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INFLUENCE OF ABSORBING MATERIAL DISTRIBUTION ON DOUBLE SLOPE SOUND DECAY IN L-SHAPED ROOM

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The sound decay process in L-shaped room was the subject of this investigation. The room with walls covered by the low absorbent material constituted the initial configuration for the study. To decrease a reverberation time, alterations of acoustic room properties were carried out by adding a high absorbent material on lateral room walls. Two different material configurations were considered and their effects on a double slope sound decay were analysed. In order to predict the behaviour of decay curve, a numerical implementation based on the wave theory was applied. A space distribution of eigenfunctions was computed using the forced oscillator method with a finite difference algorithm. Numerical results have demonstrated that an introduction of high absorbent material on selected room walls may cause an intense double slope effect. It is characterized by rapid initial and slow late decays, thus the decay curve exhibits so-called a "sagging" appearance. It was found also that a phenomenon of mode localization is an important factor in modifying the double slope sound decay.

Keywords: coupled rooms, modal analysis, reverberation, double slope effect, localization of eigenmodes.

1. Introduction

In low-frequency limit, the coupled room systems have special problems associated with their irregular shape and a size that is comparable with a sound wavelength. Thus, the acoustics of these systems has always been hard to analyse, because a complex system shape requires an application of numerical methods [5] and a theoretical description of acoustic phenomena within a room space is based on the wave theory, which is more adequate from the physical point of view but more difficult in immediate practical applications [2].

A subject of this paper is a study of reverberation behaviour of sound pressure in L-shaped room for different distribution of absorbing material on room walls. The room shape together with details of its geometry are shown in Fig. 1. The L-shaped rooms

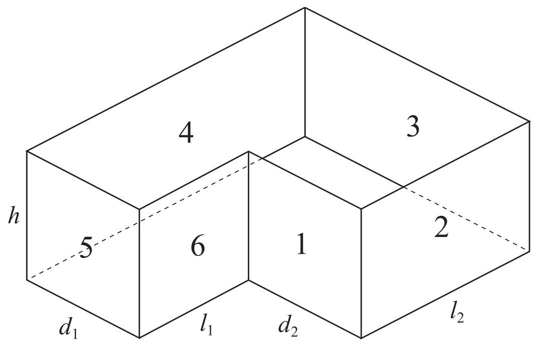

Fig. 1. Room under study having shape resembling capital letter L. Lateral room walls are numbered from 1 to 6. Dimensions of enclosure are following (in meters): $d_1 = d_2 = 3$, $l_1 = 4$, $l_2 = 6$, $h = 3$.

are a special type of coupled room systems because they consist of two rectangular rooms that are connected through an opening having an infinitely small thickness. In a theoretical model a response of a room to a sound excitation was described in terms of its normal eigenmodes and the associated decay constant of each of these modes. A space distribution of eigenfunctions and the frequency corresponding to each mode were calculated numerically and they were used to predict the early decay time (EDT) and late decay time (LDT). A ratio between LDT and EDT, commonly known as the decay ratio, characterizes the double slope sound decay. This parameter is very important in a sound perception because a rapid early decay may result in higher sound clarity, whereas a slow late decay can lead to a general increase in a perceived reverberation [1].

2. Numerical method

We first recall the numerical method used in Ref. [6]. In this method the formulations of wave acoustics were used to predict acoustical properties of enclosures, having dimensions comparable with the sound wavelength (low-frequency limit). In this approach a room with walls covered by absorbing material has been modelled by a system of uncoupled eigenmodes. Spatial distributions of modes and eigenfrequencies were computed numerically via an application of the forced oscillator method [7] with a finite difference algorithm. A decaying process of sound was described by a temporal decay of the spatial root mean square pressure determined by

$$p_{\text{rms}} = \sqrt{\frac{Q_0^2 e^{-4r_0 t}}{(r_0^2+\omega^2)^2} + \sum_{n=1}^{\infty} \frac{Q_n^2 \omega_n^2 e^{-2r_n t} \cos^2(\Omega_n t - \alpha_n)}{\Omega_n^2[(\omega_n^2-\omega^2)^2 + 4r_n^2\omega^2]}}, \tag{1}$$

where ω is a sound source frequency, Q_n is a factor determining a source intensity for Helmholtz mode ($n = 0$) and eigenmodes with non-zero frequencies ($n = 1, 2, 3\ldots$), r_n is a damping coefficient, ω_n is an eigenfrequency, $\Omega_n = (\omega_n^2 - r_n^2)^{1/2}$ is an eigenfrequency for damped oscillations and $\alpha_n = \tan^{-1}[r_n(\omega_n^2+\omega^2)/\Omega_n(\omega_n^2-\omega^2)]$. For a given frequency and a sound source location, a numerical procedure was used to calculate temporal changes in the pressure level $L_{\rm rms} = 20 \log (p_{\rm rms}/p_0)$, where p_0 is a reference pressure. Since the expression for $p_{\rm rms}$ includes harmonic terms, the method of polynomial regression was used to compute a time average decay curve of the pressure level $L_{\rm rms}$. A fit curve obtained in such a way describes average long-time changes in a sound pressure level, thus it was applied to determine the early and late decay times.

