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Sound Propagation between Two Adjacent Rectangular Workstations in an Open-plan Office, I: Mathematical Modeling

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Abstract

This paper describes the development of a mathematical model of sound propagation between adjacent workstations in an open-plan office. The model is valid for adjacent rectangular workstations consisting of small enclosures made up of partial-height screens or panels. The new model adds the effects of side and back panels to the primary effect of the common separating screen that was considered in a previous model. In both models, reflections are included using an image source technique and expressions are developed to identify those image sources that represent actual reflection paths. The orientation of openings into the workstations is also considered. Comparisons with measured attenuations of sound propagation between adjacent workstations are included. They verify that the model can quite accurately predict the expected speech privacy between workstations in an open-plan office.

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1. Introduction

Open-plan offices are widely used to accommodate large numbers of various types of office workers. In conventional open-plan offices, workstations consist of partial height enclosures or cubicles. If one considers two adjacent rectangular workstations, there is a common separating screen as well as side and back panels to each workstation. The panels of these workstations act as barriers or screens to provide a measure of speech privacy. The primary advantage of such offices is said to be that organizational changes can be implemented with less effort and at low cost. However, it is usually difficult to achieve a high degree of speech privacy between adjacent workstations while maintaining the desired flexibility, economy, and openness. In the past, there has been no comprehensive procedure for optimizing the acoustical design of all aspects of conventional open-plan offices.

For many years, much work has been performed to investigate the acoustical elements that could affect the physical acoustical environment in open-plan offices, such as office screens^[1, 2], ceiling and floor reflections^[2, 3], speaker orientation^[4, 5], and side panel reflections on the source side^[6]. Other work has discussed the factors that may improve speech privacy subjectively, such as vocal effort^[4], and added masking sound^[5]. These publications are useful to the design of a good acoustical environment in an open-plan office. However, most of these papers were based on experimental case studies and qualitative analyses. No previous studies have quantitatively considered all of the important factors influencing sound propagation between workstations in an open-plan office environment. The ray tracing method, which has been implemented with various commercial software packages, is a useful tool for the analysis of large, irregularly shaped spaces, such as auditoria. However, most ray tracing software is unable to correctly model sound propagation between workstations because they are not able to handle sound diffraction explicitly or to trace a sound ray after its first diffraction^[7]. Successful applications of the ray tracing method to open-plan office design have not yet been reported and will first require the development of more sophisticated ray tracing programs. It is still difficult to determine how best to design a new open office for superior speech privacy or how best to improve the acoustical design of an existing open-plan office. It is generally true that open offices only provide adequate speech privacy when all aspects of the design are carefully considered. There is therefore a clear

need for a general and powerful design tool, which can be used to optimize the parameters of the open-plan office to achieve superior acoustical environments.

Recently, the authors developed a general model for analyzing speech propagation over a single screen including floor and ceiling reflections in an open office^[8]. The single screen model uses the Maekawa screen diffraction results and represents floor and ceiling reflections using an image source technique. The model also included an empirical correction of diffuse field ceiling absorption coefficients to values representative of the effective absorption of the ceiling in an open plan office. This model has been successfully validated with respect to measured data and has been employed to evaluate the speech intelligibility index (SII) behind single screens^[9]. In the current paper, this single screen model is used as the basis of a new comprehensive mathematical model of sound propagation between two adjacent rectangular workstations. In addition to the effects of the screen, ceiling and floor reflections, the influence of the side, and back panels and the orientation of the workstation on the speech propagation over the dividing partition are discussed. A general model, which takes all of these factors into account, is presented here and validated by comparison with experimental results. A follow up paper describes the application of the new model to explore the importance of each component of the workstation on the expected speech privacy.

2. Theoretical Analysis

Modeling the acoustic behaviour of a workstation is more difficult than that of a single screen. It can be seen from Figure 1 that in addition to the dividing screen over which the sound diffraction occurs, the side and back panels, which are at least partially sound reflective, must be considered. Also, as pointed out by many researchers^[1, 2, 8, 9], the ceiling reflection

usually plays an important role in speech privacy in open-plan offices and must be included in the model. In [8, 9], the acoustic behaviour of a single screen in a flat room was modeled by employing the image source method. In that study, general expressions for the reflected and diffracted sound over the screen with the ceiling and floor reflection included were presented. Note that this single screen model should apply to the dividing screen of a complete workstation, and sound reflections from the side and back panels can be similarly considered by introducing appropriate image sources. The workstation model is then composed of two parts, the single screen model, and the side and back panel model. Therefore in this study, the effects of the side and back panels of a rectangular workstation are the primary new concern. In the analysis below, for convenience, the effects of side and back panels on the source side and the receiving side are discussed separately.

