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Acoustics design of open-plan offices: a short review

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The paper reports on a literature review of the relationship between acoustics and satisfaction in the open-plan office, conducted with the aim of developing empirically derived recommendations for satisfactory acoustic condition. First of all, this paper reviews historically the physical background of the model involving this subject by focusing on both theoretical and experimental implications. Then some popular models which have been published within nearly decades are investigated. In the last section, a theoretical model based on the modal analysis which contains all features such geometry scattering of sound waves from walls is proposed.

Keywords: open-plan office, acoustic condition, sound scattering.

INTRODUCTION

Nowadays the open-plan offices have become a common work environment for many people. When sharing the same floor area high demands on the planning and the acoustical treatment of the offices has to be fulfilled for creating a functional work environment. In an open-plan office the activities often means communication between team members but also concentrated work. The acoustical design should support both these activities. In the planning process and also for verification of the acoustical conditions there is a need for efficient room acoustic methods. It's recognized that the reverberation time alone as a global parameter is insufficient to reveal the acoustic conditions in open-plan offices.

Open-plan offices lack walls and doors, although one common assumption has been that such a design would encourage communication between co-workers, it has become apparent that the primary source of discomfort for occupants of the open-plan office environment is unwanted sound. The human auditory system responds to different frequencies in different ways. Sounds of the same level but at different frequencies will not be considered equally loud. In an effort to better understand the effects of different frequency ranges on the human ear, equal subjective loudness curves relate subjective loudness to sound pressure and frequency. These equal loudness curves are valid only for pure tones. Because most noises consist of many different frequencies (not just pure tones), the curves do not predict the loudness of everyday noises, although they are the basis for frequency weightings used today. These weightings, called A, B, C and D contours, are used to calculate SPL's that correct for the varying sensitivity of human hearing to differ in the weights applied to various sounds of varying frequency. The A-weighting has become the most widely used method of measuring broadband sounds because it is believed to best approximate human aural sensitivity [1]. It seems that ambient noise levels (from all sources) that exceed 45-50 dB(A) are associated with annoyance. However, studies investigated the effects of specific office noises and their relationship to employee satisfaction, rather, total annoyance with a combination of office noises was considered. There could be some sources that are more annoying even at lower levels or others that are tolerable at higher levels. Some researchers claim that it is not the overall ambient sound levels that determine annoyance ratings, but intermittent peak noises that fluctuate above the average levels [2].

1. SOUND MASKING

When trying to predict the effects of noise on speech in indoor environments, researchers usually use composite measurements such as the Articulation Index (AI) and the Speech Intelligibility Index (SII), which are frequency-weighted speech/noise ratios. The frequency weightings used for these indices are derived from psychoacoustic data on the recognition of speech under varying noise conditions. Articulation tests are tests involving how well syllables or phonemes are recognized, whereas intelligibility tests usually refer to the ability to comprehend words or sentences.

It seems that the too much high-frequency contribution comprehend words or sentences. It seems to ambient noise can be unsatisfactory or annoying; however, it is precisely those frequencies that are the best for speech masking, which decreases speech intelligibility. A masking sound spectrum that uses these frequencies can provide better masking at a lower SPL[1], which should also contribute to improved acoustic satisfaction. The balance point – the optimal SPL for sounds of varying frequencies – remains uncertain. Sound can mask speech, particularly in the context of the indoor environment, depends on two main qualities: intensity and frequency. The louder, and hence, the greater the intensity of the artificial sound, as compared to the speech sound, the more masking will occur. Sound masking can also occur if the frequency of the masker approaches that of the signal (speech). Researchers often refer to the concept of a critical band of masking which means that frequency components of the noise need to lie within a narrow band surrounding the centre frequency of the signal in order to be effective. If the noise is composed of frequencies outside of the critical band of the speech noise, for example, then interference will not occur. However, if the noise intensity is sufficiently high, it can mask the signal regardless of its frequency components [3, 4]. Speech is the most disturbing sound signal in an open-plan office. How to increase the attenuation of speech between different working groups is consequently a question of major importance in the acoustical planning. To quantify the attenuation of sound during propagation measures are appropriate. These parameters are defined in ISO standards. In this investigation A-weighted pink noise was used as a sound source. Knowing measures and specifying a target value for acceptable speech level at a work place, the distance needed between the person talking and

