NEW ACOUSTICAL MODEL FOR THE WORKPLACE DESIGN

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1 INTRODUCTION

In the field of acoustic room modelling, the main objective is to estimate the noise reduction achieved by treatments of noise sources and room walls. Sound modelling and the quality of its predictions are also two interesting topics for engineers, scientist and acoustic consultants. But the accuracy of predictions is not always as good as desired, for example, when simple empirical methods [1] or commercial software [2] are applied in the study of the acoustical conditions of real work places, i.e. large factories or open-plan offices.

In Työterveyslaitos, we have started the creation and development of our own acoustical model. This model, friendly called dBWorks, applies the ray-tracing algorithm in the calculation of sound pressure level in fitted spaces. A self made code enables modification and research of modelling parameters, i.e. optimum number of rays, number of reflections per ray, or size and shape of the receivers. Also, implementation of diffraction, scattering, and angle-dependent absorption coefficient. Simplicity is one of the aims of this project. Another one is accuracy. In this paper, dBWorks and a description of the applied mathematics are presented. A comparison of measured and modelled results of a real working place is also presented.

2 DESCRIPTION OF THE MODEL

dBWorks applies the ray-tracing algorithm, where the sound power emitted by a sound source is described by a finite number of rays, which are considered as carriers of energy. Those rays travel through the space with the speed of sound and are reflected from room boundaries, until their energy, due to the wall and air absorption, has reduced below a certain limit. During that time, the rays cross receivers (cubical volumes) where the energy calculation is performed and the sound pressure level obtained. All the mathematics applied in the model can be divided into two groups; The geometrical analysis of the room and the energy calculation.

A very simple way to study noise propagation is by geometrical acoustics. That is when the wavelength of the sound is small compared to room dimensions [3]. At first, the model needs to transform the room boundaries, i.e. walls and fittings, into geometrical relations. In this way, a surface will be expressed by the general equation of a plane (1), and a ray by the canonical form of a line (2).

$$Ax + By + Cz + D = 0 \tag{1}$$

$$\frac{x-x_1}{l}=\frac{y-y_1}{m}=\frac{z-z_1}{n} \tag{2}$$

A surface and a ray, if not parallel, have a point in common $(\bar{x},\bar{y},\bar{z})$.

$$\begin{aligned}\bar{x}&=x_1-lr\\ \bar{y}&=y_1-mr\\ \bar{z}&=z_1-nr\end{aligned} \tag{3}$$

where $r=\dfrac{A\cdot x_1+B\cdot y_1+C\cdot z_1+D}{A\cdot l+B\cdot m+C\cdot n}$.

When a ray hits a surface, it can be specularly reflected following the Snell law.

$$\begin{bmatrix} l' \\ m' \\ n' \end{bmatrix}=\begin{bmatrix} l \\ m \\ n \end{bmatrix}-\frac{2(lA+mB+nC)}{A^2+B^2+C^2}\begin{bmatrix} A \\ B \\ C \end{bmatrix} \tag{4}$$

with (l',m',n') being the new vector direction.

If the surface is diffuse, the ray can be scattered to a random direction. Its new vector direction would become, i.e. (5), where m' and n' are randomised values.

$$l'=-l \qquad m'\in[-1,+1] \qquad n'\in[-1,+1] \tag{5}$$

Normally the first collisions of each ray are specular. After a certain number of collisions (reflection order), the reflections can be considered to be diffuse. To model diffusion, dBWorks creates a random number, which is compared with the scattering coefficient of the corresponding wall. If the random number is smaller than the scattering coefficient the collision is diffuse. Otherwise, the reflection is specular.

The most comfortable way to perform the energy calculation is to work with sound power (Watts).

$$W=W_0\cdot 10^{0.1L_w}; \qquad W_0=1pW \tag{6}$$

where L_w is the sound power level of the sound source.

For an omnidirectional sound source, the initial power of every emerged ray is obtained dividing the total power of the sound source by the total number of rays N. At a certain time, t', after covering a distance L in the space and suffer M collisions with boundaries, the power of a ray is:

$$W_{t'}=\frac{W_0}{N}e^{-mL}\prod_{j=1}^{M}\left(1-a_j\right) \tag{7}$$

where m is the air absorption coefficient [3], and a_j the absorption coefficient of every collided surface.

