PRELIMINARY STUDY ON THE SPEECH PRIVACY PERFORMANCE OF THE FABPOD

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Abstract

This paper reports the preliminary measurement results for characterising the speech privacy performance of an open ceiling meeting room called Fabpod in RMIT University, where the Speech Privacy Class standardized in the ASTM E2638 was adopted in the measurements to rate the speech privacy performance. The background sound pressure level inside and outside the Fabpod and the sound pressure level differences at different locations inside and outside the Fabpod with different sound source locations were measured in one third octave bands from 50 Hz to 10000 Hz. Based on the measurement results, the Speech Privacy Class of the Fabpod was calculated. The conclusion is that the Fabpod cannot meet the normal speech privacy criteria and the meeting inside the Fabpod can easily be overheard outside. Speech privacy is affected by many factors including the speech attenuation from the sound source to the receiver and the level of the background noise. The speech attenuation from the sound source to the receiver depends on the height of the wall or barrier, the sound absorption coefficient of the ceiling and the distance between the sound source and receiver. To achieve acceptable speech privacy for the Fabpod, all design parameters have to be tuned to near optimum values. The measures that can be used to increase the speech privacy of the Fabpod are discussed.

1. Introduction

The Fabpod shown in Figure 1 is a semi enclosed meeting room located in a large indoor open plan office, where the non-rectangular overall geometry, the non-parallel wall surfaces and the highly articulated interior surface made from an aggregate structure composed of hyperboloid cells with different types of material were supposed to provide an acoustically live space with better speech intelligibility and privacy [1]. Preliminary acoustic simulations were carried out during developing the design workflows for architects to create spaces and surfaces that can define sound in a more specific way; however, the acoustic performance of the Fabpod has not been thoroughly investigated because the aim of the work was to develop rapid and accessible workflows for architects to integrate sound into the architectural design process [2-3]. This paper analyses and discusses the speech privacy performance of the Fabpod based on the preliminary measurement results carried out at RMIT University recently.

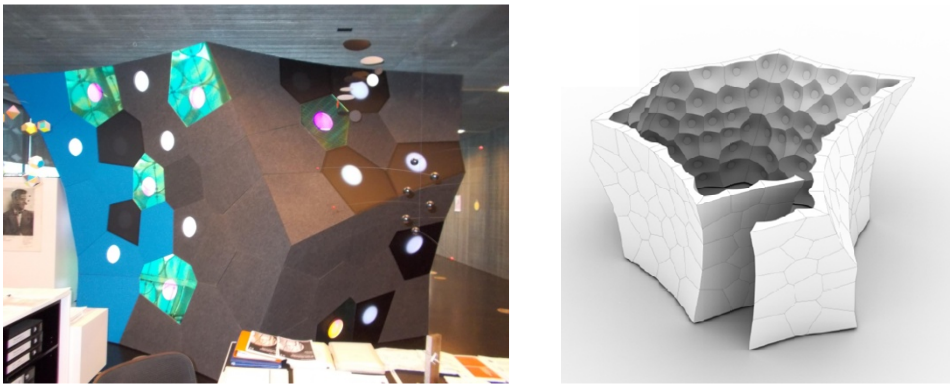

Figure 1. A photo and a picture of the Fabpod located at the Design Hub of RMIT University

ASTM International currently publishes two measurement standards for assessing speech privacy in building spaces [4]. ASTM E2638 "Standard Test Method for Objective Measurement of the Speech Privacy Provided by a Closed Room" is applicable only to enclosed spaces, which introduces a measure called Speech Privacy Class (SPC) [5]. ASTM E1130 "Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index" is applicable only to open plan spaces, which uses the Articulation Index (AI) as a privacy measure [6]. Fabpod is a semi enclosed meeting room with open ceiling located in an open plan office, and there is no specific acoustic standard that can be adopted directly for characterising its speech privacy performance.

SPC is the sum of the average noise level at the receiver position (L_b) and the level difference indicating the attenuation of a test signal between the average source room level and the transmitted level at the listener position outside the room (L_D). Unlike the conventional sound transmission measurements between rooms that assume diffuse sound fields in both spaces and measure the average transmission characteristics of the separating partition, SPC uses the level differences from room average levels in the source room to the receiver positions, usually 0.25 m from the outside of the meeting room. In practice the three SPC values 75, 80 and 85 are probably of most practical use for closed rooms. Values of 90 and higher correspond to essentially inaudible speech and values of 70 and lower would suggest very little privacy for a closed room [4].