Figure 1. Sound propagation between two rectangular workstations.

Figure 2. Image sources due to the side and back panels of the source side: S , source; R , receiver; S_s' , image sources due to side panels; S_b' , image source due to the back panel; S_{bs}' , image sources due to side and back panels.

2.1 Effects of the panels on the source side

Figure 2 shows the plan of the source side workstation and the image sources used to represent reflections from the side and back panels. It should be noted here that each image source shown in Figure 2 actually represents a vertical series of image sources associated with the ceiling and floor reflections, as discussed in [8, 9]. Also in Figure 2, the image sources due to the dividing panel are not considered. This is because the effect of the screen reflection has already been included in the single screen model. Hence, for each pair of image source S_s' (or S_b' , or S_{bs}') and receiving point R , the previous single screen model should apply. The total effects of the side and back panels would therefore be the sum of those single screen results.

It should be pointed out that not all of the image sources associated with the side and back panels make contributions at the receiving point. This is primarily because the dividing panel of a workstation is finite in length. Therefore for some image sources, a path does not exist that the sound from them could follow to reach the receiving point both via the corresponding side panel (sound reflection) and the dividing panel (sound diffraction). In the image space, it can be seen that possible image sources must lie within the triangular region with its apex at the receiving point R and as shown by the dashed lines in Figure 2. This is because when drawing a line from a receiving point to an image source, the line must intersect with a side panel and the dividing panel. Therefore, to consider the effects of the side and back panels of the source workstation, only the image sources located within the triangular region need to be considered.

In the triangular region, higher order image sources corresponding to multiple reflections between the back panel and the dividing screen, such as S_b'' shown in Figure 3(a), would also exist and should be considered in the model. Note that for each of these image sources, the effective sound paths generated (including reflected and diffracted sound paths) are those which could pass through all the image and real panels between the source and the dividing screen. Only diffracted sound paths, such as path 2 in Figure 3(a), may have some effect at the receiver, because the reflected sound, such as path 3 shown in Figure 3(a), is not able to reach the receiver directly. In fact, the contribution of the diffracted sound from these higher order image sources at the receiver is limited because the sound energy is inversely proportional to the distance between the source and the receiver. Particularly, when the panels are sound absorptive, the contribution of these image sources would decrease dramatically as the image source order increases. Therefore, it is reasonable and acceptable that only the first-order image source due to the back panel is considered in the model. (Of course, this would not be true for non-absorptive screens but their use would not be consistent with design for acceptable speech privacy).

Moreover, in the upper vertical direction, since the side and back workstation panels do not extend to the ceiling, some of the image sources associated with the ceiling and floor reflection may not exist. For example, for an image source S_b' due to the back panel shown in Figure 3(b), all of the effective paths generated from it should go through the back panel, which therefore represents the reflection of the back panel. In Figure 3(b), two of the possible paths between the image source S_b' and the receiving point R , namely path 1, and path 2, are also shown. It can be seen that path 1 does exist because the back panel does reflect the sound wave back to the dividing screen, which is then diffracted to the receiver. However, path 2 does not have an intersection with the back panel, and instead of being reflected by the back panel to the ceiling and then to the receiver, the sound wave would go directly over the back panel in the opposite direction to the receiving point, as shown in Figure 3(b). As a result, the image source S_b'' which is associated with the reflection from both the back panel and also the ceiling should not be considered in the modeling because this path does not exist.

To quantify the discussions above, the effects of the side panels and those of the back panel are examined separately. For convenience, the contribution from different image sources is summed in terms of the sound energy, which means possible interference

effects are not included. Although in principle interference effects could be included, this would require less readily available acoustical impedance data of all materials and inclusion of the phase changes on diffraction from the edge of the screen. The model based on energy summation will be shown to be sufficiently accurate while being more practically useful because the required input data is readily available.

Figure 3. The image sources due to the back panel: S , source; R , receiver;
 S_b' , image source due to the back panel;
 (a) S_b'' , the image of S_b' due to image panels, (b) S_b'' , the image of S_b' due to the ceiling.

