VIRTUAL SPACE 4D PROJECT: THE ROOM ACOUSTICAL TOOL

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1. INTRODUCTION

Computer aided room acoustical models have been applied for more than ten years as an everyday tool in different types of acoustical problems. The most interesting applications can be found among concert halls, but the application to auditoriums, open-plan offices and industrial workrooms is also usual. However, this does not mean that modelling is used in every important building project as a normal design practice. It requires both acoustical regulations and experienced consultant companies before the modelling can become a best design practice. At least in Finland, the present situation is very dispersed.

In 2004, a research program called Virtual Space 4D, was started. The aim is the ability to control and predict the indoor environment, including acoustical environment, lighting, thermal climate and air quality. This project differs considerably from previous projects where acoustical modeling has been applied, because, altogether, 28 companies from different areas of building industry, building services and engineering are participating the project. The acoustical part aims at the development of accurate, reliable and versatile prediction model, which should be validated in different types of rooms. We have studied the validity of ODEON in different industrial halls [1] and found that its prediction accuracy of sound pressure level was ± 2 dB. The survey of existing commercial models revealed that the abovementioned requirements - accurate, reliable and versatile - are not easily met. However, the acoustical part of Virtual Space 4D project should also be an open platform for research and development. Therefore, we ended up into the development of a new prediction model.

A self-made model enables the research of existing challenges, i.e. diffraction, frequency-dependent scattering and transmission, and angle-dependent absorption. Optimum design of input and output parameters makes the application of the model easier, and the modelling more cost-effective and tempting in practice.

The aim of this paper is to demonstrate the accuracy of the present version of the prediction model using a case study in an auditorium. It should be noted that the model is under development, and this study is the first serious evaluation of the model. Further work will concentrate on the validation of the model in different types of rooms and the development of the acoustical modelling features to meet the challenges in complex rooms, like open-plan offices and industrial workrooms.

2. METHODS

2.1. The model

The model is designed to calculate the sound pressure level (*SPL*), reverberation time (*RT*) and room response in octave bands between 63 Hz and 8 kHz. The applied algorithm can combine ray-tracing and image method (geometrical acoustics). The mathematics and algorithms have been summarized in [2]. In this study, pure ray-tracing was used.

At first, the room geometry is introduced. Every surface is then identified with 1/1-octaves frequency-dependent absorption coefficients and a frequency-independent scattering coefficient. The sources and receivers are placed in the room, and the sound power level of the source is introduced in 1/1-octaves. From the sound source, N virtual rays are shot and followed until their energy decrease below a certain limit (60dB), due to wall and air absorption. The reflections can be considered either specular or diffuse. The scattering property of the surface is described by the scattering coefficient *D*, having a value within 0 and 1, *D* is high for a complex surface and low for a flat surface. A collision will be diffuse, when a new generated random number, $d \in [0,1]$, is smaller than the respective scattering coefficient *D*. Another parameter is the reflection order *RO*. It indicates the number of early collisions of a ray that will be considered specular. After RO collisions are passed, the reflections can become diffuse.

The rays loose their energy while they travel in the space with the speed of sound. Once a ray crosses a receiver, its energy and time delay are stored. In that way, the room response, or better said the point response, is obtained for every receiver. For every receiver and frequency, the total *SPL* is obtained by adding all the respective energy pulses. To smooth every point response, Schroeder backward integration is applied [3], and then a straight line is fitted to it, by the method of minimum squares between the values of -5 and -25 dB below the maximum. Once the equation of the line is obtained, the calculation of the reverberation time is trivial.

2.2. The experimental part

2.2.1. Description of the room

Photos of the studied auditorium are shown in Figure 1. The walls were of concrete and the floor was covered by wool carpet. At the sidewalls, there was some absorbent material. The same material covered the ceiling suspended by 900-2000 mm. The auditorium has ten rows of audience chairs (length 10 m). There were wood tables in the speaker area. A strong flutter echo was observed between the hard sidewalls using handclaps.