AI is defined as a weighted fraction representing the effective proportion of the normal speech signal which is available to a listener for conveying speech intelligibility for a given speech channel and noise condition [7-8]. ASTM E1130 provides a rating of the speech privacy between a specific source position and orientation and receiver position in an open plan space, where a calibrated loudspeaker with a specified directionality is required, and the reference "source" level is determined in a free field [6]. The receive level is determined in the open plan space under consideration, and the difference between the two is the relevant measure of sound insulation. From this so called "level reduction", and the measured background noise level, AI is calculated, for a specified speech spectrum. AI by definition ranges from 0.0 (no intelligibility) to 1.0 (total intelligibility), and AI $\leq$ 0.05 indicates confidential speech privacy, when zero phrase intelligibility with some isolated words being intelligible. E1130 also includes the definition of a metric called Privacy Index, which is simply a renormalization of AI by using PI = $(1-\text{AI}) \times 100\%$. In open plan offices, conditions corresponding to AI $\leq$ 0.15 have been described as 'acceptable or normal' privacy.

In ANSI S3.5-1997 standard, the term AI was changed to Speech Intelligibility Index (SII), presumably to focus on the objective of speech intelligibility prediction, and SII $\leq$ 0.1 is for confidential speech privacy while SII $\leq$ 0.20 is for normal privacy [9]. The relationship between SPC and SII and their suitability for use in any type of space have been discussed, including spaces not fitting the definition of either open or closed. It has been found that the two current ASTM metrics for rating speech privacy of building spaces are highly correlated, and both are well suited for use in conditions where speech is intelligible, such as in open plan spaces [4]. SPC is best suited for use in conditions of high privacy, where speech is not intelligible. SPC also offers practicality in that a difference in, for example, 5 dB of sound insulation will correspond to a difference of 5 in SPC, whereas the corresponding difference in AI, SII or PI depends on the absolute value [6].

Although speech privacy has been determined in terms of values of AI and SII in North America, the Speech Transmission Index (STI) has been standardized by IEC standard 60268-16 and is widely used in Europe [10]. STI is a measure based on the generation and analysis of an artificial test signal instead of speech signal, which reflects the effect of signal to noise ratio and reverberation on the intelligibility of speech. STI ranges from 0.0 to 1.0 and can be calculated from the complete impulse responses measured between the source and receiver location along with the speech and noise levels at the receiver position.

AI, SII and STI are all for determining the Speech Intelligibility (SI), which is defined as the measure of the quality of speech that is comprehensible, and can be evaluated by the percentage of correctly understood words or sentences of a specific list under controlled conditions. For example, recordings of the Harvard sentences (phonetically balanced English sentences with content that is of low predictability) can be used, and SI scores are the percentage of correctly identified words in each sentence [11]. SNRuni32 is a different measure proposed by Bradley recently [11]. It can be obtained by summing the clipped one third octave band signal to noise ratios with uniform weights and was shown to be superior to the existing AI and the SII (for high privacy conditions). The thresholds of audibility and intelligibility are −22 dB and −16 dB respectively in free field conditions when 50% of a panel of attentive listeners could just detect speech sounds or could just understand at least one word of short low predictability test sentences. The threshold of intelligibility increases to −11 dB in moderate reverberant meeting rooms.

Both AI and SII are frequency weighted signal to noise ratios with the signal to noise ratio in each one third octave band limited to a range of 30 dB, and they also account for band pass limiting and noise, and can be obtained by calculation taking in account the physical properties of the transmission channel. The SII algorithm is more complex than that for STI with respect to its mechanisms to account for the upward spread of masking and hearing acuity. Theoretically, SII might be able provide a more comprehensive assessment of subjective intelligibility than STI; however, recent research shows that STI and SII values are relatively similar in general [12]. It has also been found that AI, SII and SNRuni32 are similarly accurate predictors of speech intelligibility scores for the conditions from barely intelligible to completely intelligible [11].

Subjective studies have been carried out to define conditions required for acceptable speech privacy and acceptable noise levels in conventional open plan offices. Extensive speech intelligibility tests of simulated open office conditions show that a successful open plan office design needs normal privacy ($AI \leq 0.15$) and an ambient noise level of approximately 45 dBA [13]. It should be noted that the effect of temporal and non-linear distortions is not directly included in the AI and SII. The influence of aspects of the spatial and temporal components of sound fields in typical rooms has been investigated [14]. In realistic combinations these effects are of practical importance and can change privacy criteria by 5 dB or more. Ignoring them can lead to costly over design of the sound insulation required to achieve adequate speech privacy.

If the Fabpod is treated as an acoustical screen for noise control in offices and workrooms, then ISO 17624 can be followed, and the measures include the insertion sound pressure level (SPL) difference, A-weighted insertion SPL difference, the insertion loss, and the free-field screen sound attenuation. ISO 10053 gives a method for measuring the sound attenuation of screens intended for use in rooms to increase speech privacy or noise insulation between working positions under specific laboratory conditions, and the measured screen sound attenuation is intended to be used to classify screens. ISO 11821 is used for measuring the in situ sound attenuation of a removable screen, and the measures include the unscreened SPL and screened SPL, the in situ sound attenuation, the A-weighted in situ sound attenuation, and the directivity index.