2.1.1 side panels

In the discussions above, it was argued that by introducing image sources, the effects of the side panels could be considered by applying the single screen model developed by Wang and Bradley^[8, 9]. By assuming that the source and the receiver both are on the centre line of the workstation, as shown in Figure 2, and that the heights and the sound reflection coefficients of the two parallel side panels are the same, the sound pressure due to the side panels of the source side can be written as the reflected and diffracted components, $|p_{sr}|^2$ and $|p_{sd}|^2$,

$$|p_{sr}|^2 = \sum_i \sum_K \frac{W \beta_s^{|i|} \beta_c^{\left\lceil \frac{K}{2} \right\rceil} \beta_f^{\left\lfloor \frac{K}{2} \right\rfloor} \rho_0 c_0}{4\pi [Y_K^2 + Z_i^2 + (d+l)^2]}, \quad (1)$$

$$|p_{sd}|^2 = \sum_i \sum_l \sum_J \frac{W \beta_s^{|i|} \beta_c^{\left\lceil \frac{l}{2} \right\rceil + \left\lceil \frac{J}{2} \right\rceil} \beta_f^{\left\lfloor \frac{l}{2} \right\rfloor + \left\lfloor \frac{J}{2} \right\rfloor} \rho_0 c_0}{4\pi L_{iIJ}^2} \cdot \frac{1}{3 + 20N_{iIJ}}, \quad (2)$$

where d is the distance from the source to the dividing screen, l is that from the screen to the receiver, and Z_i is the z-coordinate of the image source, as shown in Figure 2. W is the sound power of the source, β_c and β_f are the sound reflection coefficients of the ceiling and the floor, β_s is the sound reflection coefficient of side panels.

$N_{iIJ} = \frac{2f}{c_0} (A_{iI} + B_{iJ} - L_{iIJ})$ is the Fresnel number for the shortest diffraction path over the top of the screen between iI -th image source and the J -th image receiver.

$A_{iI} = \sqrt{d^2 + \left(\frac{d}{d+l}\right)^2 Z_i^2 + (h_{ef} - Y_I)^2}$ is the distance from the iI -th image source to the top

of the screen, and $B_{iJ} = \sqrt{l^2 + \left(\frac{l}{d+l}\right)^2 Z_i^2 + (y_J - h_{ef})^2}$ is the distance from the top of the

screen to the J -th image receiver. $L_{iIJ} = \sqrt{(d+l)^2 + Z_i^2 + (y_J - Y_I)^2}$ is the shortest distance from the iI -th image source to the J -th image receiver. Here Y_K and Y_I represent the image sources whose y-coordinates Y_n do, and do not respectively satisfy the relationship^[8, 9],

$$\frac{d+l}{l} (kH + h - s) < Y_n < \frac{d+l}{l} [(k+2)H - h - s], \quad k = 0, \pm 2, \pm 4, \pm 6, \dots, \pm 2n \quad (3)$$

Here H is the ceiling height and s is the source height. Also, y_J represents the image receiving point of which the y-coordinate y_m satisfies the relationship,

$$y_m < \frac{d+l}{d} (h_{ef} - Y_I) + Y_I, \quad (4)$$

Here, h_{ef} is the effective height of the screen, $h_{ef} = h - s$. However, most importantly, it should be noted that there are two conditions for which Z_i and Y_n must be satisfied in advance of equations (3) and (4), which are

$$|Z_i| < \frac{d+l}{l} \cdot \frac{U}{2} \quad (5)$$

$$\text{and} \quad [kH - 2s - h_{ef}] < \frac{Y_n}{|Z_i|} \cdot \frac{U}{2} < (kH + h_{ef}), \quad k = 0, \pm 2, \pm 4, \pm 6, \dots, \pm 2n \quad (6)$$

where $Z_i = iU$, $i = \pm 1, \pm 2, \pm 3, \dots$. Here equation (5) represents the triangular region, and equation (6) guarantees that all the sound paths considered go through the side panel, which means only the sound that is reflected by side panels is considered. According to equation (5), it is easily seen that the side panels of the source side only affect the sound field in the region $l < d$ on the receiving side.