Figure 1: *Auditorium views. Omnidirectional loudspeaker at location S1 and receiver at location R1.*

2.2.2. Measurement of room response and sound level

For two positions of the sound source and at ten locations of the receiver, altogether 20 measurement points, the room response was obtained with WinMLS2000 using a sound level meter B&K 2231 (microphone B&K

4165). At the same locations, the sound pressure level was measured in 1/3-octaves with an Investigator B&K 2260A and a calibrated microphone B&K 4189. The height of the receivers was the same height than the ears of a possible listener sitting in the audience area, 1.2 meters over the floor.

2.2.3. Laboratory measurements

The sound power level of the sound source, B&K OmniPower 4296, was measured according to ISO 3741 in a reverberant room of volume 113 m^3. The obtained values are listed in Table 1. The source is omnidirectional.

Ten different kinds of materials were used to model the auditorium. Their estimated absorption and scattering coefficients are listed in Table 2. The last column in Table 2 represents the total area covered by every material type (m^2), and the last line in Table 2 represents the average absorption distributed in the room (m^2). The most important absorption materials were studied, according to ISO 354, in a reverberant chamber, since we could not estimate their absorptive performance reliably using material database. This data corresponds with the first three rows of Table 2. The wall absorber was measured with a gap of 7 cm over the floor, and the ceiling absorber with a gap of 90 cm. The rest of the materials were estimated from material database.

Table 1: *The measured sound power level of the sound source (ref 1 pW).*

125	250	500	1000	2000	4000
103.1	111.1	107.2	102.9	103.0	96.6

Table 2: *Absorption and scattering coefficients of modeled surfaces.*

	125	250	500	1000	2000	4000	Scatt	*Area*
Wall Absorber	0.09	0.35	0.85	0.63	0.38	0.47	0.40	*32*
Ceiling Absorber	0.45	0.45	0.52	0.60	0.50	0.60	0.60	*192*
Chairs, soft side	0.13	0.45	0.75	0.94	0.94	0.91	0.80	*68*
Chairs, hard side	0.09	0.11	0.09	0.07	0.06	0.07	0.80	*116*
Concrete Walls	0.01	0.01	0.02	0.02	0.02	0.03	0.10	*210*
Hard Parts in Ceiling	0.10	0.10	0.10	0.10	0.10	0.10	0.40	*12*
Stairs (soft carpet)	0.03	0.04	0.09	0.20	0.34	0.45	0.70	*157*
Floor (soft carpet)	0.03	0.04	0.09	0.20	0.34	0.45	0.20	*94*
Tables	0.09	0.11	0.09	0.07	0.06	0.07	0.40	*28*
Doors	0.09	0.11	0.10	0.07	0.06	0.07	0.20	*6*
Total (m-2)	*0.13*	*0.17*	*0.24*	*0.29*	*0.30*	*0.35*	*0.48*	*915*

2.3. The modeling

On the same positions as in the experimental part, a sound source and spherical receivers with radius of 38 centimeters were located. The size of the receivers was conditioned by their proximity to the audience chairs, as they should not overlap such planes. In Figure 2, the layout of the auditorium and the location of receivers and sound sources are shown. Cartesian coordinates of sources and receivers are listed in Table 3. 5.000, 10.000 and 15.000 rays were traced and followed until their energy was 60 dB less than initially. The first three collisions were forced to be pure specular, after them, diffusion was modeled as mentioned.