If the Fabpod is considered as a part of an open plan office, then ISO 3382-3 can be followed, and the room acoustic parameters to be measured include the spatial sound distribution of the A-weighted SPL of speech, the spatial decay rate of speech, the A-weighted SPL of speech at a distance of 4 m, the STI, the spatial sound distribution of the speech transmission index, the distraction distance (the distance from the speaker where the speech transmission index falls below 0.50), and the privacy distance (the distance from the speaker where the speech transmission index falls below 0.20). Above the privacy distance, concentration and privacy are experienced very much the same as between separate office rooms. It is suggested that a spatial decay rate of speech no less than 7 dB be as a target value and a distraction distance value no greater than 5 m be as a target value for good acoustical conditions.

The speech attenuation from the sound source to the receiver depends on the height of the wall or barrier, the sound absorption coefficient of the ceiling and the distance between the sound source and receiver [15]. A sound propagation model in open plan offices has been used to explore the influence of each parameter of the office design on the expected speech privacy in the office, and it has been found that the ceiling absorption, the height of partial height panels and the workstation plan size are most important. Speech privacy is affected by not only the speech attenuation from the sound source to the receiver, but also the level of the speech and background noise, so a successful design should also include an optimum masking sound spectrum and an office etiquette that encourages talking at lower voice levels. It is hard to achieve 'acceptable' speech privacy if all design parameters do not have near to optimum values.

Based on the SPC determination procedures specified in ASTM E2638, this paper reports the preliminary measurement results for characterising the speech privacy performance of the Fabpod. The background sound pressure level inside and outside the Fabpod and the sound pressure level differences at different locations inside and outside the Fabpod with different sound source locations were measured in one third octave bands from 50 Hz to 10000 Hz, and these data was used to calculate the SPC value of the Fabpod. Measures that can be used to increase the speech privacy of the Fabpod will be discussed.

2. Measurement Setup and Procedures

The sound pressure level (SPL) measurements were carried out with a B&K PULSE 3560C analyser, which did one third octave CPB (Constant Percentage Bandwidth) analysing from 50 Hz to 10 kHz. The average mode was linear 10 s without any weighting. The microphones used were G.R.A.S. 1/2 pre polarized free field microphone Type 40 AE with pre-amplifiers G.R.A.S Type 26AK. The power for the preamplifiers was provided by a G.R.A.S. Power Module Type 12 AA. Channel A corresponded to Input 1 and Channel B corresponded to Input 2 of the B&K PULSE 3560C system. The measurement system was calibrated by a B&K Type 4231 and checked before and after the measurements.

An onsite SPL (94 dB at 1000 Hz with a calibrator) check was made before and after all measurements to make sure the system worked normally. In the measurements, the sound source used was the omni directional sound source Norsonic Nor 276 together with a power amplifier Nor 280. The power amplifier used its inherent Pink source with a level of 0.0 dB. The equalizer was selected to ON. A remote control was used during moving the microphones. Two channel simultaneous measurements were carried out for the whole test. One microphone in the Fabpod remained at the same position for all measurements while the other microphone was moved around to different positions. In the measurements, the height for both the sound source (source centre) and the microphones was 1.2 m and the locations of them are shown in Figure 2.