[1] The SPL is a measure that relates the physical energy of sounds of 1 s or shorter to auditory system responses to sounds.

the workplace is given where depends directly to the distance of comfort, the level of speech and the acceptable speech level at the work place. This (comfort) distance gives an indication of how to proceed in the acoustical design work concerning absorbing materials, screens, furnishing etc. and acts as a useful tool for the architects. As a consequence and according to some mathematical formulas the distance to reach an acceptable speech level has been shortened. Speech heard from neighboring desks is the most distracting noise source in open-plan offices. In the planning of open-plan offices, the aim is efficient attenuation of speech and reduction of speech intelligibility between workstations so that the concentration of the worker will not be disturbed. Speech can be attenuated, e.g. using absorbing ceiling material and screens between adjacent workstations. A properly planned masking noise system can also be used, if the background noise level of the room is not sufficient to mask the speech. However, the resulting acoustics in an open-plan office can not be predicted only using product information such as the absorption coefficients of a suspended ceiling or the type of a screen but the outcome depends on many variables in a complex way.

2. STEADY STATE LEVELS

In many public rooms such as classrooms, day-care centers, offices etc. the acoustical treatment consists of a suspended absorbent ceiling. In these rooms, the conditions and relations for the diffuse field theory are not fulfilled. Reverberation time as calculated by Sabine formula often show large discrepancies to measured values. It is also recognized that even if the reverberation times are equal, the acoustical conditions can still be perceived as different. Consequently, there is a need for supplementary acoustical descriptors for a more complete description of the acoustical conditions in this type of rooms. From concert hall acoustics it’s known that up to five or six parameters are needed to represent the subjective impression of a sound field. Thus, it seems plausible that the reverberation time, even in ordinary rooms, needs some assistance for a more relevant characterization of the acoustical conditions.

The grazing sound field can be described as an almost two-dimensional field since the main contributions are from waves traveling in a plane parallel to the ceiling absorber. This equation can be considered as the two-dimensional equivalent to Sabine formula. However, a most important distinction is the interpretation of the equivalent absorption area. The equivalent absorption area also contains the effect of scattering objects in the room. It is assumed that the dominating effect of scattering objects is to divert sound energy from the grazing to the non-grazing field. Thus, for the grazing field this flow of energy to non-grazing field appears as absorption of sound and can be quantified in an equivalent scattering absorption area. One important difference is the way that in which the ceiling absorber is taken into account. The statistical absorption coefficient do not enters the mathematical formula, instead the ceiling absorbers properties for almost grazing incidence appear as a grazing absorption coefficient.

3. PHYSICAL QUANTIFIED MEASURES

Sound consists of pressure changes that travel in a wave-like manner through the air and can be detected by the human ear. Sound varies according to frequency and pressure. The number of times per second the air pressure increases, decreases, and then returns to normal pressure is defined as frequency in hertz (Hz) or cycles per second (cps). Frequency can also be referred to as pitch. The human ear can perceive sound between 20 Hz and 20 kHz. The degree to which air particles are compressed and rarefied from their normal state is called sound pressure. Sound energy is directly proportional to the square of sound pressure [4]. In order to relate the intensity of sound to its effects on people, three general measurements have been developed: Sound Pressure Level (SPL), Event Exposure Level (Lex), and the Multiple-Event Sound Equivalent Level (Leq), all of which are defined in decibels (dB).

The Lex comprised of successive 1 second SPL's summed is used for sounds of longer duration, and is over time. The Leq is an averaged measure of 1 second SPL's over a specific period of time (e.g., 5 minutes, or 1 hour); in other words, it is a cumulative measure of noise exposure. The measured quantities were RASTI (Rapid Speech Transmission Index), insertion loss of the screen and received speech level at the listener's position.