If a ray that travels with a certain power W_i crosses a receiver, the sound intensity excited by it is:

$$I_i = \frac{W_i \cdot d_{ri}}{V_r} \tag{8}$$

where d_{ri} is the distance that the ray has travelled inside the receiver of volume V_r. Once all the rays have been worked out, the scalar accumulated intensity of the receivers will allow us to obtain the sound pressure level.

$$L_I = 10 \cdot \log\left(\frac{\sum_i I_i}{I_0}\right); \qquad I_0 = 1 pW/m^2 \tag{9}$$

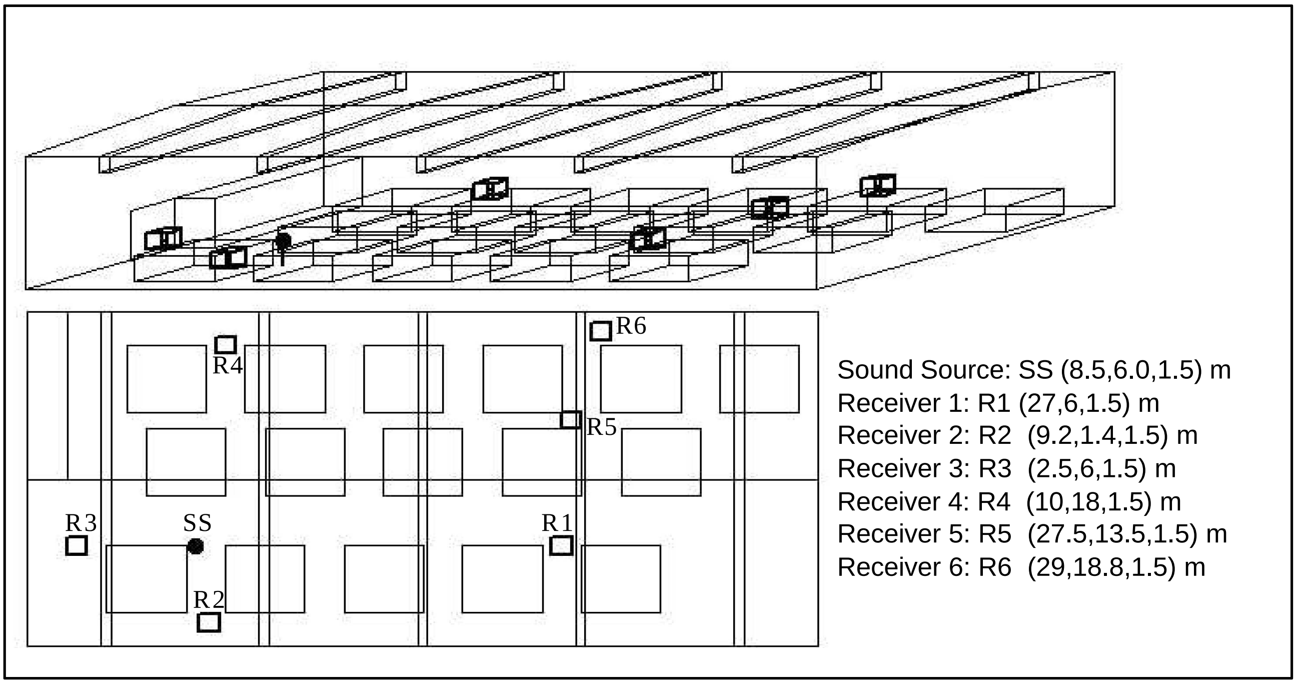
3 MODELLING A FACTORY ROOM

From a previous work [2], we have chosen a room of a textile factory for the first comparison between measured values and modelled results. This place has been selected because there were good organised measurements of it. It fulfils the conditions where the dBWorks needs to be validated.

3.1 The room

The selected room, 40x20x8.5 m, has a saddle roof with 5 balks, 16 weaving machines, some shelves as fittings, one corridor to another hall, and opposite to it an open wall to another space. Floor and other walls were made of concrete.

The sound propagation in the space was measured in six different positions uniformly distributed while the sound source was placed at the point (8.5, 6.0, 1.5). For more information about the measurements we refer to [2].



Sound Source: SS (8.5,6.0,1.5) m
Receiver 1: R1 (27,6,1.5) m
Receiver 2: R2 (9.2,1.4,1.5) m
Receiver 3: R3 (2.5,6,1.5) m
Receiver 4: R4 (10,18,1.5) m
Receiver 5: R5 (27.5,13.5,1.5) m
Receiver 6: R6 (29,18.8,1.5) m

Figure 1: 3D and layout figures of the weaving factory (dBWorks graphical output figures)

3.2 Modelling

The modelling is carefully but simply done. In Fig.1, the outlook of the room model is shown, with the sound source and receivers positions. In Table 1, the absorption coefficients of the different materials and their scattering coefficient are listed. It is important to notice now, the simplicity of the fittings, machinery, material library and absorption coefficients which have been used. The floor and walls have been modelled highly reflective while the open end of the room almost totally absorbent. The weaving machinery was highly absorptive. Its estimated absorption coefficient was 0.5 for all the frequencies. The corridor to another hall has been modelled, for the sake of simplicity, to 0.5 for all the frequencies.