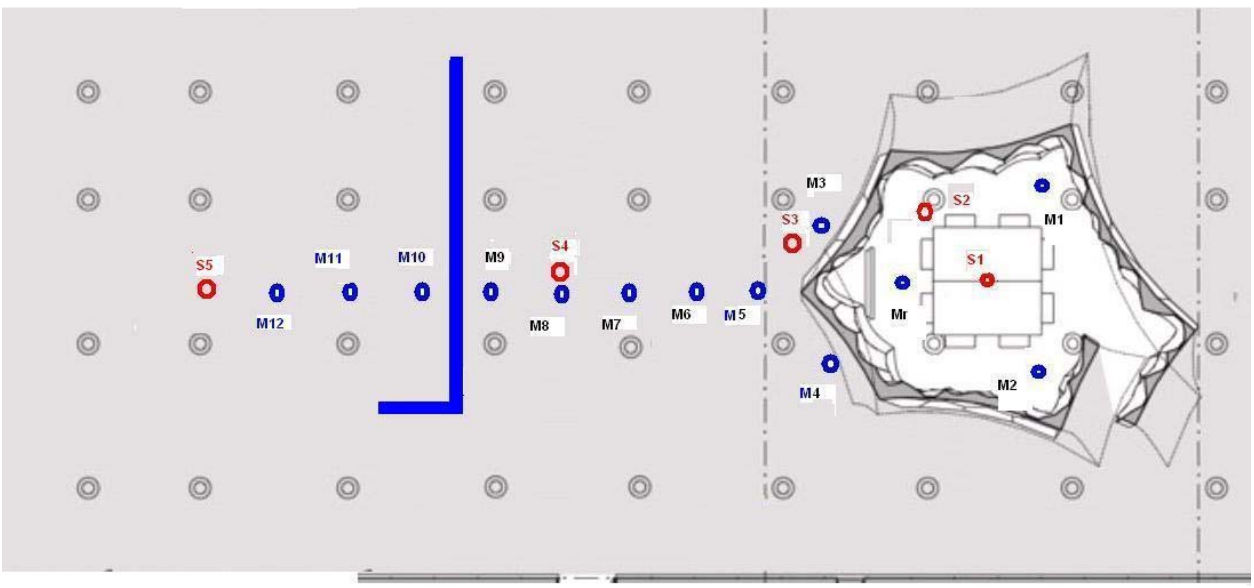

Figure 2. SPL measurement positions (S indicates source location and M indicates microphone location)

In Figure 2, S indicates the source location, M indicates the microphone location, and there were 12 SPL measurements for each source location. M3, M4 and M5 were approximately 0.25 m away from the nearest wall of the Fabpod (the walls of the Fabpod are not vertical, and the distance between the microphones to the walls on the floor was approximately 0.5 m). The distance between the two neighbouring points from M5 to M12 was approximately 1.0 m, and M10 to M12 were behind a long partition with a height of approximately 1.8 m and a width of 0.6 m. M5 to M9 were in an approximate semi open enclosure made by the partition, the walls of the building and the Fabpod. The Input 1 (microphone 1) at location M_r remained at the same place as a reference to all measurements. S1 and S2 were inside the Fabpod, S3 was near the location of M3, S4 was at almost the same location as M8, and S5 was 1 m away further from M12 from the Fabpod. All the measurements were carried out at night when there was no human activity inside the building.

3. Results and Discussions

3.1 Results

The background noise levels inside and outside the Fabpod were measured first as shown in Figure 3, where the background SPL inside the Fabpod was approximately 5 dB lower that that outside the Fabpod. This was because the background noise inside the building mainly came from the street and traffic noise outside the building and the Fabpod walls further insulated approximately 75% of the outside background noise energy, so it was quieter inside the Fabpod. The average A weighted SPL inside and outside the Fabpod was approximately 35.8 dBA and 41.0 dBA. This implied that a person inside the Fabpod might be more easily distracted by the people talking outside the Fabpod. More noise masking (approximately 10 dB) might be needed inside the Fabpod to reduce the distraction from outside people talking [16].

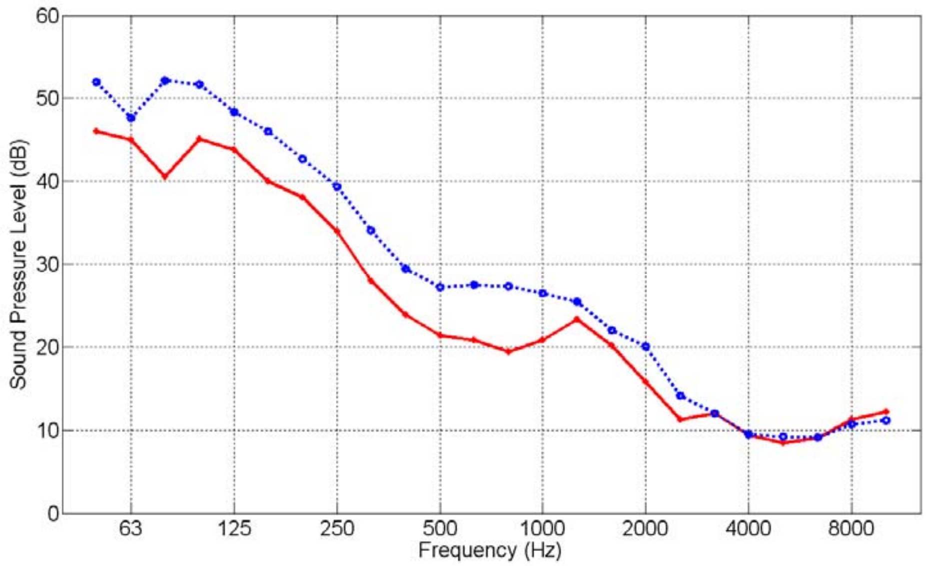

Figure 3. Typical background SPL inside (red solid line with *, overall SPL is 35.8 dBA and 52.0 dB) and outside (blue dash line with o, overall SPL is 41.0 dBA and 58.3 dB) the Fabpod

Figures 4 to 6 show the SPL difference between the reference point and the measurement points as a function of frequency for the sound sources inside the Fabpod. It is obvious that the SPL outside the Fabpod was more than 10 dB lower than that inside at most frequencies. For frequencies below 250 Hz, the SPL difference was around 10 dB and at some frequencies it could even be as low as 3 dB. For frequencies above 250 Hz, the SPL difference was usually grater than 10 dB and increased with the frequency to nearly 25 dB at 8000 Hz. The value of SPL difference varied with the positions of the sound source and the microphones. One interesting thing was that the SPL at positions from M3 to M9 were similar for the sound source inside the Fabpod, indicating that the sound field in this area was quite uniform because of the reflections from the partitions and the walls. The average level difference L_D in Figure 6 was obtained by averaging the one third octave band level value from 160 Hz to 5000 Hz arithmetically, which will be used for calculating SPC in the next section.