RASTI reflects the speech intelligibility and takes into account the effects of background noise and reverberation. Therefore, it is perhaps the most appropriate quantity of these three to characterize the speech privacy between two adjacent workstations. Background noise and reverberation of the room make it more difficult to perceive speech. In open-plan offices, the aim is naturally as low RASTI as possible (high speech privacy). An adequate value between two workstations would be below 0.50, i.e. the neighbor's speech can still be heard but it does not cause distraction. RASTI values were measured with equipment. Insertion loss of the screen, DS, was measured according to the ISO standard. Pink noise was played with a loudspeaker placed at the talker position. The produced sound pressure levels were measured with and without the screen at the listener position with a real-time analyzer. The weighted screen insertion loss was then determined from the octave band insertion losses. The speech level at the listener position was measured in the following way. A 40 second speech sample of a male speaker was played with a loudspeaker placed at the talker position. The received speech level, LAeq,S, was measured at the listener's position with the real-time analyzer. The long-term speech spectrum level of the speech sample was in conformance with standardized speech spectrum at normal speech effort at distance of 1 m in front of the speaker in free field.

4. EXPERIMENTAL STUDIES

In real open-plan offices, the sound can bypass the screen also from below and from the sides. The room walls are reflective and the positions of the mutual workers differ. These factors typically deteriorate the attenuation and improve the speech intelligibility between workstations. This, on the other hand, means that lower RASTI values are a bit easier to reach than expected. As a whole, the laboratory values should not be used as such but yet they reflect the combinatory effects of different ceiling and screen combinations between workstations, and, therefore, they can be exploited in the acoustical planning of open-plan offices. An efficient attenuation and low speech intelligibility are the main goals when planning an open-plan office. Speech intelligibility can be most efficiently reduced when all the affecting factors – background noise level, the suspended ceiling height, ceiling material and screen height – are taken into account simultaneously. In practice there is no use of screens and ceiling materials if the background noise level is not sufficient.

5. POPULAR MODELS

5.1. Acoustics design program for rooms

For an appropriate acoustic design it is important to consider the activities going on and the type (shape/diffusivity) of the room. Further, the fact that the hearing is a multi-dimensional experience several room acoustic parameters are needed for an evaluation that is related to the subjective impression of the acoustic conditions. Thus, for different room types and activities different room acoustic parameters will be of more or less importance. Taking into account the human perception of sound, the room type, and the activities going on, the probability of a successful acoustic design will increase. In open-plan offices measures related to the spatial behavior of sound propagation seems to be well suited for the acoustic characterization. These types of measures were suggested in a first draft of a standard for acoustic evaluation of open-plan offices.

5.2. Supplementary materials for room

There are some evidences that the speech levels in open-plan offices can be a few decibels lower than the standard speech level. Measurements were made using six commercial suspended ceiling materials: two glass wool plates, three perforated gypsum plates and one no perforated gypsum plate, which was almost totally sound reflecting. The plate elements (590 mm × 590 mm) were mounted either at a height of 2.5 m or 3.3 m so that there was left either a 1.1 m or 0.3 m wide air gap between the plates and the ceiling, respectively. In addition, measurements were made with 300 mm glass wool plates mounted directly on the ceiling without any air gap. Both self-made and commercial screens were used. There were two different Stacks screens, a glass and a fabric coated. The fabric coating was only 5 mm thick and not very sounds absorbing. Measurements were made with screen heights of 130 and 168 cm. The fabric coated was 168 cm high. An acoustically hard non-commercial screen (“hard”) was made of 12 mm thick chipboard. An absorbing version of it (“soft”) was made attaching a 45 mm thick glass wool plate on the transmission side of the screen. The noncommercial screen heights were 210, 168 and 130 cm. Some of the tests were conducted by covering the floor with soft textile plates and the results are presented in future paper [4].

6. MODAL ANALYSIS OF A RECTANGULAR ROOM USING THE EIGENVALUES OF THE HELMHOLTS OPERATOR

Modal analysis is a classical method for solving problems in room acoustics; see, for example, [5, 8]. Using this method, once all the normal modes are known, the acoustic pressure distribution for an arbitrary sound source in a room can be easily computed. Although the modal theory of room acoustics was established and fully formulated over a half century ago, it is still incomplete in the sense that there is no well-developed, general method for finding eigenvalues that correspond to room modes for walls with arbitrary impedances.

