Applied Acoustics 112 (2016) 59–69

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Contributions of various transmission paths to speech privacy of open ceiling meeting rooms in open-plan offices

Jingxia Yu [a,*], Shuping Wang [a], Xiaojun Qiu [b], Abu Shaid [c], Lijing Wang [c]

[a] Institute of Acoustics, Nanjing University, Nanjing, China
[b] School of Electrical and Computer Engineering, RMIT University, Melbourne, Australia
[c] School of Fashion and Textiles, RMIT University, Melbourne, Australia

ARTICLE INFO

Article history:
Received 11 March 2016
Received in revised form 1 May 2016
Accepted 6 May 2016
Available online 20 May 2016

Keywords:
Speech privacy
Open-plan office

ABSTRACT

Installing open ceiling meeting rooms inside a large open-plan office provides a solution to increase speech privacy and to reduce speech disturbance in the office. The open ceiling meeting rooms have advantages of low cost construction and flexibility, but have lower speech privacy than that of enclosed rooms due to the open ceiling. Existing research shows that many factors should be taken into account to achieve good speech privacy in open-plan offices and improving only one of these factors may result in little improvement, so it is important to distinguish contributions of different acoustic transmission paths of open ceiling meeting rooms in open-plan offices. This paper proposes an impulse response separation method to quantify contributions of various acoustic paths of open ceiling rooms on speech privacy in open-plan offices. The method is verified with simulations based on the Odeon software and the experiments carried out in 3 different types of rooms. Finally, the proposed method is applied to the Fabpod, a semi enclosed meeting room located in a large indoor office at the Design Research Institute of the RMIT University, to obtain the contributions of different acoustic transmission paths to its speech privacy. The method proposed in this paper and the knowledge obtained are useful for architects to improve the acoustic performance of the next generation Fabpods which are now under design at RMIT University.

1. Introduction

Since late 1960s, open-plan offices have been popular among design professionals [1]. Large open-plan offices have advantages of low cost construction and flexibility, but sometimes they lack speech privacy and result in speech disturbance when people are talking. Installing small closed meeting rooms inside open-plan offices provides a solution to the problem; however, the ceiling increases the cost of the meeting rooms due to the requirements of fire safety regulations and extra ventilation and lighting systems. Keeping the ceiling open or removing the ceiling of meeting rooms is an option; but the challenge is the low speech privacy due to sound propagating out through the open ceiling. There are several acoustic transmission paths through which sound radiates out from open ceiling meeting rooms into open-plan offices, and their relative contributions to speech privacy will be analyzed in this paper.

Speech privacy is related to the speech to noise ratio and represents the opposite of Speech Intelligibility (SI) to some extent [2]. In North America, Articulation Index (AI) and the Speech Intelligibility Index (SII) are widely used to represent the speech privacy while the Speech Transmission Index (STI) is used in Europe to represent speech privacy in open-plan offices [3]. STI is a physical quantity representing the transmission quality of speech with respect to intelligibility, and this paper uses it to evaluate the speech privacy of open ceiling meeting rooms in open-plan offices [4].

The relationship between room acoustic parameters and speech privacy of open-plan offices has been investigated by some researchers [5–7]. An international measurement standard was published in 2012, which uses single number quantities to indicate the general acoustic performance of open-plan offices [5]. The converted four single number quantities are the distraction distance, the spatial decay rate of speech, the A-weighted Sound Pressure Level (SPL) of speech at 4-m-distance and the average A-weighted background noise level, and can be determined by the spatial curves of A-weighted SPL of speech and STI in the office [6]. On the other hand, these single number quantities can be estimated by physical and acoustic parameters of rooms, which include the length, width, height of the room, the ceiling absorption, the screen height and apparent furnishing absorption [7].

* Corresponding author.
E-mail address: xindy0728@163.com (J. Yu).

http://dx.doi.org/10.1016/j.apacoust.2016.05.002
0003-682X/

To achieve good speech privacy performance, many room acoustic parameters should be considered at the same time and improving only one of these factors may result in little improvement if it is not the most critical one [3]. To identify the most critical factor, it is necessary to explore the influence of each parameter separately. Acoustical elements that can affect the acoustical environment in open-plan offices, such as windows, walls, ceilings and partial height screens, have been investigated experimentally [8]. But these experimental case studies lack quantitative analysis, which makes it hard to consider all important factors at the same time and compare the influence of different room acoustic parameters. An alternative way is to develop analytical models. A simple model of a single screen in an open-plan office with ceiling and floor reflections has been developed by using the image source technique [9]. A more complicated model took the effects of side and back panels of the common separating screen into account, and was used to investigate the sound propagation between two adjacent rectangular workstations in an open-plan office [10]. Some models even considered wall reflections and reverberation [11].

There are many acoustic transmission paths for open ceiling meeting rooms to radiate sound out into open-plan offices. The paths of reflecting from the ceiling and diffracting over the panel are relatively important while transmitting through the panel, reverberating in the room and reflecting by office equipment cannot be ignored either [11]. Based on the analytical models, the ceiling sound absorption, the panel height of the open-plan office and the office size were found to be the most important factors, while panel absorption, panel transmission loss, floor absorption, ceiling height and the details of ceiling mounted lighting could not be ignored though less important [2]. By optimizing all these room acoustic parameters simultaneously, good acoustic design can be obtained to meet the criterion for acceptable speech privacy.