The receivers were cubical and their centre was at the same level than the human ear and than the top of all the fittings, (1.5 m). From the sound source, 2000, 5000 and 8000 rays were randomly traced. The first collisions of each ray were specular reflected (4). After the reflection order, the rest of collisions were diffuse (5). Diffraction by fittings was not implemented. The rays were traced along the equivalent time of the reverberation time T_{60}. Temperature and humidity conditions were modelled with same values obtained while measuring.

Table 1: Absorption and scattering coefficients of modelled surfaces.

	125	**250**	**500**	**1000**	**2000**	**4000**	**Scatt.Coef.**
Floor (Painted concrete)	0.01	0.01	0.01	0.02	0.02	0.02	0.50
Walls, Brick Walls, Balks	0.02	0.03	0.03	0.04	0.05	0.07	0.50
Corridor, Machinery	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Open Wall	0.99	0.99	0.99	0.99	0.99	0.99	0.99

4 RESULTS

Many series of calculations were performed with different modelling parameters, like number of rays, size of the receivers, number of reflections per ray, and reflection order. In this way, some conclusions have been made and they will be explained in the discussion part.

To illustrate the results obtained with dBWorks, we refer to the case when 5000 rays were traced in six different series, the size of the receivers was one cubic meter, and reflection order was set to 4. Fig.2 includes six graphical representations of the six receivers. There, the six series of running processes, their mean value, and measured values are plotted for every receiver.

For the six different receivers, the standard deviation obtained when running those six series is listed in Table 2.

Table 2: Standard deviations of modelled SPL. RecSize=1 m^3. Number of rays=5000.

	125	**250**	**500**	**1000**	**2000**	**4000**
R1	2.9	3.0	2.3	3.1	4.2	2.5
R2	0.5	0.4	0.3	0.6	1.3	0.6
R3	0.4	0.8	0.9	1.3	1.0	1.4
R4	0.6	1.4	1.0	1.7	1.4	1.2
R5	0.8	2.6	3.2	0.8	2.1	2.5
R6	1.2	2.1	2.6	2.8	2.8	4.2

