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Acoustics of small rectangular rooms: Analytical and numerical determination of reverberation parameters

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ABSTRACT

A small rectangular room with hard walls has a number of acoustic flaws and the most serious drawback is a long reverberation time. A technique commonly used for improving room acoustics consists in increasing a sound absorption on a ceiling. In this study, the impact of acoustical treatment of a ceiling on reverberant properties of a small rectangular room was examined. Changes in the modal reverberation time due to this treatment were investigated by the analytical method. As was evidenced by calculations, the initial increase in a sound absorption on a ceiling causes a substantial decrease in the modal reverberation time and a treatment efficiency decreases with a further absorption increase. It was found also that for a room with hard walls statistical and wave theories give the same result as the modal reverberation time for oblique modes and the Sabine's reverberation time are identical. A more detailed information about reverberant properties of a room was provided by the numerical method employing a backward integration of the squared room impulse response. Using this method, global and local reverberation parameters were determined. Numerical simulations discovered a quite good agreement between global and local reverberation time and high differences between global and local early decay time resulting from a nonlinear shape of a decay curve. Therefore, one can conclude that the global decay times characterize reasonably well a reverberation process in a late stage of sound decay but they are not correctly describe this process in an initial stage.

1. Introduction

Small rooms represent enclosed acoustic spaces that have interior volumes in the range from a few cubic meters to a few hundred cubic meters. In the acoustical sense, one has to deal with rooms having sizes of the same order of magnitude with the wavelength at the frequencies in question or rooms in which the early reflections by walls, ceiling, and room objects arrive within milliseconds of the direct sound [1]. Small sizes cause that a room response is dominated by modal behavior, thus, acoustics of small rooms is often characterized by irregular sound distributions at low frequencies [2–4]. A shape of a small room is rectangular usually, therefore, attempts have been made to classify room's low frequency sound distribution with regards to its aspect ratio [5,6]. Common metrics have relied on the homogeneous distribution and from these an optimal aspect ratios have found [7,8]. However, to avoid a flutter echo and other unwanted artifacts typical for rectangular rooms, enclosures with nonrectangular shapes are often recommended [9–11]. Another acoustic issues in small rooms stem from some amplification or attenuation of sound at certain frequencies because it causes the so-called boomy sound and unwanted sound coloration [12,13]. These effects and improper reverberation properties may prevent the correct perception of sound in rooms where speech, music, listening or recording is part of normal use. Therefore, the acoustic behavior of small spaces has been extensively studied when they were used as performance studios, studio control rooms, listening rooms, audio program assessment rooms or small conference and lecture rooms [14–17].

The relationship between the reverberation time and absorption properties of room walls has been a fundamental question in the development of room acoustics because the importance of reverberation time is well recognized as the criteria for hearing of speech and music [18]. A simple dependence between the reverberation time and the random-incident absorption coefficient of room walls provides the Sabine's formula first published near the end of the nineteenth century [19]. The plainness of this equation and its applicability for acoustical design purposes have made it one of the most important formulas in room acoustics. The Sabine's theory of reverberant rooms is based on the diffuse sound field hypothesis that the acoustic energy is uniform in the field and

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sound waves travel with equal probability in every direction. An example of a room that can be classified as diffuse is a small rectangular room with very low absorption uniformly distributed at walls, termed as a hard-walled rectangular room. Acoustics of this room can be improved by placing absorbing materials on room walls. However, in several cases a use of these materials on a floor or lateral room walls is impossible for practical reasons, therefore the acoustical treatment is limited to a ceiling absorber. As was reported in the literature [20–22], it causes that the room behaves like non-diffuse one because the reverberation time does not only depend on the wall absorption, but also a room shape plays important role.

The objective of this paper is to examine the effect of acoustical treatment of a ceiling on reverberant parameters of small rectangular room. In the research, two computational methods were used for this purpose. Both are based on a modal expansion approach for lightly damped room systems. This means that the reverberant sound field is decomposed into a series of normal modes and room walls provide a weak sound absorption. The first method enables to assess a spread of the reverberation time upon the minimal and maximal values of modal reverberation time and this technique is suitable for the preliminary evaluation of acoustic quality of a room. The second method allows to determine a decay function via a backward integration of the squared room impulse response. This method was employed for simulating the global decay times which characterize reverberant properties of a whole room. A similar technique was used for predicting the actual decay times which are dependent on the source and receiving positions, thus representing local reverberation parameters. A comparison of simulation data discovered a quite good agreement between global and local reverberation time and substantial differences between global and local early decay time at some receiving points resulting from a nonlinear shape of a decay curve.

