Normal incidence sound absorption coefficient of direct piercing carved wood panel with star and diamond dominated geometric patterns

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ABSTRACT

Direct piercing carved wood panels (DPCWP) are wooden panels carved with numerous patterns and elements. They are used in traditional houses, palaces, mosques and other buildings. In mosques, DPCWP are used as parts of wall panel and for the upper partition of doors and windows. Among the earliest DPCWP were in the Sultan Zainal Abidin mosque in 1700s, Kuala Terengganu, Malaysia. The current DPCWP usage in the modern mosques is mainly for esthetic and as a reflection of traditional Malay wood carving. In contrast, the use of DPCWP in earlier mosques was to help achieving good indoor speech intelligibility. DPCWP has the ability to allow sound waves to pass through the panel, hence sound reflection to the main prayer area is contained. Minimizing sound reflection toward the mosque main area ensures optimization of speech intelligibility. This qualifies DPCWP as a sound absorber material, inline with Sabine, Kutruff and Maekawa definition of sound absorption coefficient. In this paper, the normal incidence sound absorption coefficient of DPCWP with star and diamond dominated geometric patterns are discussed. This star and diamond patterns were chosen and designed for 33% and 38% perforation ratios. Numerical experiments were conducted using Boundary Element Method (BEM) while measured results were obtained using sound intensity measurements technique. Comparisons of sound absorption coefficient obtained through both methods are discussed in details. Analysis of resonance frequencies due to the types and sizes of apertures in relation to sound absorption coefficient are also highlighted. The measured and numerical results suggest that DPCWP dominated with star and diamond dominated geometric patterns are able to act as good sound absorber. This finding suggests that DPCWP could be used as effective sound absorbers in future mosques construction.

INTRODUCTION

Direct piercing carved wood panels (DPCWP) are unique perforated wall panels used in Malay building architecture. Direct piercing carved wood panel with geometric pattern is among the complex form of standalone direct piercing carved wood panel. It allows sound waves to pass through that qualify DPCWP as sound absorber material (Cremer & Muller 1978, Kutruff 1979). It has been extensively used as decoration element in Malay architecture especially in palaces, mosques, houses and public buildings (Wan Mustafa 1998, Ahmad 1983). In houses and mosques, wood carving perforated panel have been used as wall panels and also on the upper part partition of the doors and windows. In tropical country like Malaysia, the wood carving perforated panels are also used to help achieving indoor thermal comfort and fresh air circulation. In addition, it also allows natural lighting during the day. (Lim 1987)

GEOMETRIC PATTERN AND PERFORATION RATIO

DPCWP with 33% and 38% perforation ratio with star and diamond geometric patterns possess similar geometric design as shown in Fig. 1 were investigated. The full dimension of the pattern is 1.2m x 1.2m, contains 4 repetitive apertures with 2 columns and 2 rows on each side. Eight pointed stars at the centre of the single aperture are surrounded by a group of eight diamonds at different positions, three different sizes of small rectangles and 45^{o} arrow at each corner. The thickness of this DPCWP is 20mm.

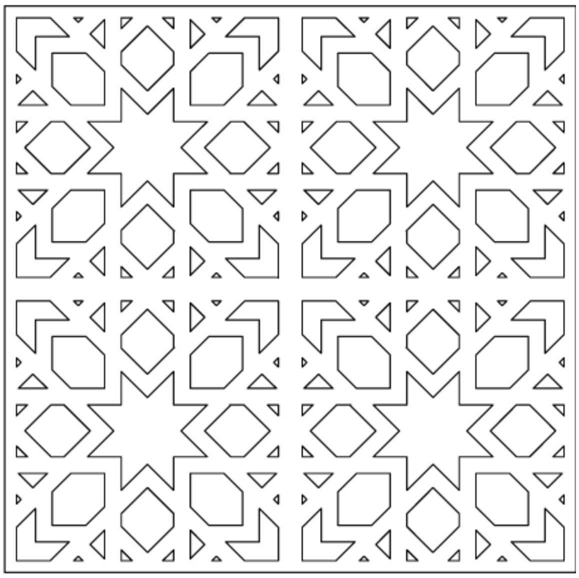

Figure 1. DPCWP of 38% perforation ratio

Perforation ratio is defined as the percentage of the hollow compared to the solid wood area. The perforation ratio for DPCWP is calculated based on the geometric pattern pierced on the wood panel. However, only ¼ from the single pattern is needed (as shown in Fig. 2) since ¼ perforation ratio is equivalent to the full size perforation ratio due to pattern repetitiveness.