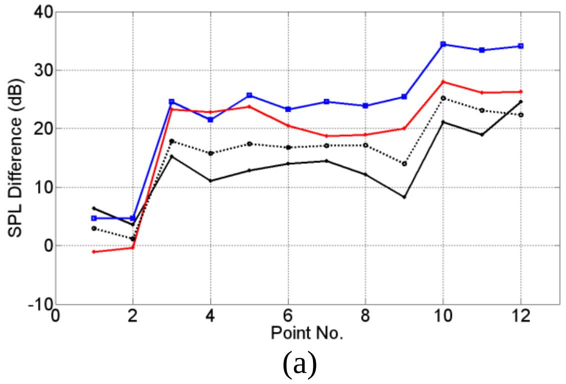

Figure 4. The SPL difference between the reference point and the measurement points in 3 typical third octave bands (125 Hz: black solid line with *, 1000 Hz: blue solid line with square, 4000 Hz: red solid line with +) and for the whole frequency band (black dash line with o) for S1 (a) and S2 (b)

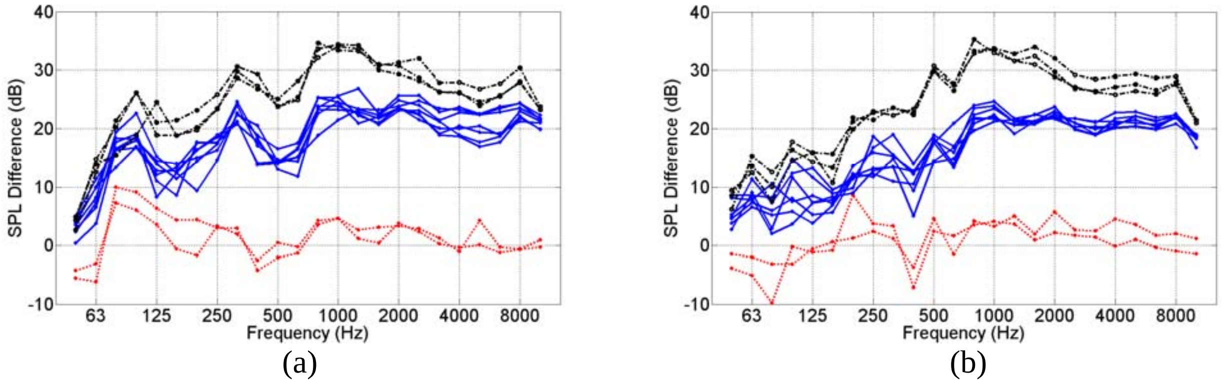

Figure 5. The SPL difference between the reference point and the measurement points in one third octave bands for all the measurement points (red dash lines with * are for M1 and M2, blue solid lines with + are for M3 to M9, black dash-dot lines with o are for M10 to M12) for S1 (a) and S2 (b)