Table 3: *Locations of sources and receivers (in meters).*

	S1	**S2**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**
X	2.85	1.01	4.15	4.25	5.20	5.97	8.05	8.12	9.01	11.07	12.01	13.12
Y	11.30	7.19	10.12	4.56	3.06	11.26	9.60	3.58	7.41	3.55	10.80	7.98
Z	1.50	1.50	1.20	1.20	1.65	2.10	3.00	3.00	3.45	4.35	4.80	5.20

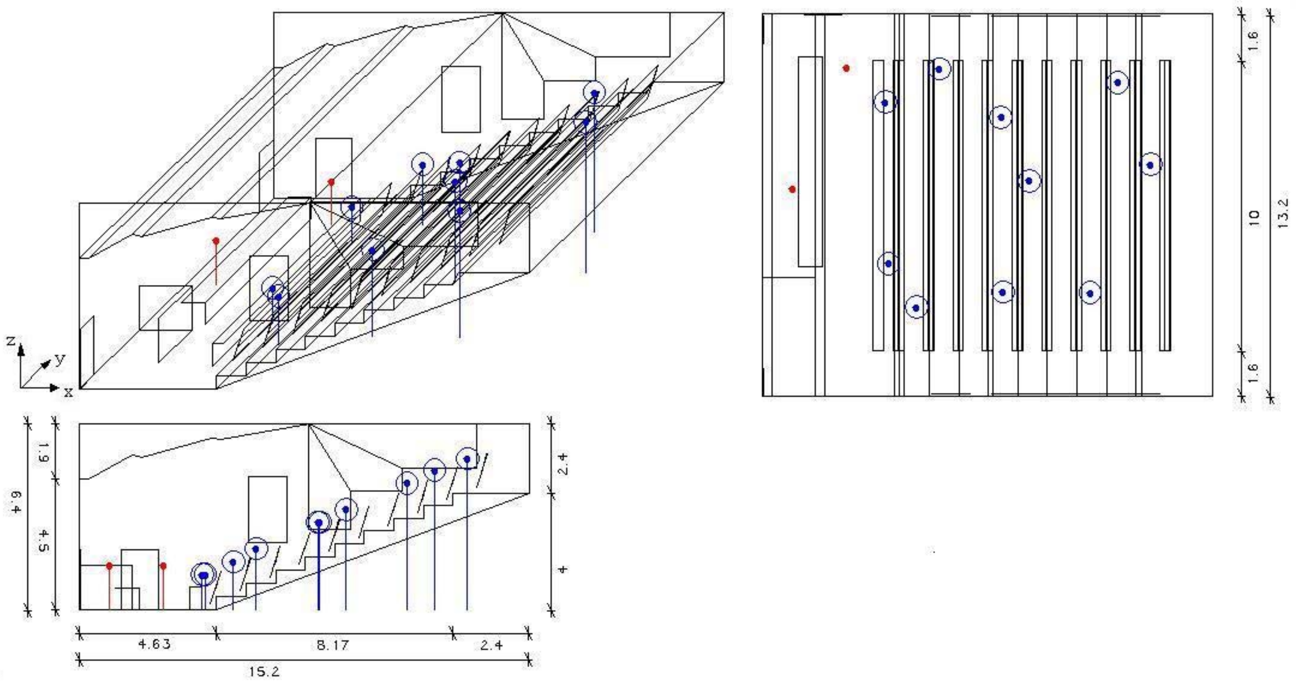

Figure 2: *3D view, 2D top view and 2D side views. Dimensions in meters.*

2.4. Statistical evaluation of data

For every receiver and at every frequency octave, a point response is obtained. From them, sound pressure level *SPL* and reverberation time *RT* are obtained. The *SPL* at a point is calculated by adding all the energy pulses of the corresponding point response. This procedure is done in our modeling method, but also by the measuring device. Both data can be compared for every frequency *f*, by averaging the respective difference (1) over all receivers (2), and by its standard deviation (3).

$$A_{i,f} = SPL_{i,f,Modelled} - SPL_{i,f,Measured} \tag{1}$$

$$A_{SPL_f} = \frac{1}{n}\sum_{i=1}^{n} A_{i,f} \tag{2}$$

$$STD_f = \sqrt{\frac{n\sum_{i=1}^{n} A_{i,f}^2 - \left(\sum_{i=1}^{n} A_{i,f}\right)^2}{n(n-1)}} \tag{3}$$

To obtain RT at every point, Schroeder's backward integration is done. Then, a line is fitted to it by the method of minimum squares. The slope of that line gives the *RT*. Comparison of modeled and measured reverberation time can be done, if in formulas (1), (2) and (3), the terms *SPL* are substitute by *RT*.