$$\sigma = \frac{Total\ area\ of\ 1/4\ perforated\ block}{Total\ area\ of\ 1/4\ solid\ block} \quad (1)$$

where,

$\sigma = Perforation\ ratio$

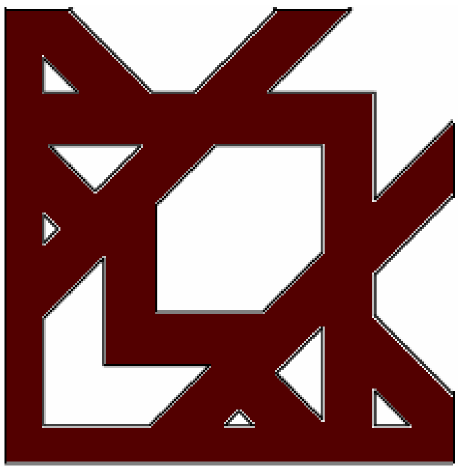

Figure 2. ¼ single perforated block.

NUMERICAL RESULTS

Numerical experiments were conducted using Boundary Element Method (BEM) using BEASY Acoustic software. The resultant sound intensity in front of the panel in anechoic room (RSIP)is compared with the one for empty anechoic room (RSIE). The measurement points for the sound intensity are located at a distance $\lambda/4$ from the perforated aperture of DPCWP. At 250Hz and 500Hz, the mass transfer phenomenon is dominant as proven in our initial work (Ula 2006). However, as the frequency increases to 1kHz, 2kHz and 4kHz, the interaction of sound waves with the DPCWP becomes more complex. It is apparent that sound reflection occurs at these frequency regions. This as indicated primarily in the acquired sound intensity behaviour at 2kHz and 4kHz. The numerical simulation results indicate that there are two different phenomena for RSIP. When RSIP<RSIE and RSIP>RSIE. The condition RSIP<RSIE occurs at 250Hz and 500Hz clearly indicate that mass transfer phenomena is dominant. The condition of RSIP>RSIE occurs mainly at 2kHz and 4kHz is also a clear indication of sound reflection due to sound wave interaction with DPCWP. The reflection phenomena when RSIP>RSIE requires correction to ensure correct sound intensity acquired to determine its α_n.

For RSIP<RSIE, α_n used to determine the absorption coefficient is as shown below (Lai 1991, Maekawa & Lord 1994).

$$RSIE = I_i \quad (2)$$

$$RSIP = I_n \quad (3)$$

$$\alpha_n = \frac{RSIP}{RSIE} \quad (4)$$

where,

I_n = net sound intensity
I_i = incident sound intensity
α_n =sound absorption coefficient.

However, for RSIP>RSIE, the measurement points of RSIP consist of RSIE and IR (reflected sound intensity). Consequently, the RSIP are greater than the RSIE which is obtained from the simulation of empty anechoic room model. The equations to determine the sound absorption coefficient are different from (4).

$$IR = RSIP - RSIE \quad (5)$$

$$I_n = RSIE - IR \quad (6)$$

$$\alpha_n = \frac{RSIE - IR}{RSIE} \quad (7)$$

Using (7), $\alpha_n = 0$ when $IR = RSIE$. By substituting $IR = RSIE$ into (5),

$$RSIP = 2RSIE \quad (8)$$

According to (8), the maximum value of RSIP is double of RSIE. Thus, if the value of RSIP exceeds this limit, that particular measurement point shall be ignored and considered invalid because the α_n and I_n result in negative value. Equations (4) and (7) can be used to determine the normal incident sound absorption coefficient of DPCWP if the condition is statisfied. This mainly at 2kHz and 4kHz octave centre frequency.

The simulated α_n result for 33% and 38% perforation ratio tabulated in Table 1 and Fig. 3 show that 33% α_n value exhibit a smooth decrement trend from 250 Hz to 1k Hz, followed by slight increment from 1kHz to 2kHz. Then, the α_n value decreases as the frequency increases from 2kHz to 4kHz. This trend is similar to the DPCWP, 38% perforation ratio except at 500Hz.

Table 1. α_n simulated for 33% and 38% perforation ratios

	250Hz	500Hz	1kHz	2kHz	4kHz
33 %	0.98	0.86	0.67	0.69	0.59
38 %	1.0	0.84	0.71	0.71	0.65

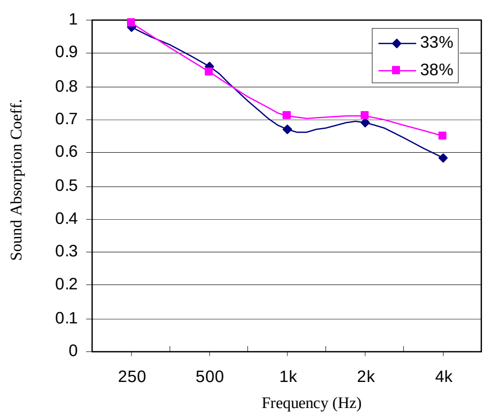

Figure 3. α_n simulated for 33% and 38% perforation ratio

EXPERIMENTAL RESULTS

The experimental works on α_n measurements were conducted in the anechoic chamber at Acoustic Lab, Electrical Engineering Faculty, Universiti Teknologi Malaysia (UTM) with a dimension of 3.42m x 3.42m x 2.17m using sound intensity technique.

