ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

PREDICTION OF THE REVERBERATION TIME IN ROOMS WITH NON UNIFORM ABSORPTIONS USING A DIFFUSION MODEL

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Abstract

The acoustical comfort is now a comfort's criterion which is taken into from the conception. The designers need therefore accurate tools to predict the acoustic quality of enclosures. Most of the acoustical comfort criteria are based on the reverberation time. When the room has proportionate dimensions and an uniform absorption, the statistical theory through Sabine or Eyring formulas allows good predictions of the reverberation time. Moreover, extensions of these relations by Millington or Cremer and Müller among others give quite satisfactory when the room is composed of materials with different sound absorption. In this study, the reverberation time in an enclosure is calculated via the numerical resolution of unstationary diffusion equation, model validated in coupled and industrial rooms. Firstly, an improvement of the boundary condition is proposed for highly absorbent surfaces. The diffusion model is then compared to several formulations of the statistical theory and a ray-tracing software for a cubic room with homogeneous walls' absorption and with non homogeneous walls' absorptions. Finally, an experimental validation is conducted for an enclosure with non uniformly distributed absorption.

INTRODUCTION

Reverberation time is one the key criteria to qualify the sound quality of an enclosure. Its prediction before the building construction is then needed. Sabine [1] and Eyring [2] proposed very simple relations between the acoustical and geometrical outlines of an enclosure and its reverberation time. These relations give birth to the statistical theory and are the most accurate for rooms with quasi-cubic shape and homogeneous absorption and, for Sabine's one, limited to low absorptions. However, in most applications, the sound absorption of walls is inhomogeneous and the shape differs greatly from a cube. The Sabine's and Eyring's models have been refined over the years and other methods have been developed like ray, beam, cone and sound particle tracing, integral equation method, image-source method and for low frequencies, modal theory.

Recently, a model has been proposed in which a diffusion equation is solved numerically to obtain the reverberant sound field [3]. In this study, this model is modified and compared to several models derived from the statistical theory, the diffusion equation based model, and a commercial ray-tracing software, CATT-Acoustic, to experiments for a quasi-cubic room fitted with non-uniformly distributed absorptions.

Firstly, several models based on Eyring and Sabine formulations used in this paper are presented. Then, the diffusion model is introduced and a modification is proposed to improve its predictions for the high absorptions. To validate the modification of the diffusion model, numerical comparisons are carried out in Section 3 with statistical theory based models and the ray tracing software in a cube with homogeneous absorptions. In Section 4, an experimental set-up is presented and its results are compared to the models predictions.

MODELS PRESENTATION

In this section, several models based on the statistical theory are presented. In a second time, a recently proposed model based on the numerical solving of a diffusion equation is showed. A modification of the boundary condition for high absorption coefficient is then proposed.

Statistical theory based models

For rooms with homogeneous dimensions and absorption, Sabine [1] obtained an expression of the reverberation time,

$$Tr = \frac{0.16V}{\bar{\alpha}_{Sab} S}, \tag{1}$$

where S and V are the total wall surface and the volume of the room.

$$\bar{\alpha}_{Sab} = \frac{1}{S} \sum_i \alpha_i S_i , \tag{2}$$

is the arithmetic average sound absorption coefficient of the α_i absorption coefficient associated to the surface S_i: Eyring [2] has extended this relation to higher absorption coefficients:

$$\alpha_{Eyr} = -\ln\left(1-\bar{\alpha}_{Sab}\right). \quad (3)$$

Afterwards, it can be easily shown that the Sabine is special case of the Eyring formulae, limited to the low absorption. Millington [4] and Sette [5] suggested to geometrically averaging the absorption to improve the reverberation time predictions as following:

$$\alpha_{Mil} = -\frac{1}{S}\sum_i S_i \ln\left(1-\alpha_i\right). \quad (4)$$

As this expression can lead to underestimation of the reverberation time [6] (reverberation time becomes close to 0 if one of the surface, even very small, is very absorbent), Dance and Shield [6] proposed a conversion graph to correct this behavior. This correction can be crudely approximated by,

$$\alpha_{Dan} \approx -0.3\times\alpha_{Mil}^2 + 0.97\times\alpha_{Mil}. \quad (5)$$