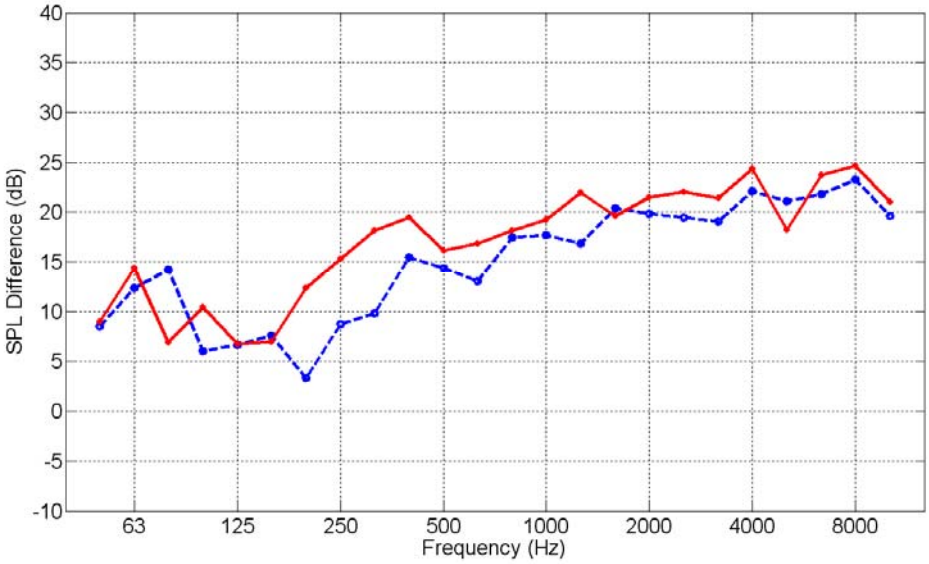

Figure 6. The average SPL level difference between that inside (M1 and M2) and outside (M3 to M5) the Fabpod for S1 (red solid line, L_D = 18.2 dB) and S2 (blue dash line, L_D = 15.4 dB)

Figure 7 shows the SPL difference between the measurement points and the reference point for S4, where the SPL is the largest at M8 because M8 was near the sound source. SPL decreased as the distance between the sound source and the microphone increased, and SPL differences in the whole frequency range from M8 to M4 was approximately 27 dB, 19 dB, 15 dB, 13 dB and 11 dB, respectively. Figure 8 shows the SPL difference between the measurement points and the reference point for S4 in one third octave bands for all measurement points.

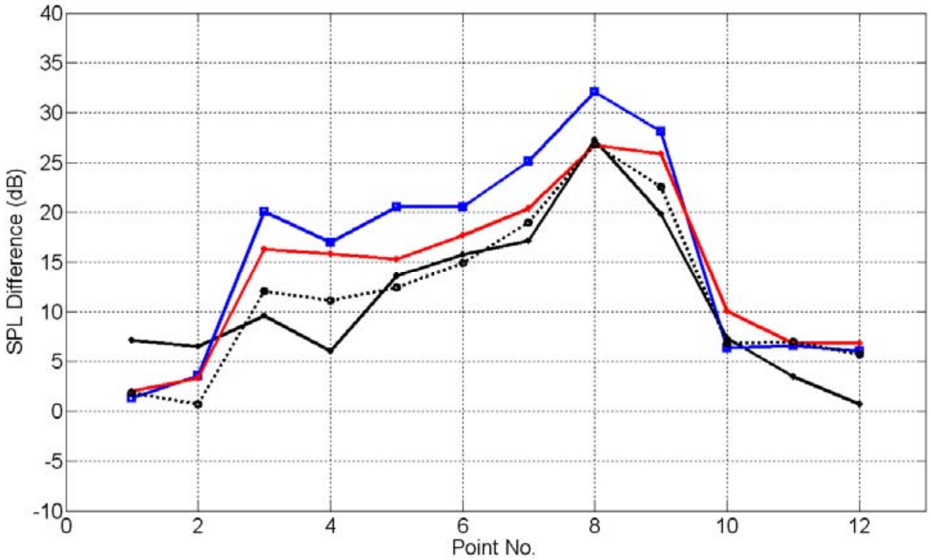

Figure 7. The SPL difference between the measurement points and the reference point in 3 typical third octave bands (125 Hz: black solid line with *, 1000 Hz: blue solid line with square, 4000 Hz: red solid line with +) and for the whole frequency band (black dash line with o) for S4

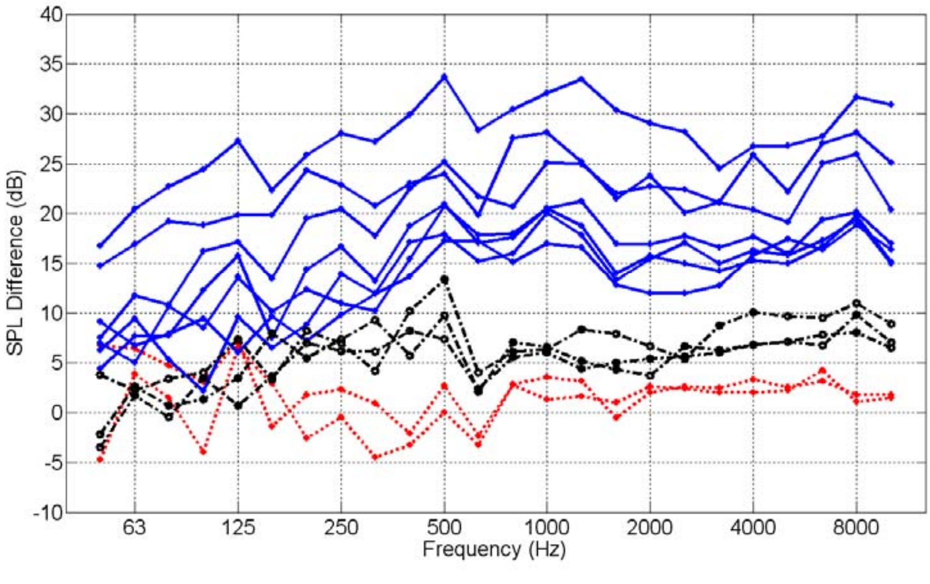

Figure 8. The SPL difference between the measurement points and the reference point in one third octave bands for all the measurement points (red dash lines with * are for M1 and M2, blue solid lines with + are for M3 to M9, black dash-dot lines with o are for M10 to M12) for S4