3. RESULTS

The following results correspond to the case N=10.000 rays, $RO=3$, $n=10$ and sound source at location S2. Figure 3 represents two point responses of the fourth receiver, at 125 Hz and 1 kHz. The integration time of the point response was one millisecond.

The difference between modeled and measured *SPL* has been illustrated with black in Figure 4, where the dots represent what was obtained by (2) and the error lines what was calculated by (3). The same calculations were repeated to compare also the predictions of Sabine theory with the measured data. That has been represented with red.

The modelled reverberation times can be compared with what was measured. This comparison, when source is at location S2, is represented in Figure 5. The modelled data has been illustrated with black color and the measured with red. For both data, the middle point represents the result obtained in (2), A_{RT_f} , and the error bars are limited by the maximum and minimum of (1). Blue circles are obtained with Sabine's theory. Finally, the standard deviation of modeled and measured process was calculated (3) and added in the lower part of Figure 5.

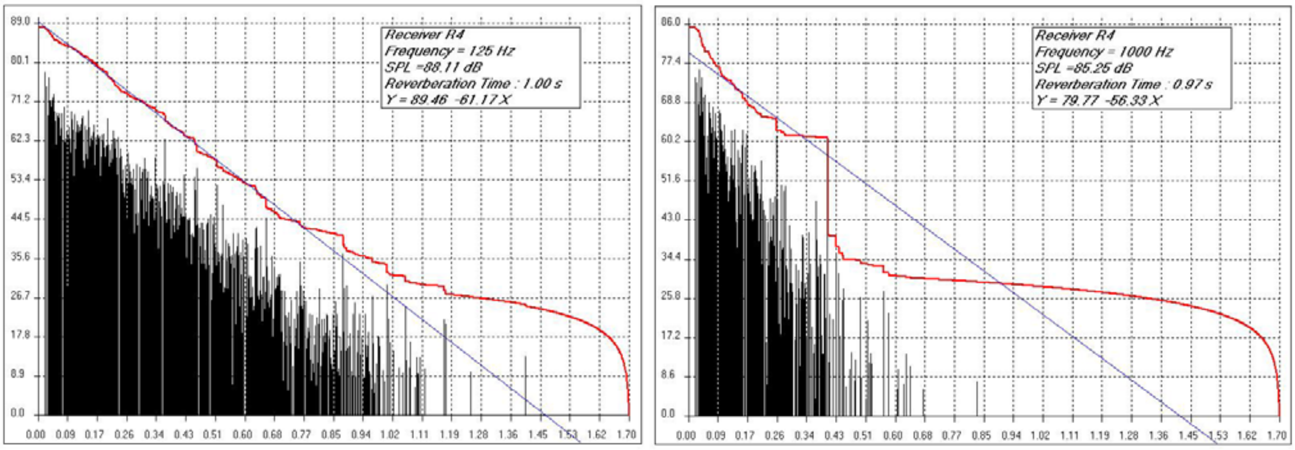

Figure 3a and 3b: *Point response of 4th receiver at 125 Hz and at 1000 Hz with source at location S2. The y-axis is sound pressure level (dB) and x-axis is time (s).*

