	1,22	1,83	20,3	0,3
10	93,92	73,09	20,83	1,4	-0,58	20,3	0,3
20	93,92	70,67	23,25	1,49	-3,32	19,9	-0,1
30	93,92	69,08	24,84	1,51	-5,02	19,8	-0,2
40	93,92	67,86	26,06	1,53	-6,21	19,8	-0,2

3. EXAMPLE OF A SIMULATED MEASUREMENT OF AIRBORNE SOUND INSULATION

3.1. The test case

This is a constructed test case to show an example of how the transmission model can be applied. In a corner of a hall is an office with different sound transmitting surface, see Table 5. In total surfaces of 60 m^2 are treated as sound transmitting surfaces, and the combined resulting reduction index is also shown in Table 5.

Table 5. *Areas and reduction indexes of the different parts of the sound transmitting surfaces.*

		Frequency, Hz							
	S (m2)	63	125	250	500	1000	2000	4000	8000
Wall	31	16,1	31,2	39,5	44,8	49,2	50,0	46,5	49,8
Roof	24	16,5	21,9	34,3	41,8	46,4	48,8	45,0	48,0
Door	2	16,0	20,0	24,0	27,0	30,0	28,0	30,0	30,0
Window	3	15,6	19,5	24,1	28,7	32,4	30,1	37,0	39,9
Total	60	16,2	24,1	32,7	37,5	41,1	39,5	41,7	43,0

A view into the model is shown in Fig. 4, and in Fig. 5 is a plan showing the position of the source in the hall and three measuring positions in each of the two rooms.

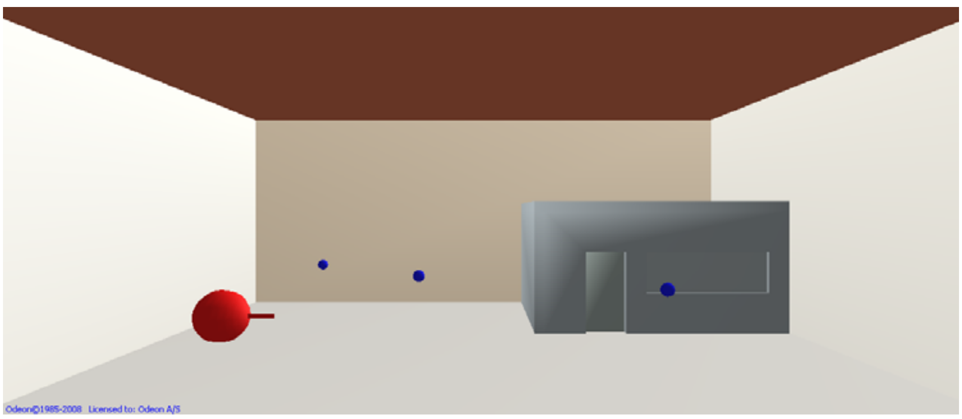

Figure 4. *A view into the test hall with the office in one corner.*

Calculations are made with the Odeon model in order to simulate two different measurements of the sound insulation, one with the sound source in the large hall and the other one with the sound source in the small office. The sound pressure levels in each room are determined as the average values over the three positions. The number of rays used for the calculations is 10.000. While the walls and the ceiling are modeled as double surfaces, i.e. with a thickness, the door and window are modeled as thin single surfaces. The volume of the hall is 814 m^3 and the reverberation time is 2.5 s at 500 Hz. The office is 72 m^3 and the reverberation time is 0,9 s at 500 Hz.