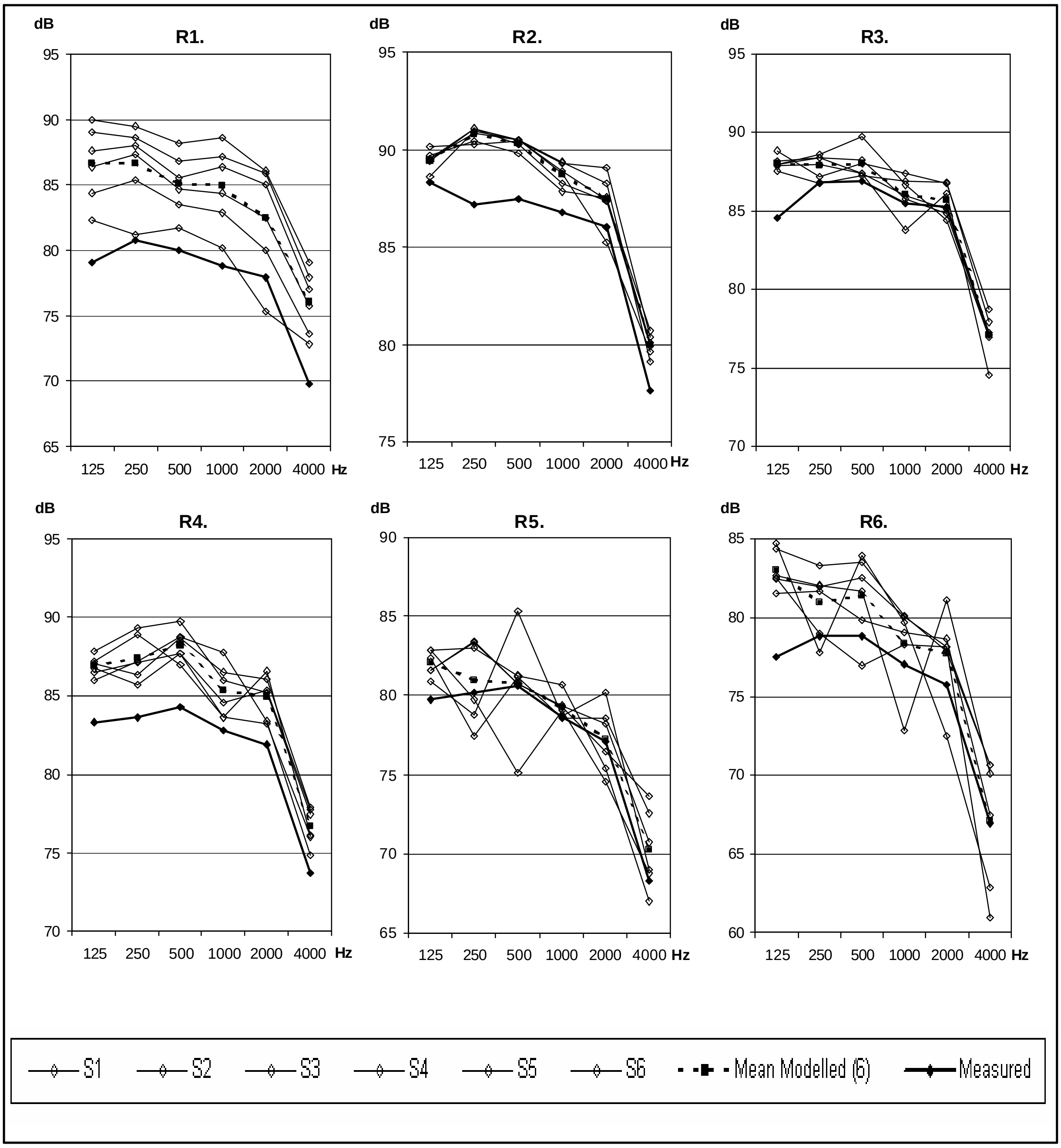


Figure 2: Measured and modelled SPL (6series) in the six receivers.

5 DISCUSSION

The number of rays was not a determining factor. 2000, 5000 and 8000 rays produced similar results and deviations for the six receivers in all the frequency range.

The size of the receivers needs to be at least 0.8 m. For this value and for 1.0 m, the results were approximately the same. With smaller receiver size, the applied mathematics seemed not to work properly and low values of sound pressure level were obtained.

The reflection order was an important factor and best results were obtained when high diffusion was modelled. A good value was found to be 4.

dBWorks overestimated the sound pressure level. One reason for this can be the lack of diffraction in our model. It has been found that the receivers close to sound source and to wall or fittings, are often affected by diffraction from obstacles nearby.

The processes that create the rays and re-direct them in diffuse reflections, are completely based on random algorithms. This is one of the reasons for the existence of standard deviations.

It is observed correlation within the same series for the different frequencies. But even in the same series, all the calculus was frequency dependent. So the rays traced for different frequencies only have the first collisions in common. After reflection order, diffusion affects different to different frequencies.

The highest errors (whatever modelled parameters were used) were obtained for receiver 1 (R1), which was placed about 20 meters from the sound source and shadowed by the edge of three machinery fittings. The model overestimated the sound pressure level by 5-8 dB.

R2 and R3 were the closest receivers to the sound source. While R2 gets direct sound from the source, R3 is shadowed by one machine. Those two receivers are so close to the sound source, that for them the effect of later collisions is not very important. That explains why the smallest standard deviations were obtained here.

R4 was about 12 meters from the sound source and close to one sidewall. This receiver gave low values of standard deviation, but for some frequencies overestimated the sound pressure level value by 3-4 dB.

R5 and R6 had the further positions from the sound source, and R6 was also placed close to a sidewall. It is interesting to notice that for R5, the mean value of the six series had good agreement with the measured result, even though, the standard deviation is 3 dB for the 500 Hz frequency.

The mean value of the six series (except for R1) and the standard deviation (except R6 at 4000Hz) are within 3 dB.

dBWorks has proven its capability to become an effective and alternative tool for noise prediction and sound pressure level distribution. The values are quite good when comparing with measured (measurement errors can be ± 2 dB), but in general, always too high. We notice that this model is not finished yet and that a lot of work will be done in the following, e.g. the implementation of diffraction and better definition of diffuse reflections. In the future a complete validation of dBWorks will be carried out using measurement data of several different workplaces.

6 REFERENCES

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