The average SPL level difference between the measurement points inside (M1 and M2) and outside (M3 to M5) the Fabpod for the 3 sound source locations are shown in Figure 9, where the frequency averaged values of SPL level difference for S3, S4 and S5 are approximately 20.1 dB, 13.4 dB, and 12.5 dB, respectively.

3.2 SPC calculation and discussions

Fabpod is a semi enclosed meeting room with an open ceiling located in an open plan office. Although neither standard ASTM E2638 (using SPC for closed rooms) nor standard ASTM E1130 (using AI for open plan offices) are applicable to the speech privacy performance characterisation of the Fabpod, SPC is adopted in this paper because SPC can also be used for rating speech privacy of open plan spaces as well and SPC is especially suitable for the conditions where high speech privacy is desired [4].

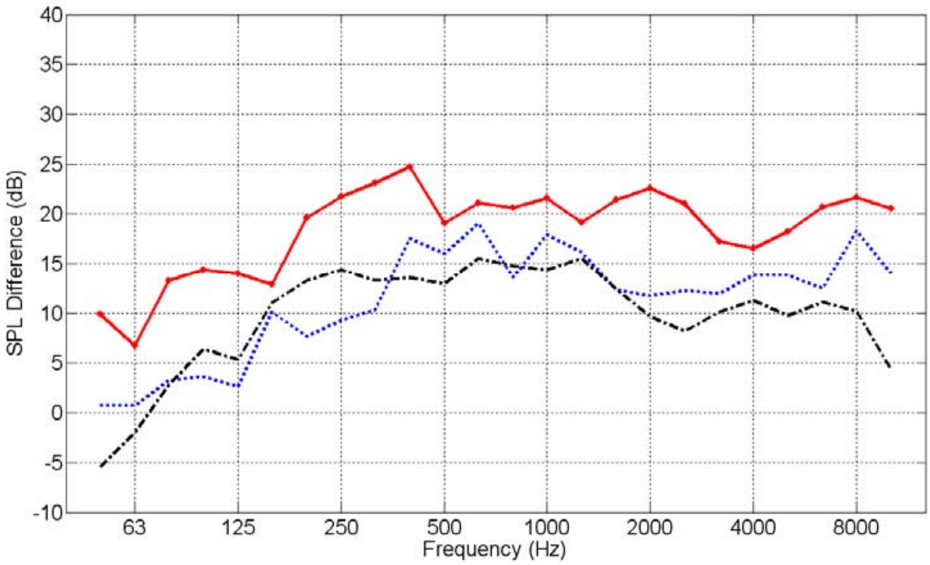

Figure 9. The average SPL level difference between the measurement points outside (M3 to M5) and inside (M1 and M2) the Fabpod for S3 (red solid line, L_D = 20.1 dB), S4 (blue dot line, L_D = 13.4 dB), S5 (black dash dot line, L_D = 12.5 dB)

ASTM E2638 provides the method to rate the speech privacy of a space to each of a number of listener positions outside the room close to the room boundaries without any assumptions as to the talker location. The level of a spatially uniform, broadband noise sound field is taken as the "source" level, and the corresponding levels at listener positions are taken as the "receive" levels. For each receiving point, the average level difference L_D between the two is added to the average background noise L_b to yield the Speech Privacy Class by using the equation SPC = $L_D + L_b$. The average for the frequency means that the one third octave band values are arithmetically averaged from 160 Hz to 5000 Hz.

Based on the measurements in Section 3.1, when the sound sources were inside the Fabpod, the average level difference L_D was approximately 17 dB, while the average background noise L_b outside the Fabpod was approximately 26 dB (this was not the overall sound pressure level of the background noise but the frequency averaged value for the one third octave band sound levels from 160 Hz to 5000 Hz), so the SPC of the Fabpod was approximately 43, which is smaller than the minimum speech privacy requirement of the SPC value 60 [4]. This implies that people outside the Fabpod could overhear the talking inside the Fabpod easily.

In order to compare the speech privacy for people inside and outside the Fabpod, SNR_{uni32} is calculated for both cases by using [11]

$$SNR_{uni32} = \sum_k \max\{[L_s(k) - L_n(k)],\ -32\}\ /16 \qquad (1)$$

where $L_s(k)$ and $L_n(k)$ are the speech and noise levels in the kth 1/3-octave band. The summation is made over 16 one third octave bands from 160 Hz to 5000 Hz. The 1/3-octave band level differences, $L_s(k) - L_n(k)$, are clipped so that they were never less than –32 dB.