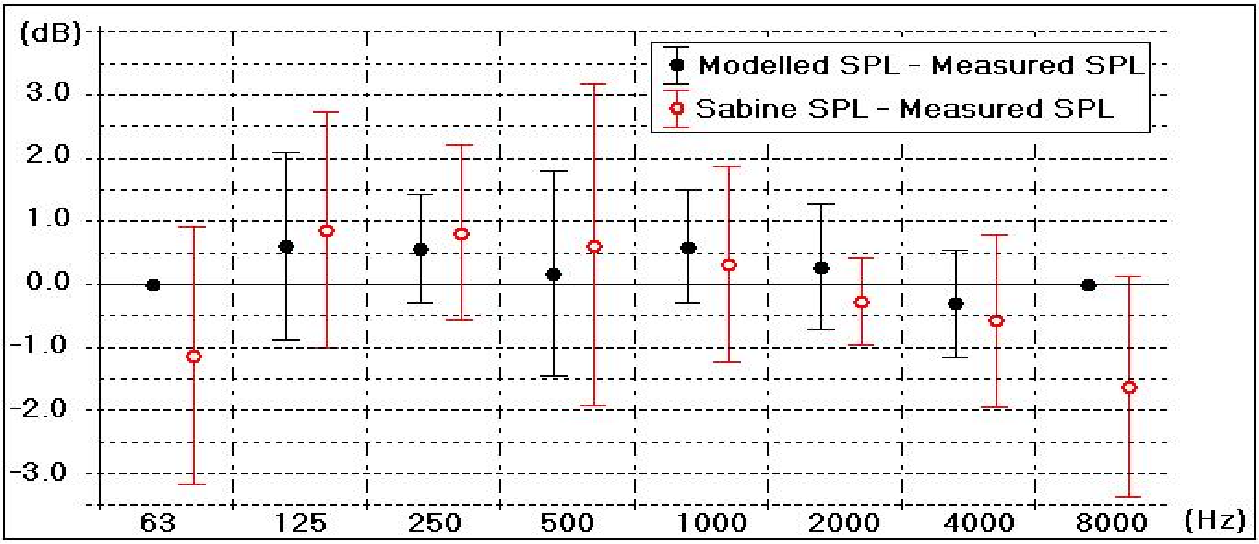

Figure 4: *Averaged difference between modeled and measured, and between modeled and Sabine.*

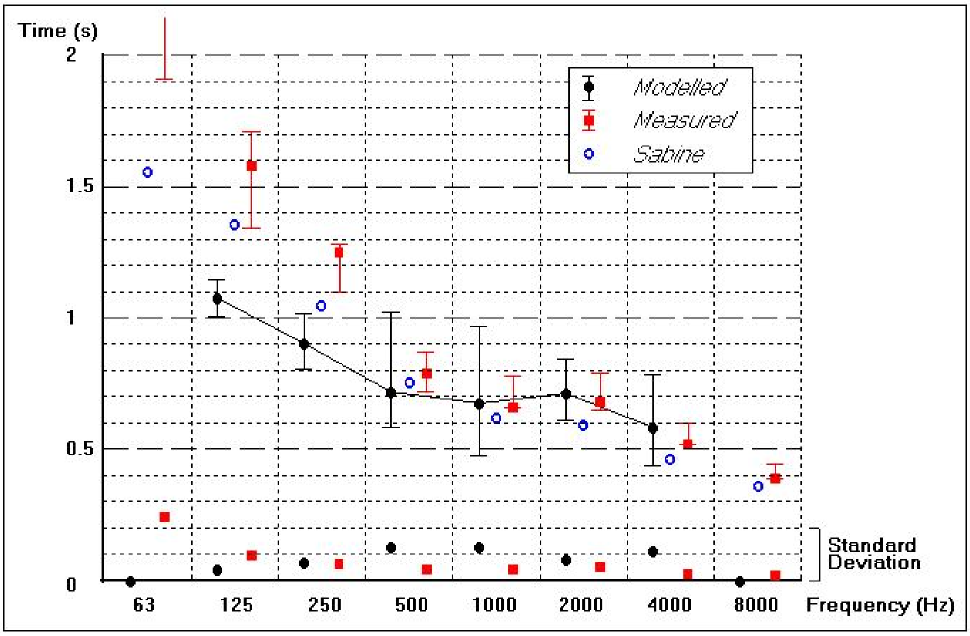

Figure 5: *Modeled, measured and Sabine reverberation times for source at location S2.*

4. DISCUSSION

According to Figure 4, the mean value of the difference between modelled and measured *SPL* (2), is smaller than ± 1 dB and the standard deviation (3) is within ± 2 dB. Those deviations are acceptable and also smaller than expected. This seems to confirm that the evaluation of the sound power level of the sound source was correct and to suggest the reliability of the estimated absorption coefficients.