The acoustic impulse responses of a room can provide most important acoustic information of the room [12]. For example, some important room acoustic parameters like reverberation time can be estimated from the room impulse responses [13]. Commercial room acoustic software such as Odeon and Dirac can be used to obtain a variety of parameters from the impulse responses [14,15]. Bradley used the impulse responses to describe energy diffracted by the panels and reflected by the ceiling to compare their influence on speech privacy in actual rooms [3]. But these studies are limited to qualitative analysis and hardly provide direct solutions to acoustic design of open ceiling meeting rooms in open-plan offices.

This paper extends the existing research to quantitative analysis of room impulse responses in different frequency bands. An impulse response separation method is proposed, and it is verified with simulations based on the Odeon software and the experiments carried out in 3 different types of rooms. Finally, the proposed method is applied to the Fabpod, a semi enclosed meeting room located in a large indoor office at the Design Research Institute of the RMIT University, to obtain the relative contributions of different acoustic transmission paths to its speech privacy. This method and knowledge obtained can be used by architects to improve the acoustics performance of the next generation Fabpods which are now under design at RMIT University.

2. The method

Open ceiling rooms in large offices can be treated as workstations in the acoustic design in open-plan offices. The layout and arrangement of the workstations are important in open-plan office design, while other factors cannot be ignored as well, such as sound absorption, height of screens, degree of workstation enclosure, and room dimensions [5]. The speech signal received in a closed room is the superposition of direct sound and reverberant sound. Reflections arrived within 50 ms after the direct sound are defined as early reflections, which are considered as useful for speech communication while those arrived later are defined as later reflections and are considered as harmful [11]. Thus, the contributions of direct sound and early reflections are considered first.

For positions outside an open ceiling meeting room in a large office, sound transmitting through panels is usually negligible compared with that transmitting through other paths because the transmission loss of the panels is usually more than 20 dB. Sound diffracting over the panels usually dominates the sound field outside the meeting room; however, if the absorption of ceiling is not large, sound reflecting from the ceiling might also become important. Sometimes, sound reflecting from the ground also plays an important role. Several acoustic transmission paths are shown in Fig. 1. Other paths such as reflecting from the ground or other walls inside the meeting room and then diffracting over the panel are less important, so they are not illustrated in the figure.

2.1. The theoretical method

The sound pressure level of sound transmitting through the direct path (without panel blocking) depends on the sound power of the sound source and the distance between the source and receiver [11]

$$L_{\mathrm{p,d}} = L_{\mathrm{W}} - 10\log_{10}(4\pi d^2), \quad (1)$$

where L_{w} is the sound power level of the sound source and d is the distance between the source and receiver. The sound diffracting over the panel can be obtained with the MacDonald solution [16,17].

$$L_{\mathrm{p,diff}} = L_{\mathrm{p,d}} - IL, \quad (2)$$

where the insertion loss IL can be calculated with

$$IL = 20\log_{10}\left| \frac{\mathrm{e}^{\mathrm{i}(kR+\pi/4)}}{r}\sqrt{\frac{\pi R_1}{2k}} \begin{bmatrix} \frac{\mathrm{sgn}(\pi+\alpha-\phi)\mathrm{e}^{\mathrm{i}kR}}{\sqrt{k(R_1+R)}} Fr\left(\sqrt{\frac{2k}{\pi}}(R_1-R)\right) \\ +\frac{\mathrm{sgn}(\pi-\alpha-\phi)\mathrm{e}^{\mathrm{i}kR'}}{\sqrt{k(R_1+R')}} Fr\left(\sqrt{\frac{2k}{\pi}}(R_1-R')\right) \end{bmatrix}^{-1} \right|, \quad (3)$$

where α and ϕ are the angle coordinates of source and receiver in cylindrical coordinates, k is the wave number, R and R' are the distance from the receiver to the source and mirror-image of the source, R_1 is the shortest distance from the source to the receiver over the panel, sgn is the signum function and Fr is the Fresnel integral

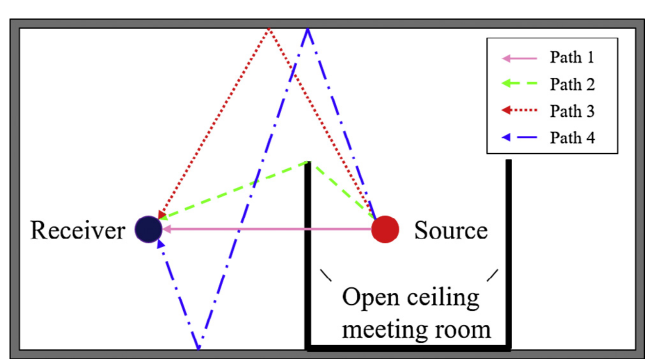

Fig. 1. Typical acoustic paths for sound transmitting from inside to outside a meeting room, where Path 1 is that transmitting through the panel, Path 2 is that diffracting over the panel, Path 3 is that reflecting from the ceiling, and Path 4 is that reflecting from the ceiling and ground.