3. Analysis of calculation data

The method described above was used to evaluate decay times in L-shaped room shown in Fig. 1. It was assumed that in an untreated room all walls were uniformly covered with an absorbing material having the random-absorption coefficient $\alpha = 0.04$ (brick lateral walls, hard floor and ceiling), thus this room configuration can be characterized as acoustically hard. The standard reverberation time evaluated for this configuration was over 3 seconds, thus it is unsatisfactory for normal-hearing listeners. In order to improve acoustic conditions of the room, a special room treatment should be applied which, in general, resolves itself into an introduction of an additional high absorbent material on room walls. In the present study two distributions of absorbing material were examined. In the first case, the material required for the reduction of reverberation time was mounted on the lateral walls denoted by 1, 2 and 3, whereas in the second one it was located on the walls 4, 5 and 6 (Fig. 1). The random-absorption coefficient α for this material was 0.48 (5 cm medium density mineral wool).

The plots in Fig. 2 depict frequency dependences of the decay ratio and the early decay time for the first configuration of high absorbent material. From these data it results that the decay ratio – the most important measure of the double slope effect, changes substantially with a frequency. The range of its values: 1–2.6, suggests that an irregular distribution of high absorbent material on lateral walls may cause an intense double slope sound decay. An explanation of this fact is that in the initial stage of sound decay a time history of the pressure level is dominated by strongly damped modes, whereas in the late stage – by modes which were only lightly damped. Such a dissimilarity of mode damping is a result of differences between space distributions of eigenfunctions. The mode is fast damped when it possesses such a distribution that its energy is concentrated in a room space between walls 1, 2 and 3. On the contrary, if a mode energy is accumulated in a room space between walls 4, 5 and 6, a mode damping is small and its decay occurs usually in a late stage of reverberation process.

It results from Fig. 2 that local minima in a frequency dependence of the decay ratio correspond to local maxima of the early decay time. An inspection of frequencies of these peaks has shown that they are in agreement with frequencies of modes which are strongly localized in a room space between walls 4, 5 and 6. For some of these frequencies the decay ratio approaches unity. It means that a sound pressure level decreases almost linearly with a time and it occurs when a reverberation process in early and late stages is dominated by a decay of the above-mentioned strongly localized eigenmode.

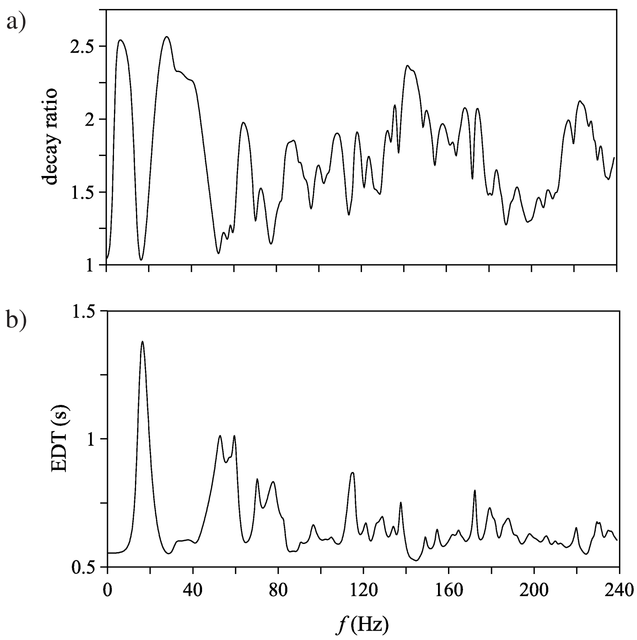

Fig. 2. Frequency dependences of decay ratio (a) and EDT (b) for absorbing material on walls 1, 2 and 3.