Diffusion model

Recently, Valeau et al. [3] generalized to arbitrary three dimensional enclosures, a model first proposed by Ollendorff [7], applied by Picaut et al. [8] and validated in long enclosures [9]. To obtain the sound decay within a volume, the following diffusion equations are solved using a finite element solver:

$$\frac{\partial w(\mathrm{r},t)}{\partial t} - D\Delta w(\mathrm{r},t) = P(\mathrm{r}_s)\,\delta(t-t_0) \text{ in } \mathcal{D}, \quad (6)$$

and $D\dfrac{\partial w(\mathrm{r},t)}{\partial \mathbf{n}} + hw(\mathrm{r},t) = 0$ on $\mathcal{S}$. (7)

In these equations, Δ is the Laplace operator, w the acoustic energy density, D the coefficient diffusion, **r** the location, t the time, $\mathcal{D}$ the domain delimited by the room surface $\mathcal{S}$ and **n** the exterior normal to the boundaries. The right-hand term of Eq. (7) account for the impulse sound source both in terms of output power and location $\mathbf{r_s}$. The analytical expression of the diffusion coefficient is borrowed to the diffusion of particles by a scattering medium:

$$D = \frac{\lambda c}{3} = \frac{4Vc}{3S}, \quad (8)$$

where c is the sound velocity and λ the mean free path. In this analogy, the mean free path is given by the relation 4V/S and account for the room's morphology. The wall's absorption is described by an exchange coefficient:

$$h = \frac{\alpha c}{4}. \tag{9}$$

As the Sabine absorption coefficient is used, one can wonder if the model is able to accurately predict sound decay for rooms with highly absorbent surfaces. A natural way to solve this problem is to replace the Sabine coefficient by the Eyring coefficient, giving a new exchange coefficient:

$$h = -\frac{c \ln(1-\alpha)}{4}. \tag{10}$$

In the following, the diffusion model using the Sabine coefficient is denoted diffusion-Sabine and the one employing the Eyring coefficient, diffusion-Eyring.

Ray-tracing

The ray tracing software CATT-Acoustic V8.0c is used in this study to obtain the sound decays in the enclosures [10]. This program is able to model specular, diffuse and mixed reflections. The diffuse part of the reflection has been set to 40%. This value represents a mean scattering surface: 10% depicting a smooth one and 70% a rough one [11].

NUMERICAL VALIDATION

The geometrical configuration used in this section is a 6 meters long cubic sketched in Fig.1 with homogeneous absorption varying between 0.1 and 0.95. For CATT-Acoustic and the diffusions models the sound source is located at the center of the room (x=3, y=3 and z=3 for the cube).

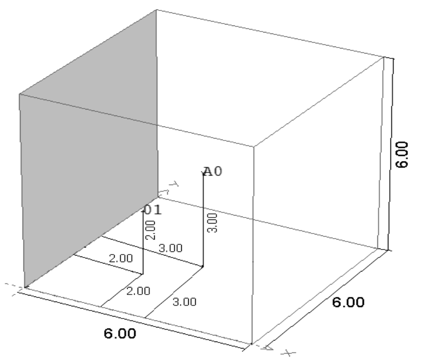

Figure 1 - cubic room: A0 is the sound source and 01 the measurement locations.

The volume is discretized in 6000 elements for the diffusion models and the impulse responses are obtained in a few second. For the ray tracing software, 1 000 000 rays are emitted. The reverberation time are evaluated for the diffusion models and CATT-Acoustic at the same location (2,2,2).

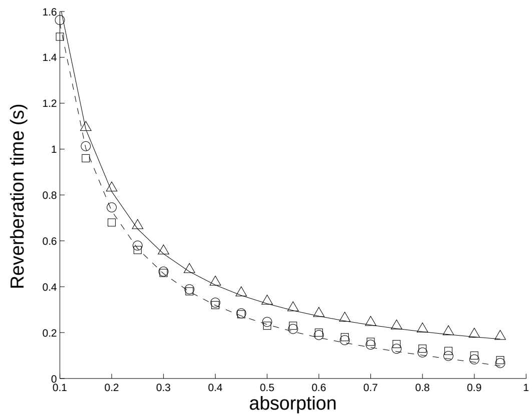

Figure 2 - Reverberation time as a function of the sound absorption coefficient: Sabine's model (solid line), Eyring's model (dashed line), CATT-Acoustic (□), diffusion-Sabine (Δ) and diffusion-Eyring (o).