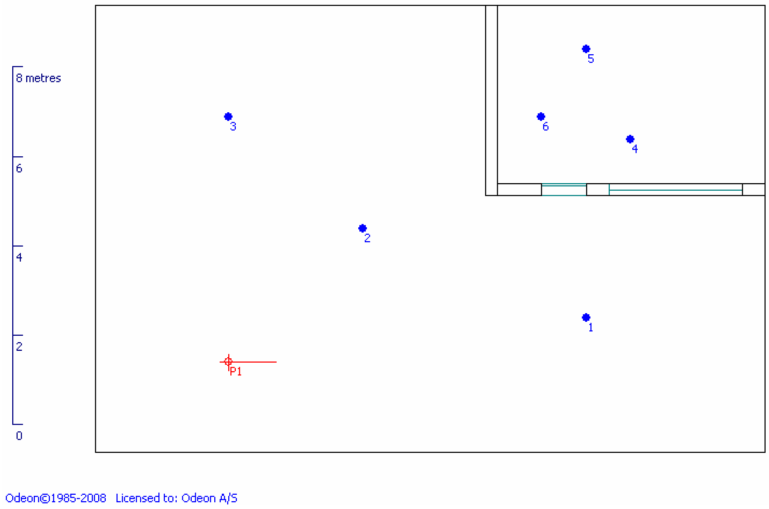

Figure 5. *Plan of the test example indication positions of source in the hall and six microphone positions.*

3.2. Results

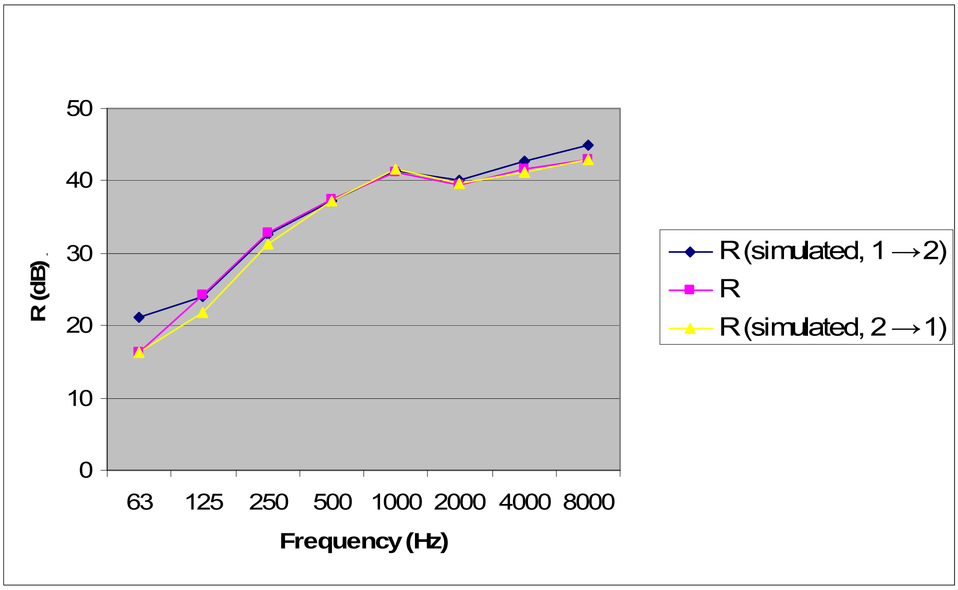

Figure 6. *The simulated sound reduction index; results from two different directions of sound transmission; for comparison the calculated resulting reduction index from Table 5 is also shown*

The results of the simulated sound transmission measurements are shown in Fig. 6 together with the theoretically calculated resulting reduction index from Table 5. With the source in the hall the result is within 1 dB from the theoretical result in the frequency range 125 Hz – 4000 Hz, but at 63 Hz the deviation is 5.0 dB, and it is 1.9 dB at 8000 Hz. In the opposite direction with the source in the office the maximum deviations are 2.4 dB at 125 Hz and 1.5 dB at 250 Hz; at all other frequencies the deviations are very small, less than 0.6 dB.

4. APPLICATIONS AND LIMITATIONS

The result of the test example above suggests that the transmission method can be applied with a reasonable accuracy, which is comparable to the measurement accuracy of real measurements. Thus the method may be useful for the acoustic design and evaluation of various types of buildings like schools, office buildings, etc.

An interesting application is to make auralization examples to demonstrate with sound the sound insulation that is obtained with a certain acoustical design. As auralization is created from the calculated binaural room impulse responses, some examples from the previous case are shown in Fig. 7. Although the calculated impulse responses in this case are 3 s long, only the first part is presented in order to show more details.

The limitations of the suggested method are that it should not be applied for very low sound insulation (0 – 10 dB), and it does not include flanking transmission.

Very low sound insulation should instead be modeled in Odeon using a different method, namely by assigning a transparency coefficient to the relevant surface. Thus as an example a reduction index of 6 dB is modeled by a transparency coefficient of 0.25.