The same conclusions can be drawn from Fig. 3, where calculation data for a second configuration of high absorbent material are presented. An important difference lies in

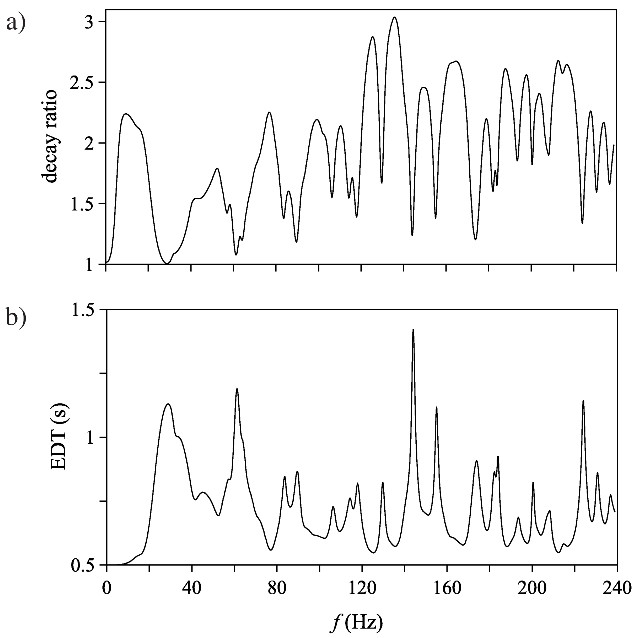

Fig. 3. Frequency dependences of decay ratio (a) and EDT (b) for absorbing material on walls 4, 5 and 6.

the facts that in this case there are more sharp peaks in a frequency dependence of the early decay time. It evidences that a bigger amount of modes is strongly localized in the space between walls 1, 2 and 3.

The same strong influence of a mode localization on the reverberation process has been previously observed for room systems consisting of two rectangular enclosures connected with an acoustically transparent opening having small but non-zero thickness [3, 4]. In these cases the rooms, which form a coupled system, are visibly distinguished, thus the localization occurred in the first or the second partial room and frequencies of localized modes were very similar to the frequencies of modes which are created in rectangular rooms having the same dimensions as the partial rooms [4]. In the room geometry considered in the paper, two pairs of rectangular rooms may be perceived, therefore modes can be localized in different four parts of the room. Examples of eigenfunctions shapes for various mode localizations are shown in Fig. 4. The calculation results are plotted in a form of filled contour maps, that are a two-dimensional representation of three-dimensional data, in which black and white colours denote minimal and maximal values of eigenfunctions, respectively.

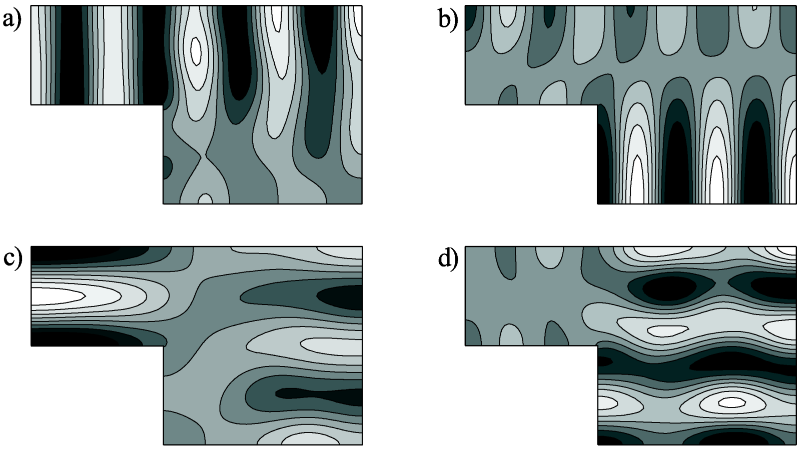

Fig. 4. Shapes of eigenfunctions for modes localized in: (a) upper, (b) bottom, (c) left and (d) right parts of room. Black and white colours denote minimal and maximal values of eigenfunctions, respectively.

4. Conclusions

In low frequency range the method of eigenmodes has been used for studying a process of sound decay in the room having a shape resembling the capital letter L. The numerical procedure presented in the paper [6] has been used to model a reverberant sound field in the room and to generate sound echograms from which the early and late decay times were calculated. Frequency dependencies of these decay times were investigated for two various distributions of absorbing material on room walls. Results of numerical calculations have demonstrated that an irregular location of high absorbent material on lateral walls may produce the double slope sound decay in which a late slow decrease in a sound pressure is preceded by an initial sudden sound decay. It was found that this effect is a result of the mode localization which may appear in different four parts of the enclosure in the case of L-shaped room geometry.

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