The behaviors of the diffusion models are strongly tied to their boundary conditions (Fig. 2). The diffusion-Sabine gives a mean discrepancy of 1.6% to the Sabine formulae whereas it reaches 3.5% between the Diffusion-Eyring results and the Eyring's relation. The ray tracing's discrepancy is lightly superior to 10%.

EXPERIMENTAL VALIDATION

The experimental data herein are extracted from an experimental work reported by Ducourneau and Planeau [12]. A reverberation chamber (Fig. 3) is fitted three 1.95x0.65 m² and four 1.26x1 m² glass wool panels of one wall (7.12 m² of glass wool).

f(Hz)	100	125	160	200	250	315	400	500	600	800	1000	1250	1600	2000	2500	3150	400	5000
Walls	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.05	0.05	0.06	0.07	0.08
Glass wool	0.35	0.35	0.40	0.58	0.67	0.88	0.85	0.80	0.84	0.88	0.92	0.93	0.92	0.93	0.95	0.91	0.95	0.77

Table I: Absorption coefficients of the reverberation chamber and the glass wool panels by third octave band.

The absorption coefficients of the empty room have been measured and are given in Tab. I. The glass wool absorption coefficients, measured independently using the free field method developed by Allard [13] are also presented in Tab. I. The measurements have been carried out following the recommendations of the ISO 3382 norm [14].

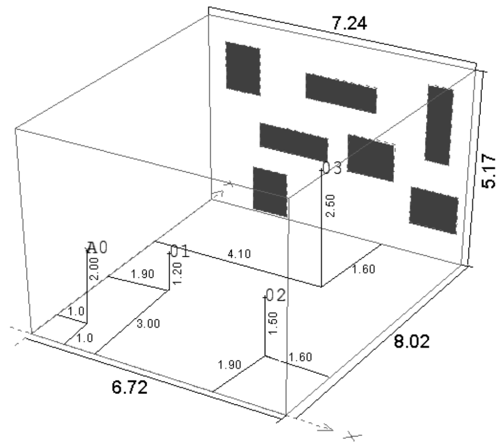

Figure 3: Studied configuration, the shaded zones indicate the glass wool panels. A0 is the sound source and 01, 02 and 03 are the microphones locations (dimensions in m).

Measurements by third octave band between 100 to 5000 Hz were carried out with a 9 mm blank pistol and three ½" microphones type B&K 4188 connected to 5935 preamplifier, all manufactured by Brüel & Kjaer. Signals were filtered using a Multimetrics Industries low-pass band AF 220 type and were recorded on a DAT. Reverberation time were estimated from the measured energy decay included 10 dB below the maximum sound level and 10 dB above the background noise. Experienced decays were linear and showed a dynamic superior to 30 dB allowing one to calculate the reverberation time from -10 to -40dB. The reverberation times reported in the following are the average of the measurements at the three microphone's locations.

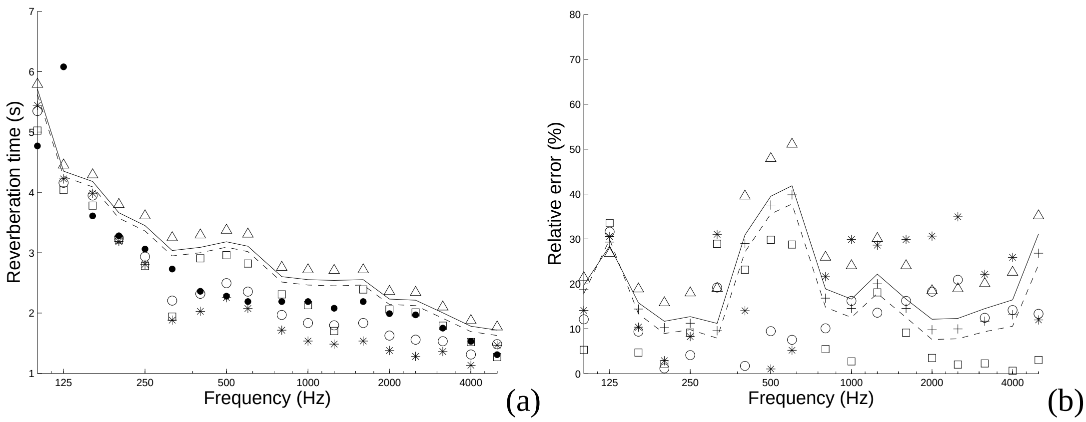

Figure 4: Reverberation time by third octave band and relative error to the experimental data: experimental data (●), Sabine model (solid line), Eyring model (dashed line), Dance model (*), CATT-Acoustic (□), diffusion-Sabine (Δ) and diffusion-Eyring (o).