2.1.2 back panel

The effect of the back panel can be treated in the same way as that for the side panels. If the height of the back panel is the same as that of the side panel, the sound pressure due to the back panel of the source side can be written as,

$$|p_{br}|^2 = \sum_i \sum_K \frac{W \beta_b \beta_s^{|i|} \beta_c^{\left\lceil \frac{K}{2} \right\rceil} \beta_f^{\left\lfloor \frac{K}{2} \right\rfloor} \rho_0 c_0}{4\pi [Y_K^2 + Z_i^2 + (2V - d + l)^2]}, \quad (7)$$

$$|p_{bd}|^2 = \sum_i \sum_I \sum_J \frac{W \beta_b \beta_s^{|i|} \beta_c^{\left\lceil \frac{I}{2} \right\rceil + \left\lceil \frac{J}{2} \right\rceil} \beta_f^{\left\lfloor \frac{I}{2} \right\rfloor + \left\lfloor \frac{J}{2} \right\rfloor} \rho_0 c_0}{4\pi L_{iIJ}^2} \cdot \frac{1}{3 + 20N_{iIJ}}, \quad (8)$$

where $Z_i = iU$, $i = 0, \pm 1, \pm 2, \pm 3, \dots$, β_b is the sound reflection coefficient of the back panel.

$$N_{iIJ} = \frac{2f}{c_0} (A_{iI} + B_{iJ} - L_{iIJ}), \quad \text{in which} \quad A_{iI} = \sqrt{(2V - d)^2 + \left(\frac{2V - d}{2V - d + l} \right)^2 Z_i^2 + (h_{ef} - Y_I)^2},$$

$$B_{iJ} = \sqrt{l^2 + \left(\frac{l}{2V - d + l} \right)^2 Z_i^2 + (y_J - h_{ef})^2}, \quad \text{and} \quad L_{iIJ} = \sqrt{(2V - d + l)^2 + Z_i^2 + (y_J - Y_I)^2}.$$

Correspondingly, the conditions associated equations (3) - (6) that Y_n , y_m and Z_i have to satisfy are,

$$\frac{2V - d + l}{l} (kH + h - s) < Y_n < \frac{2V - d + l}{l} [(k + 2)H - h - s], \quad k = 0, \pm 2, \pm 4, \pm 6, \dots, \pm 2n \quad (9)$$

$$y_m < \frac{2V - d + l}{2V - d} (h_{ef} - Y_I) + Y_I, \quad (10)$$

$$\text{and} \quad |Z_i| < \frac{2V - d + l}{l} \cdot \frac{U}{2} \quad (11)$$

$$[kH - 2s - h_{ef}] < \frac{Y_n}{2V - d + l} \cdot (V + l) < (kH + h_{ef}), \quad k = 0, \pm 2, \pm 4, \pm 6, \dots, \pm 2n \quad (12)$$

Again, equation (11) is for determining whether the image source, S_b' or S_{bs}' , is in the triangular region. Equation (12) is the condition for which the sound reflected from the back panel is considered.

It should be noted that according to equations (7) and (8), the reflected and the diffracted sound due to the back panel may also depend on the reflection coefficient of the side panels. This is because the sound reflected by the back panel may also be further reflected by a side panel and then go over the dividing screen. These propagation paths correspond to the image sources S_{bs}' shown in Figure 2. For the image source S_b' , which corresponds to $i=0$ in equations (7) and (8), it can be seen that the reflected and the diffracted sound only depends on the existence of the back panel. This is simply because the back panel is perpendicular to the centre line of the workstation, and therefore reflects the sound directly to the receiver.

Figure 4. Image sources due to the side and back panels of two rectangular workstations: S , source; R , receiver; S_s' , image sources due to side panels; S_b' , image sources due to the back panel; S_{bs}' , image sources due to side and back panels; R_s' , image receivers due to side panels; R_b' , image receiver due to the back panel; R_{bs}' , image receivers due to side and back panels.

2.2 Effects of the panels on the receiving side

When side and back panels exist on the receiving side, sound reflection due to these panels to the receiving point must also be considered, as illustrated in Figure 1. These reflections can also be considered by introducing image receiving points. In Figure 4, the layout of the workstation and the image receiving points are shown. Therefore, for each pair of the source or image source, and the receiving point or image receiving point, the single screen model should apply. The total effect would be the sum of these single

screen results. However, as shown in Section 2.1 due to the finite size of the panels, not all the image sources have an effect at a particular receiving point. This therefore means that for each receiving point, including the image receiving points, equations (1) – (12) have to be applied correspondingly. As the number of image receiving points considered increases, the calculation becomes more complicated.