Only for rooms with perfectly or nearly rigid walls or rooms with the same impedance on each pair of parallel walls are the eigenvalues or their approximations easy to evaluate. Hence, only these cases have typically been considered in the acoustics literature [5, 6, 7]. However, the effect of finite wall impedances on quantities of interest, such as the reverberation time, is of general interest and important for real-world problems. Hence there is a need for an efficient and accurate method for evaluating eigenvalues for the more general case. The difficulty in finding the acoustic eigenvalues arises from the nonlinear and transcendent nature of the acoustic eigenvalue equation, which necessitates the use of numerical methods [8]. In addition, for the modal solution to be accurate, these methods must be able to evaluate all the roots of this equation within a given interval. Classical numerical approaches for solving nonlinear equations such as Newton's iteration are not suitable for solving these equations because they yield one root for a single initial guess. Moreover, the initial guess must be good in order to obtain a root in the range of interest. If the number of roots in a range of interest is unknown, which is often the case in the acoustic eigenvalue problem with a room with finite wall impedances these methods cannot be applied. In this stage the numerical methods must be used [9]. One of these methods is the interval Newton/generalized bisection IN/GB method is applied to the acoustic eigenvalue equation to overcome the above-mentioned difficulties [10].

6.1. Limits and approximations of acoustic eigenvalues

Although the IN/GB method is guaranteed to find all roots in a given interval, an intelligent choice of the initial intervals makes it more efficient. The limits and the asymptotic behavior of the acoustic eigenvalues are derived in the following theorem: the solutions of the acoustic eigenvalue equation appear in pairs of opposite signs.

6.2. Finite element solution

For comparison, the same interior Helmholtz problem was solved using the finite element solution (FEM). Example of FEM application will be presented in details in future paper [4]. In this simulation a uniform mesh of square elements with bilinear interpolations was used. The edge of each square element was 0.002 m long. This corresponded to 1571, 314, and 157 elements per wavelength for wave numbers (k) in Fourier analysis for values k = 2, 10, and 20, respectively. With this resolution, the finite element solution converges well for all the driving wave numbers considered. We will discuss this analysis in the next work via finite element method [4]. The finite element solution provides a reliable benchmark solution and was used to check the validity of the modal solution.

7. COMPARISON OF MODAL AND FINITE ELEMENT SOLUTIONS

The steady-state sound pressure level is related to the diffuse part of the sound field, mainly determined by the total amount of sound absorption in the room, and much less influenced by sound scattering objects. The IN/GB method was applied to the acoustic eigenvalue equation of a rectangular room with arbitrary, uniform wall impedances to find all eigenvalues within a given interval. Furthermore, the limits and asymptotic behavior of these eigenvalues were derived. These properties were used to restrict the interval range in the IN/GB method and to provide good initial guesses, increasing its efficiency in finding all eigenvalues. Several numerical tests were performed to validate the proposed method and to demonstrate its accuracy and efficiency. In the first test, it was verified that the roots obtained using the IN/GB method satisfied the analytical estimates. These data are also will be presented in the next authors' paper [4]. In the second test, the IN/GB method was used to compute the modal solution corresponding to a point source in a two-dimensional room. This solution was compared with a well-resolved FEM, which was used as a benchmark. It was found that as the number of modes in the modal solution is increased, it converged to the FEM solution at the expected analytical rate. Finally, the IN/GB method has been used to evaluate the reverberation times for a three-dimensional room with finite wall impedances. It was found that the IN/GB results were in good agreement with the other numerical results. With the development of interval arithmetic software, it will become increasingly easy to apply the interval method. Therefore, in conjunction with the properties of acoustic eigenvalues derived, the IN/GB method presents an efficient method for solving the acoustic eigenvalue equation for rectangular rooms with arbitrary, uniform wall impedances.

CONCLUSIONS

In this short review we discussed some topics about acoustic design of open office plans. We considered the popular models and also we introduced a new method based on the Modal analysis method for solving the Helmholtz wave equation under some rectangular boundary conditions imposes on the wave equation. This analysis has been done both using mesh finite element method and IN/GB frame. This analysis is not complete and we leave it to the next work [4].

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