2. Modal behavior of room response

Room of rectangular shape, also known as a rectangular prism, a rectangular parallelepiped, a cuboid, a cuboidal room or a shoebox room, represents the most popular type of actual small rooms. A sketch of the rectangular room under study together with the associated coordinate system is shown in Fig. 1. The floor of the room is taken to be in xy plane and the height along z axis, and it is assumed that room dimensions satisfy the relations: $L_x \geqslant L_y \geqslant L_z$. The most convenient way of describing the indoor sound field is to use the room impulse response (RIR). The RIR is very useful in acoustics because a knowledge of the RIR function $h(\mathbf{r}', \mathbf{r}, t)$, describing the pressure response at the receiving point $\mathbf{r} = (x, y, z)$ to the time impulse at the point $\mathbf{r}' = (x', y', z')$, enables

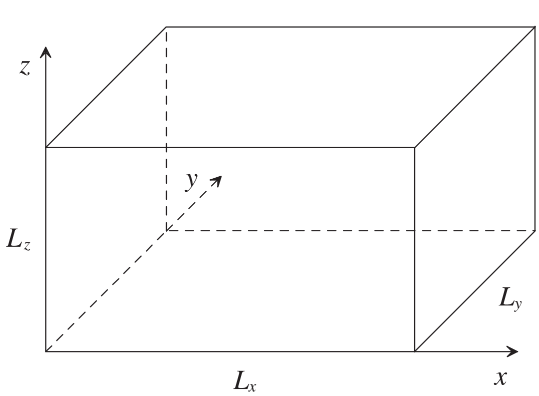

Fig. 1. A rectangular room under study together with the associated coordinate system.

to predict the room response for arbitrary sound source. If spatial and temporal properties of the source is characterized by the function $q(\mathbf{r}', t)$, the pressure response $p(t)$ to this excitation can be found from the equation

$$p(t) = \int_V q(\mathbf{r}', t) * h(\mathbf{r}', \mathbf{r}, t)\,\mathrm{d}^3\mathbf{r}' = \int_{-\infty}^{t}\int_V q(\mathbf{r}', \tau) h(\mathbf{r}', \mathbf{r}, t-\tau)\,\mathrm{d}^3\mathbf{r}'\mathrm{d}\tau, \tag{1}$$

where V is the room volume, the symbol $*$ denotes a convolution operation and $\mathrm{d}^3\mathbf{r}'$ is a symbol for the volume element $\mathrm{d}^3\mathbf{r}' = \mathrm{d}x'\mathrm{d}y'\mathrm{d}z'$. From practical reasons, a point source is most often considered. If the source is located at the point $\mathbf{r}_0 = (x_0, y_0, z_0)$, the source function in the integrand takes the form

$$q(\mathbf{r}', \tau) = Q\delta(\mathbf{r}' - \mathbf{r}_0)\, s(\tau), \tag{2}$$

where Q, which depends on the source power $\mathcal{P}$, is determined by $Q = \sqrt{8\pi\rho c\mathcal{P}}$ [23] and the non-dimensional function $s(\tau)$ describes a time behavior of the source. By inserting Eq. (2) into Eq. (1) one can obtain

$$p(t) = Q\int_{-\infty}^{t} s(\tau) h(\mathbf{r}_0, \mathbf{r}, t-\tau)\,\mathrm{d}\tau. \tag{3}$$

In the following it will be assumed that a sound damping inside a room is small. In this case the room walls are characterized by a low absorption: $\mathrm{Re}(\beta) = \gamma \ll 1$, where β and γ are the specific wall admittance and specific wall conductance, respectively. Enclosures with such absorption properties are termed "lightly damped rooms" [24,25]. In such rooms, a modal behavior of the sound field is dominant at low- and mid-audio frequencies. Thus, in these frequency ranges the response function describing the modal behavior of the RIR is as follows [26]

$$h(\mathbf{r}_0, \mathbf{r}, t) = c^2 \sum_{m=1}^{M} \frac{e^{-r_m t}\sin(\Omega_m t)\,\Phi_m(\mathbf{r}_0)\,\Phi_m(\mathbf{r})}{\Omega_m}, \tag{4}$$

where M is the number of modes included in the series expansion (theoretically, M approaches infinity). In the above equation c is the sound speed, $\Omega_m = \sqrt{\omega_m^2 - r_m^2}$ are the modal frequencies for damped vibrations, ω_m are the natural frequencies and r_m are the modal damping factors given by

$$r_m = \frac{c}{2}\int_S \gamma\Phi_m^2(\mathbf{r})\,\mathrm{d}s, \tag{5}$$

where S is the surface of room walls and Φ_m are the mode shape functions which fulfill the orthonormal property in the room volume. In lightly damped rectangular rooms the mode shape functions are the products of cosine functions in three dimensions [27]

$$\Phi_m(\mathbf{r}) = \Phi_{n_x n_y n_z}(\mathbf{r}) = \sqrt{\frac{\epsilon_{n_x}\epsilon_{n_y}\epsilon_{n_z}}{V}}\cos\left(\frac{n_x\pi x}{L_x}\right)\cos\left(\frac{n_y\pi y}{L_y}\right)\cos\left(\frac{n_z\pi z}{L_z}\right), \tag{6}$$

where the modal indices n_x, n_y, n_z are non-negative integers and they are not simultaneously equal to zero (the trivial solution of the wave equation was excluded), $\epsilon_{n_s} = 1$ if $n_s = 0$, and $\epsilon_{n_s} = 2$ if $n_s > 0$. The natural frequencies ω_m corresponding to these functions are as follows

$$\frac{\omega_m}{2\pi} = f_{n_x n_y n_z} = \frac{c}{2}\sqrt{(n_x/L_x)^2 + (n_y/L_y)^2 + (n_z/L_z)^2}. \tag{7}$$

Among acoustic modes excited in rectangular rooms there are three main types of modes which exhibit variant acoustic properties: the axial modes featured by one non-zero modal index, the tangential modes characterized by two non-zero modal indices and the