However, it should be noted that among all the pairs of source and receiving points, the real source and the real receiving point are the primary combination, which has been analyzed by Wang and Bradley^[8, 9]. The other pairs, either between any of the image sources and the real receiving point or between the real source and any of the image receiving points, correspond to first-order reflection effects because each of these sound paths involves at least one reflection from the side or the back panel. Furthermore, the pairs between any image source and any image receiving point then have higher order reflection effects because each of these sound paths includes sound reflection at least twice from the side and back panels. Clearly, as the sound absorption of the side and back panels increases, higher order effects become negligible. Therefore, in order to simplify the problem, it is reasonable and sufficient to consider the first-order reflection effects only. In fact, since most of the panels used in open-plan offices have a certain amount of sound absorption, especially at high frequencies, and because for higher order reflections the distance between the image source and the image receiving point get quite large, neglecting the higher order effects shouldn't cause much error in the final results. Therefore, in this section, only the sound paths between the real source and the image receiving points are considered.

2.2.1 side panels

The image receiving points associated with the side and back panels on the receiving side are shown in Figure 4. As in the discussion in Section 2.1, it is expected that not all the image receiving points have a direct link with the real source on the source side simply because the dividing screen is finite in length. A condition similar to equation (5) therefore exists, which is,

$$|z_j| < \frac{d+l}{d} \cdot \frac{U}{2} \quad (13)$$

where $z_j = jU$, ($j = \pm 1, \pm 2, \pm 3, \dots$) are the z -coordinates of the image receiving points. This equation indicates that only the image receiving points located in the triangular region

with its apex at the real source S , as shown by the dash-dotted lines in Figure 4, need to be considered. Also, because of the finite height of the side panel, the other condition that has to be satisfied for those image receiving points whose positions have already fulfilled equation (13), is,

$$\left[kH - 2s - h_{ef} \right] < \frac{Y_n}{|z_j|} \cdot \frac{U}{2} < (kH + h_{ef}), \quad k = 0, \pm 2, \pm 4, \pm 6, \dots, \pm 2n \quad (14)$$

Here, it is assumed that the two parallel side panels have the same height. By assuming that the sound reflection coefficients of the two parallel side panels are the same, the additional sound energy due to the side panel reflections on the receiving side can be written as,

$$|p_{sr}|^2 = \sum_j \sum_K \frac{W\beta_s^{[j]} \beta_c^{\left\lceil \frac{K}{2} \right\rceil} \beta_f^{\left\lfloor \frac{K}{2} \right\rfloor} \rho_0 c_0}{4\pi[Y_K^2 + z_j^2 + (d+l)^2]}, \quad (15)$$

$$|p_{sd}|^2 = \sum_j \sum_I \sum_J \frac{W\beta_s^{[j]} \beta_c^{\left\lceil \frac{I}{2} \right\rceil + \left\lceil \frac{J}{2} \right\rceil} \beta_f^{\left\lfloor \frac{I}{2} \right\rfloor + \left\lfloor \frac{J}{2} \right\rfloor} \rho_0 c_0}{4\pi L_{jIJ}^2} \cdot \frac{1}{3 + 20N_{jIJ}}, \quad (16)$$

where β_s is the sound reflection coefficient of the side panel. $N_{jIJ} = \frac{2f}{c_0} (A_{jI} + B_{jJ} - L_{jIJ})$,

in which $A_{jI} = \sqrt{d^2 + \left(\frac{d}{d+l}\right)^2 z_j^2 + (h_{ef} - Y_I)^2}$, $B_{jJ} = \sqrt{l^2 + \left(\frac{l}{d+l}\right)^2 z_j^2 + (y_J - h_{ef})^2}$, and $L_{jIJ} = \sqrt{(d+l)^2 + z_j^2 + (y_J - Y_I)^2}$. Y_K and Y_I represent the image sources whose y -coordinates Y_n do and do not respectively satisfy the relationship,

$$\frac{d+l}{l} (kH + h - s) < Y_n < \frac{d+l}{l} [(k+2)H - h - s], \quad k = 0, \pm 2, \pm 4, \pm 6, \dots, \pm 2n \quad (17)$$

Also, y_J represents the image receiving point of which the y -coordinate y_m satisfies the relationship,

$$y_m < \frac{d+l}{d} (h_{ef} - Y_I) + Y_I, \quad (18)$$

It should be mentioned here that according to equation (13), it can be seen that the side panels on the receiving side only affect the sound field in the region $l > d$.