The calculation of the speech privacy values depends on the speech and noise levels. The AI and SII standards include standard speech spectra for 'normal' speech, which has an A-weighted SPL of 59.2 dBA and a frequency averaged level value of 47.5 dB. Although 'normal' speech levels have frequently been used to estimate speech privacy in open plan offices, it is found that people talk more quietly in open offices than this normal spectrum [15]. Therefore, a conservative speech source level, the Intermediate Office Speech Level (IOSL), which has an A-weighted SPL of 53.2 dBA and a frequency averaged level value of approximately 42.0 dB instead of the 'normal' speech level, is used in this paper as the source speech level [15]. For peoples talking inside the Fabpod, the arithmetical average of the sound pressure level at M1 and M2 is set as the IOSL, and the sound level outside the Fabpod is obtained by arithmetical average of the sound pressure level at M3, M4, and M5. For peoples talking outside the

Fabpod at S3, S4 and S5, the SPL at M5, M7 and M12 (approximately 1 m away from the source) are assumed to be the IOSL, respectively, and the sound level inside the Fabpod is obtained similarly by arithmetical average the SPLs at M1 and M2. The results are listed in Table 1.

Table 1. Speech privacy in terms of SNR_{uni32} for speakers inside and outside the Fabpod

Speaker location	SNR_{uni32} (dB)	Estimated AI value [11]
Inside Fabpod (S1)	–2.5	0.30
Inside Fabpod (S2)	1.0	0.41
Outside Fabpod (S3)	–1.1	0.37
Outside Fabpod (S4)	0.0	0.40
Outside Fabpod (S5)	–1.8	0.36

Table 1 shows that the SNR_{uni32} is from –2.5 dB to 1.0 dB for sound sources inside and outside the Fabpod, corresponding to AI from 0.30 to 0.41 for receivers outside and inside the Fabpod [11]. With AI values, 'confidential privacy' requires AI < 0.05, which is defined as corresponding to 'zero phrase intelligibility with some isolated words being intelligible'. The 'acceptable' or 'normal privacy' for open plan offices conditions requires AI < 0.15, which is described as not too distracting and corresponds to a level of speech privacy that can be achieved in a well designed open plan office in practice. It is obviously that the Fabpod cannot meet the normal speech privacy criteria of AI = 0.15.

As can be analysed from Equation (1), the main reason for the low speech privacy of the Fabpod is because of the low transmission loss between sound sources and receivers inside and outside the Fabpod, which is around 15-20 dB. On the other hand, the background noise inside the building was quite low. If an optimize masking noise with a SPL of 45 dBA is introduced into the background to increase the background level by approximately 10 dB, then SNR_{uni32} is reduced to approximately –10 dB, corresponding to an AI of approximately 0.12. This meets the 'acceptable' or 'normal privacy'for open plan offices (AI = 0.15) [11, 15]. If 'confidential privacy' is to be met, AI = 0.05 corresponds SNR_{uni32} of –15 dB, this means a requirement of at least 5 dB more sound transmission loss from the archtecture design.

Speech privacy is affected by many factors including the speech attenuation from the sound source to the receiver and the level of the background noise. The speech attenuation from the sound source to the receiver depends on the height of the wall or barrier, the sound absorption coefficient of the ceiling and the distance between the sound source and receiver. To achieve acceptable speech privacy for the Fabpod, all design parameters have to be tuned to near optimum values [11]. For example, to have the minimum speech privacy requirement of the SPC value 60, either the average level difference inside and outside of the Fabpod should increase or the background noise level or both of them should increase so the sum of the two level increments is greater than 17 dB. This value is similar to the requirements obtained in the last paragraph when analysing AI and SNR_{uni32}.

4. Conclusions

The Speech Privacy Class (SPC) regulated by ASTM E2638 was used for rating the speech privacy of the Fabpod. The background SPLs inside and outside the Fabpod and the SPL differences for different locations inside and outside the Fabpod with different sound source locations were measured in one third octave bands from 50 Hz to 10000 Hz. Based on the measurement results, the SPC of the Fabpod obtained was approximately 43, corresponding to an SNR_{uni32} value of –1 dB and an Articulation Index (AI) value of 0.32 with the Intermediate Office Speech Level. The conclusion is that the Fabpod cannot meet the normal speech criteria under current conditions. The SPC of the Fabpod can be increased by increasing the background noise level or the sound transmission loss of it. Future work includes detailed acoustical modelling of the Fabpod both numerically and experimentally, conducting a comprehensive investigation on the acoustic effects of different transmission paths, the non-rectangular overall geometry and the hyperboloid cells, and applying active control to the sound field of the Fabpod.

Acknowledgements

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