In a diffuse room, the sound is homogeneously distributed in the space and the reverberation time is constant in the room volume. As flutter echo was observed in this auditorium, the room could not be considered as a diffuse space, even when the audience chairs, the stairs, and the wall and ceiling absorbent material have clear diffuse properties. Reasonably small standard deviation of measured reverberation time confirms the partially diffuse properties of the room.

The ray-tracing algorithm is a statistical method. It cannot represent correctly the wave nature of sound. In Figure 5, it was observed that at high frequencies, the mean value of the modeled and of the measured reverberation times were similar. That could again indicate that at those frequencies the estimation of the absorption coefficients was accurate. On the other hand, for the frequencies 125 and 250 Hz the difference between modelled and measured data becomes large, probably because the ray-tracing algorithm is not able to represent standing modes and other wave-phenomenal effects. Those effects are easily observed at low frequencies, and can increase the reverberation time.

The uncertainty of the modelled *RT* reduces with decreasing frequency. The explanation of this is in Figure 3a and 3b, and in the last line of Table 2. Firstly, it is observed that the shape of the decay depends directly on the amount of absorption distributed in the room. Then Figure 3b shows two very high peaks have appeared (0.26 and 0.40 s) and affected to the Schroeder's smoothing curve. That receiver is in the lower part of the room where no absorbents were on the smooth sidewalls (scatt=0.1). It can be suggested that some rays were trapped between the sidewalls without being attenuated, until they finally crossed the receiver. In that case, according to the speed of sound, those high peaks would correspond to 6 and 10 collisions between both walls since they were shot. At 125 Hz the decay is not as steep as at 1 kHz and those peaks are not so clearly observed, even when they also exist, like one with a time delay of 0.37 seconds in Figure 3a.

As a test, the running process was repeated considering all collisions purely diffuse. In this way, the high peaks disappeared as the effect of some rays trapped between sidewalls was avoided. That case produced bigger underestimation of *RT*, but the standard deviation became smaller.

Another thing that should not be forgotten and could explain the underestimation of the reverberation time at low frequencies, is the size and height of the receivers (0.38 and 1.2 meters). In [2] was stated that the size of the receivers was an important factor, as smaller sizes could produce bigger standard deviations. In this study, the receivers were placed at the same height of a possible listener sitting in the audience area, and their size was affected by their proximity to the chairs. The effects at low frequencies that happen at so close distances to obstacles might not be able to be reproduced at all by the ray-tracing method.

Over a certain limit, the number of rays, N, did not take a significant role in the obtained results. 5000 rays did produce same deviations as 10000 and 15000.

Successive repetitions of the running process lead to the same results and deviations. That was expected because the randomizing process was successful.

5. FUTURE WORK AND CONCLUSIONS

So far, scattering coefficient has been considered constant for every kind of surface in the frequency range, but the experience while using this model teaches us that it should be frequency dependent, and it will be considered in the nearly future. For that reason the new ISO/DIS 17497-1, Measurement of the sound scattering properties of surfaces, will be studied in laboratory and its results applied in the model.

In the future, STI and RASTI methods will be introduced to the VS4D acoustical tool, as well as auralization and frequency-dependent transmission. Diffraction should also be included, but its use might depend on the final user, who depending of the geometry of the room will choose which screens are of main interest and for which receivers its effect is of importance.

As a result of the acceptable results obtained in the modelling of this auditorium, its acoustics cannot be considered to be difficult to study by statistical methods. The closest future involves a complete validation of the model in different spaces, including auditorium and speech rooms, factories and open-plan offices.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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