For the diffusion models, the configurations are discretized in around 8000 elements and the computation time is about 2 minutes. For the CATT-Acoustic model, 1 000 000 rays are emitted. The computation time is about 2 hours.

The reverberation time and the error relative to the experimental data are presented in Fig. 4. All models depict a similar behavior to the experimental one: the reverberation time decreases with the frequency due to the increasing of the absorptionThe mean relative error are 21.7% for the Sabine's model, 17% for Eyring, 19.6% for Dance, 11.8% for CATT-Acoustic, 26.5% for the diffusion-Sabine model and 12.9 % for the diffusion-Eyring model. The more accurate problem's description in CATT-Acoustic and the diffusion-Eyring model improves the prediction of the reverberation time. Nevertheless, the results accuracy is over the recommended 10% for practical applications [15] but close to the one obtained in similar configurations with calibrated diffuse ray tracing models [16].

CONCLUSION

This study has evaluated the ability of a modified diffusion model to give consistent predictions of the reverberation time in rooms with non-uniformly distributed absorption. Firstly, a modification of the boundary conditions of the diffusion model to account for the high absorptions is proposed. This modification is compared to several statistical theory's relations and a ray tracing software for a homogeneously absorbent cubic room with a good agreement. Then, the diffusion models and the ray tracing software are compared to experimental data as well as several models based on the statistical theory. The tested configurations consist in a reverberation chamber covered with patches of glass wool. The modified boundary condition allows a significant improvement of the predictions obtained with the diffusion model. However, all models present discrepancies superior to 10% compared to the experimental data in both configurations. Nevertheless, the ray tracing and the modified diffusion models gives the best results with average discrepancies of 11.8% and 12.9% respectively. The much shorter computation time required by the diffusion model shows the interested of such model.

REFERENCES

[1] Sabine WC., *Collected papers on acoustics*. (New York: Dover Publisher, 1964).

[2] Eyring CF., "Reverberation in "dead" rooms", J. Acoust. Soc. Am. **1** 217-241 (1930)

[3] Valeau V., Picaut J., Hodgson M., "On the use of a diffusion equation for room-acoustic predictions", J. Acoust. Soc. Am. **119** 1504-1513 (2006).

[4] Millington G., “A modified formula for reverberation”, J. Acoust. Soc. Am. **4** 69-82 (1932).

[5] Sette WJ., “A new reverberation time formula”, J. Acoust. Soc. Am. **4** 193-210 (1933).

[6] Dance SM., Shield BM., “Modelling of sound fields in enclosed spaces with absorbent room surfaces. Part I: performances spaces”, Appl. Acoust. **58** 1-18 (1999).

[7] Ollendorff F., “Statistische Raumakustik als Diffusionproblem”, Acustica **21** 236-245 (1969).

[8] Picaut J., Simon L., Polack J-D., “A mathematical model of diffuse sound field based on a diffusion equation”, Acustica **83** 614-621 (1997).

[9] Picaut J., Simon L., Polack J-D., “Sound field in long rooms with diffusely reflecting boundaries”, Appl. Acoust. **56** 217-240 (1999).

[10] Dalenbäck B-IL., “Room acoustics prediction based on a unified treatment of diffuse and specular reflections”, J. Acoust. Soc. Am. **100** 899-909 (1996).

[11] Howath MJ., Lam YW., “An assessment of the accuracy of a hybrid room acoustic model with surface diffusion facility”, Appl. Acoust. **60** 237-251 (2000).

[12] Ducourneau J., Planeau V. Etude de l’absorption acoustique équivalente des parois planes hétérogène dans un local industriel. Document de travail [UMAP 2001/JD/2001]; 2001.

[13] Allard JF. *Propagation of sound in porous media*. (London: Elsevier Applied Science, 1993).

[14] ISO 3382. Mesurage de la durée de reverberation des salles en reference à d’autrees parameters acoustique. mai 2000.

[15] Hodgson M., “When is the diffuse-field theory applicable?” Appl. Acoust. **49** 197-207 (1996).

[16] Bistafa SR., Bradley JS., “Predicting reverberation time in a simulated classroom”, J. Acoust. Soc. Am. **108** 1721-1731 (2000).