2.2.2 back panel

The back panel on the receiving side can be treated in the same way as the back panel on the source side. By assuming that the back panel on the receiving side has the same height as that of the side panels, the sound pressure level due to the back panel reflection can be written as,

$$|p_{br}|^2 = \sum_j \sum_K \frac{W\beta_b\beta_s^{|j|}\beta_c^{\left\lceil\frac{K}{2}\right\rceil}\beta_f^{\left\lfloor\frac{K}{2}\right\rfloor}\rho_0c_0}{4\pi[Y_K^2 + z_j^2 + (2V-l+d)^2]}, \quad (19)$$

$$|p_{bd}|^2 = \sum_j \sum_I \sum_J \frac{W\beta_b\beta_s^{|j|}\beta_c^{\left\lceil\frac{I}{2}\right\rceil + \left\lceil\frac{J}{2}\right\rceil}\beta_f^{\left\lfloor\frac{I}{2}\right\rfloor + \left\lfloor\frac{J}{2}\right\rfloor}\rho_0c_0}{4\pi L_{jIJ}^2} \cdot \frac{1}{3 + 20N_{jIJ}}, \quad (20)$$

where $z_j = jU$, $j=0, \pm 1, \pm 2, \pm 3, \dots$, β_b is the sound reflection coefficient of the back panel.

$$N_{jIJ} = \frac{2f}{c_0}(A_{jI} + B_{jJ} - L_{jIJ}), \quad \text{in which} \quad A_{jI} = \sqrt{d^2 + \left(\frac{d}{2V-l+d}\right)^2 z_j^2 + (h_{ef} - Y_I)^2},$$

$$B_{jJ} = \sqrt{(2V-l)^2 + \left(\frac{2V-l}{2V-l+d}\right)^2 z_j^2 + (y_J - h_{ef})^2}, \text{ and } L_{jIJ} = \sqrt{(2V-l+d)^2 + z_j^2 + (y_J - Y_I)^2},$$

Correspondingly, the conditions associated equations (3)-(6) that Y_n , y_m and z_j have to satisfy are,

$$\frac{2V-l+d}{d}(kH + h - s) < Y_n < \frac{2V-l+d}{d}[(k+2)H - h - s], \quad k=0, \pm 2, \pm 4, \pm 6, \dots, \pm 2n \quad (21)$$

$$y_m < \frac{2V-d+l}{2V-d}(h_{ef} - Y_I) + Y_I, \quad (22)$$

$$\text{and} \quad |z_j| < \frac{2V-l+d}{d} \cdot \frac{U}{2} \quad (23)$$

$$\left[kH - 2s - h_{ef}\right] < \frac{Y_n}{|z_j|} \cdot \frac{U}{2} < (kH + h_{ef}), \quad k=0, \pm 2, \pm 4, \pm 6, \dots, \pm 2n \quad (24)$$

In the discussions above, the sound reflection coefficients of the side panels on both the source side and the receiving side are assumed to be the same, and the source and the receiver are assumed to be on the centre line of the workstations. Also, the workstation size and the height of the side and back panels on both the source and receiving sides are assumed to be the same. However, since the effects of the side and back panels on both the source and receiving sides are considered separately, the method and the results obtained here can be extended for the analysis of other workstation configurations and source or receiver positions with appropriate modifications.

2.3 Effects of the workstation orientation

In the discussions above, the workstation opening, which allows people to go in and out was not considered. Such openings would affect the sound propagation between two adjacent workstations because the existence of the opening would alter the sound

propagation paths associated with the corresponding panel. In practice, the position of the opening could be different from one workstation to another because the orientation of a workstation very much depends on its location in an open-plan office. Figure 5 shows three typical workstation orientations. For convenience, the source side and the receiving side shown here are chosen to have the same layout. But in practice, the orientations of the two adjacent workstations are not necessarily the same but could have any combination of the three layouts shown in Figure 5. Obviously, the diversity of the workstation orientations causes more difficulties for developing a general model of the workstation. However, in Sections 2.1 and 2.2, the effects of the side and back panels either on the source side or the receiving side were analyzed separately. It may therefore be possible to discuss the influence of the opening in a relatively general way.