The sound intensity in an empty anechoic room (IE) and the sound intensity in front of the DPCWP (IP) are obtained from the experimental result of empty anechoic room and anechoic room with DPCWP, respectively. Using the B&K sound intensity measurement system, the measurement for both IE and IP were done in term of sound intensity level (SIL) in decibel unit. Conversion unit from sound pressure level to sound intensity were done before the results analysis and calculation of sound absorption coefficient can be made. The relationship between sound pressure level and sound intensity is shown in (9).

$$SIL(dB) = 10 \log_{10} \frac{I}{I_0} \tag{9}$$

where,

I_0 = reference sound intensity, 1×10^{-12} W/m^2

By arranging the formula above, sound intensity for IE and IP is shown in (10).

$$I(Wm^{-2}) = 10^{\frac{SPL\,(dB)}{10}} * I_0 \tag{10}$$

The experimental results for 33% and 38% perforation ratios are shown in Table 2 and Fig. 4, which show that overall α_n value for 33% perforation ratio illustrates a slight decrement trend from 250Hz to 500Hz followed by deeper decrement trend from 500Hz to 1kHz. Then, the α_n value exhibits a drastic increment trend from 1kHz to 2kHz followed by also drastic decrement trend from 2kHz to 4kHz. For 38% perforation ratio, overall, α_n is higher than α_n at 33%. It is also observed that α_n trend is similar with 33% α_n trend, except from 250Hz to 500H. The α_n value exhibit slight increment trend as compared to 33% at this particular range of frequencies.

Table 2. α_n measured for 33% and 38% perforation ratio

	250Hz	500Hz	1kHz	2kHz	4kHz
33 %	0.94	0.88	0.36	0.67	0.35
38 %	0.92	0.90	0.55	0.76	0.47

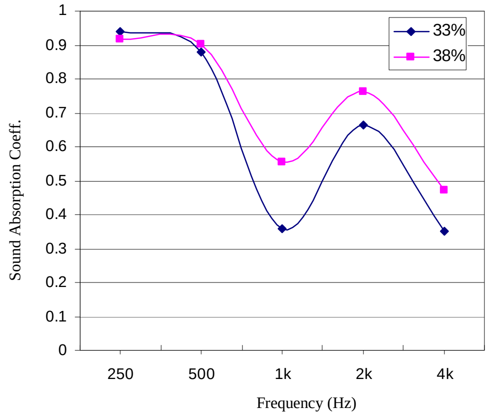

Figure 4. α_n measured for 33% and 38% perforation ratio

RESULTS COMPARISON

A precise α_n comparison for 33% and 38% perforation ratio from 250Hz to 4kHz is shown in Fig. 5. It is shown that α_n trending for numerical and experimental results for both perforation ratios are comparable except the values are much differs particularly from 1kHz to 4kHz. Works are currently ongoing to further understand these differences among numerical and experimental α_n results, in particular for 1kHz and 4kHz centre frequencies.

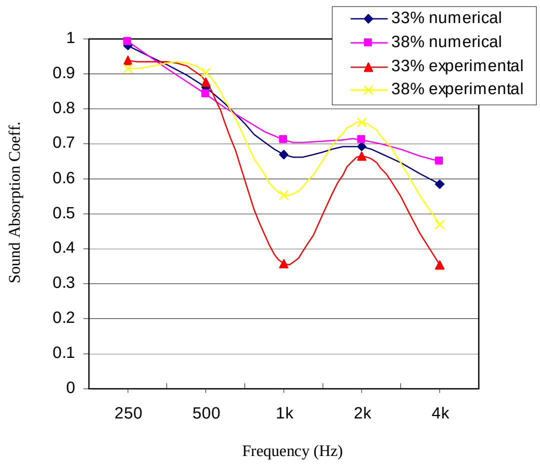

Figure 5. α_n simulated and measured for 33% and 38% perforation ratio

RESONANCE FREQUENCY ANALYSIS

The α_n differences between 2kHz and 4kHz for both simulation and measurement could be due to resonance frequencies inside the air column in DPCWP aperture. Therefore, the resonance analysis of the sound waves inside column of the apertures with geometric pattern is conducted based on the longest length of the pattern to identify the resonance frequency.