There is no obvious way in which flanking transmission can be included in the transmission method, except by including the flanking transmission in the values applied to the reduction index.

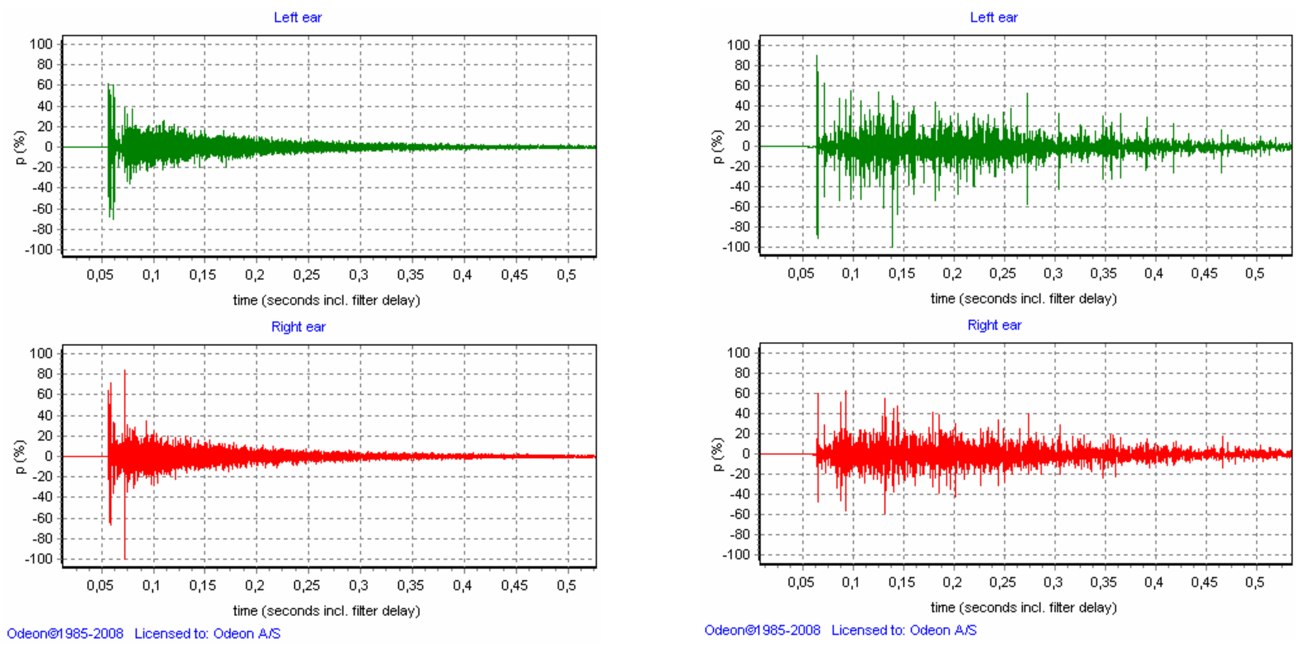

Figure 7. *Calculated binaural room impulse responses from the example in section 3 with sound source in the hall; left: position 1 in the hall; right: position 4 in the office. Only the first approx. 0.5 s is shown.*

5. CONCLUSION

The transmission model in the Odeon version 9.2 has been presented and evaluated in a number of tests. The results from the tests are very satisfactory; compared to the test results obtained with the diffusion model in ref. [2] the present model is found to be equally accurate within the investigated range of variation of the absorption coefficient and room volume, and actually it is more accurate in the case of varying the sound absorption in the source room. The method also yields accurate results in the tested cases of non-diffuse sound in very long rooms.

The results from a special test case have demonstrated that the method can handle correctly combinations of several transmitting surfaces with different areas and reduction indexes.

6. REFERENCES

[1] Christensen, C.L. "ODEON Room Acoustics Program, Version 9.0, Industrial, Auditorium and Combined Editions," ODEON A/S, Lyngby, Denmark, 2007.

[2] Billon, A., Cédric, F., Picault, J., Valeau, V., and Sakout, A. "Modeling the sound transmission between rooms coupled through partition walls by using a diffusion model," *J. Acoust. Soc. Am.*123: 4261-4271, 2008.