Figure 5. Different workstation layouts: D , the opening size; S , source, R , receiver.

2.3.1 case (a)

Case (a) (in Figure 5) is the base case studied in this project. With this orientation, the effects of the side panels are not affected by the opening. Therefore, the theoretical analysis made in Sections 2.1.1 and 2.2.1 should apply directly. However, the results obtained for the back panel in Sections 2.1.2 and 2.2.2 require some modifications.

On the source side, due to the opening at the back panel, a part of the sound energy wouldn't be reflected back to the dividing screen, as shown in Figure 5(a). In the image source space, this means that some of the image sources associated with the back panel shouldn't be considered, for which a condition can be found as,

$$\frac{2V-d+l}{V+l} \left(\frac{U}{2} - D \right) < Z_i|_{x=-(2V-d)} < \frac{2V-d+l}{V+l} \left(\frac{U}{2} + D \right) \quad (26)$$

Similarly, the condition for which the image receiving points shouldn't be considered due to the opening at the back panel on the receiving side is,

$$\frac{2V-l+d}{V+d} \left(\frac{U}{2} - D \right) < z_j|_{x=2V-l} < \frac{2V-l+d}{V+d} \left(\frac{U}{2} + D \right) \quad (27)$$

In Figure 5(a), the opening is on the positive side of the z direction. If the opening is on the negative side of the z direction, $-Z_i$ and $-z_j$ should be substituted into equations (26) and (27) respectively.

2.3.2 case (b)

In case (b) of Figure 5, the opening is in the side panel but close to the back panel. The conditions for which the image sources and the image receiving points should not be considered due to the opening on the source side and the receiving side respectively are,

$$\frac{U}{2} < Z_i|_{x=-(2V-d)} < \frac{2V-d+l}{V+l-D} \frac{U}{2} \quad (28)$$

$$\frac{U}{2} < z_j|_{x=2V-l} < \frac{2V-l+d}{V+d-D} \frac{U}{2} \quad (29)$$

It should be mentioned here that as in case (a), case (b) also includes sound reflection from the back panel, which means only that the results obtained for the back panel in Sections 2.1.2 and 2.2.2 need to be modified. This is because as discussed before, the results obtained for the side panel in Sections 2.1.1 and 2.2.1 correspond to the sound reflection occurring in the range, $-d < x < l$, of the side panel.

Also, if the opening is on the negative side of the z direction, $-Z_i$ and $-z_j$ should be substituted into equations (28) and (29) correspondingly.

2.3.3 case (c)

Case (c) of Figure 5 is of particular interest. Since the opening is close to the dividing screen, some of the sound energy may not be reflected to the receiver, as shown in Figure 5(c). Similar to cases (a) and (b), conditions for which the image sources and the image receiving points should not be considered due to the opening on the source side and the receiving side respectively are,

$$\frac{d+l}{D+l} \cdot \frac{U}{2} < Z_i < \frac{d+l}{l} \cdot \frac{U}{2} \quad (30)$$

$$\frac{d+l}{D+d} \cdot \frac{U}{2} < z_j < \frac{d+l}{d} \cdot \frac{U}{2} \quad (31)$$

However for the layout of Figure 5(c), although the presence of the opening may reduce the effects of the side panel reflections, sound diffraction at the vertical edge of the dividing screen will increase the sound energy at the receiver. Since this is basically a single screen diffraction effect, the method developed by Wang and Bradley^[8] can be employed.

3. Experimental Verification

In order to verify the theoretical results obtained above, experiments were carried out at the Institute for Research in Construction, National Research Council Canada. The measurements were made in a test room in which the walls were covered with 0.1 m thick sound absorbing foam to simulate a much larger space. As a result, the influence of wall reflections can be neglected, and especially at higher frequencies. The floor is covered with thin commercial carpet. To be representative of a range of typical open-plan offices, sound propagation between adjacent workstations was measured with different ceiling systems. These included: 25 mm thick high absorption type H-B ceiling tiles (sound absorption average^[10] (SAA)=0.97) at a height of 2.74 m, and 37 mm thick high absorption type H-A ceiling tiles (SAA=1.08) at a height of 2.44 m, which were examined separately. Figure 6 shows the location of source and receiver positions for the measurements and a typical workstation plan. For each workstation configuration, sound propagation measurements were made for the 25 combinations of 5 source positions and 5 microphone positions, one of which is at the centre of the workstation, and the other four are 0.91 m away from the four panels, as shown in Figure 6. The average of these 25 sets of data were used to represent typical practical situations where the source and receiver are approximately at the centre of the workstation but with possible movements within a small area. The shielding effects of the workstation were evaluated in terms of the attenuation, defined as the difference between the averaged received sound pressure levels and the expected levels at a distance of 0.91 m from the source in a free field. The workstation tested was 2.74 m × 2.74 m in plan. The height of the dividing screen and the panels was 1.52 m. When absorptive panels were required, the screen was covered with 50 mm thick acoustical foam for which the normal incidence sound absorption coefficients were given in [8].

Figure 6. Experimental set-up for the workstation measurements.

In Figure 7, the calculated attenuation is compared with the experimental result for two adjacent 2.74 m x 2.74 m workstations with the orientation shown in Figure 6. In the calculations, the absorption coefficients of the ceiling system were determined by using the corrected ASTM C423 data^[9]. It can be seen that the two curves agree with each other very well at medium and high frequencies. Larger differences occur at lower frequencies because the energy summation approach does not correctly model lower frequency interference effects. Improved agreement at low frequencies could be achieved by including the phase information of each propagation path and the acoustic impedances of the ceiling, floor and panels in the model, as described in [8]. The agreement in speech intelligibility index (SII) again indicates that the low frequency components are not very important to speech privacy. Here the SII was calculated based on the ‘normal’ speech spectrum level included in ANSI S3.5-1997^[11] and an assumed ambient noise equal to an RC40 spectrum.

ISO17624^[12] includes an empirical expression for estimating the sound attenuation due to an acoustical screen in offices, in which the sound reflection from side walls is said to be "approximately accounted". For comparison, the results obtained from this empirical model are also shown in Figure 7. However, large discrepancies are found not only in the attenuation curve but also in the derived SII values. The empirical model does not accurately account for the effects of ceiling, floor, side and back panels on the sound propagation over the dividing screen and is only a very rough estimate of the measured results.

Figure 7. The sound attenuation between two adjacent 2.74 m x 2.74 m workstations: $h=1.52$ m, the source and the receiver are at the centre of the workstation, no lights on the ceiling, (a) 2.74 m high absorption type H-B ceiling tiles, no foam on the screens; (b) 2.74 m high absorption type H-B ceiling tiles, 50 mm thick foam on the screens; (c) 2.44 m high absorption type H-A ceiling tiles, 50 mm thick foam on the screens, --□--, prediction; —◆—, measurement; -----, ISO17624.

4. Conclusions

This paper has described the development and details of a mathematical model of sound propagation between rectangular workstations in an open-plan office. It is assumed that workstations consist of small enclosures or cubicles made up of partial-height screens and panels. The new model made use of a previously developed single screen mathematical model that included the effects of ceiling and floor reflections as well as diffraction at the screen. The new model reported here has added the effects of side and back panels to the primary separating screen. Image source techniques were used to model reflections and expressions were developed to identify those image sources that represent possible reflection paths. The effects of the orientation of openings into the workstations were also considered. The model includes the simplifying assumptions, that only first order reflections from the workstation panels need to be included and the contributions of various sound paths can be added on an energy basis. However, in spite of these simplifications the model is seen to be quite accurate at frequencies important for speech sounds.

Comparisons with measured attenuations between adjacent rectangular workstations included varied ceiling tile type, varied ceiling height and varied screen absorption. At mid to high frequencies, measured and predicted attenuations agreed quite well. Some larger differences occurred at lower frequencies because, for practical purposes, the model ignores interference effects. However, these low frequency attenuations are not important for estimating speech privacy and measured and predicted Speech Intelligibility Index (SII) values agreed within 0.02. This was shown to be much more accurate than simple empirical estimates. The model is a useful tool that now makes possible the optimization of the acoustical design of open plan offices so that speech privacy is maximized.

It should be mentioned that the model developed in this study is based on the principles of geometrical acoustics. Therefore, the model may be less accurate when the wavelength is comparable to or larger than the workstation dimensions. The current work also ignored the effects of furnishings in workstations, which would act as diffusing elements.

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