Resonance frequency inside air column

The aperture of the perforated panel can act as wave guide as shown in Fig. 6. Resonance will occur within the wave guide when the sound wave which is at resonance frequency travels through the wave guide. This phenomenon also happens to the apertures of perforated panel whose structure is similar to the wave guide. The resonance frequency for wave guide is given by (11). (Fahy 2001)

$$f_n = \frac{nc}{2d} \tag{11}$$

where,

f = Resonance frequency, Hz
n = Integer (1, 2, 3,…)
d = Hole diameter, m
c = Speed of sound, ms^{-1}

Referring on (11), the diameter of the hollow opening plays an important role to determine the resonance frequency of WCPP. The larger the hole, the lower the resonance frequency and vice versa.

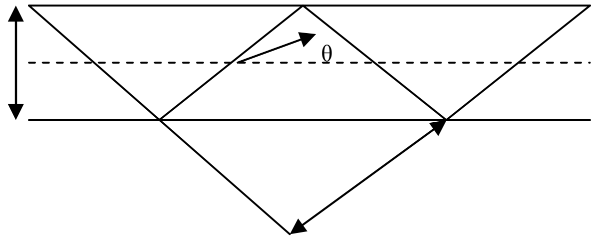

Figure 6. Maximum periodic spacing for a given direction of propagation

Resonance frequency on apertures of DPCWP

The behaviour of sound wave in waveguide is used to analyse the sound wave resonance inside the air column (apertures) on DPCWP geometric patterns. Referring to Fig. 6, as $\theta = \pi / 2$, the sound waves inside the DPCWP air column apertures resonate under the following condition (Fahy 2001).

$$f_n = \frac{nc}{2d} \tag{12}$$

where,

f = Resonance frequency, Hz
n = Integer (1, 2, 3,…)
d = Longest length of aperture in DPCWP
c = Speed of sound, ms^{-1}

Resonance frequency of DPCWP with 33% and 38% perforation ratio

Various aperture openings (*noted in Roman numbering*) and longest length (d_n) of the openings for each pattern are taken into consideration in the resonance analysis of the DPCWP with geometric pattern. Six apertures for each perforation ratio (see Fig. 7) are analysed of their resonance frequency. Various longest lengths have been chosen for the individual aperture investigation as shown from Fig. 8 to Fig. 12.

Figure 7. 6 Apertures investigated for resonance frequency analysis

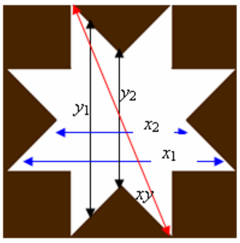

Figure 8. Various distance for aperture I

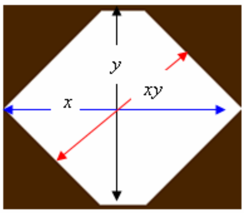

Figure 9. Various distances for aperture II

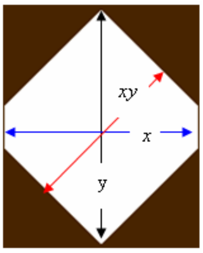

Figure 10. Various distances for aperture III

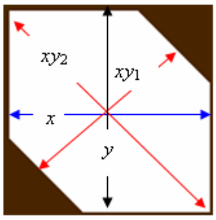

Figure 11. Various distances for aperture IV

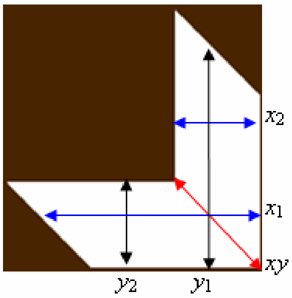

Figure 12. Various distances for aperture V

The calculated resonance frequency for DPCWP with 33% and 38% perforation ratios are tabulated in Table 3 and Table 4, respectively. For octave band centre frequency at 1kHz, the frequency band is from 707Hz to 1.4kHz. For octave band centre frequency at 2kHz, the frequency band is from 1.4kHz to 2.83Hz. For the octave band centre frequency at 4kHz, the frequency band is from 2.83kHz to 5.65kHz.

The principal resonance frequency (f_1) for 33% perforation ratio at 1kHz, 2kHz and 4kHz are 5, 7 and 2, respectively. The principal resonance frequency (f_1) for 38% perforation ratio at 1kHz, 2kHz and 4kHz are also 5, 7 and 2, respectively. Analysis of resonance frequencies suggest that resonance frequencies mostly occur at 1kHz and 2kHz for both 33% and 38% perforation ratio. The α_n trend for the 33% perforation ratio at 2kHz is 0.69. This is highest for frequencies from 1kHz to 4kHz. For 38% perforation ratio, α_n at 1kHz and 2kHz is 0.71 before it reduces to 0.65 at 4kHz. These are an interesting α_n phenomena that requires further indepth work such as setting the DPCWP to resonate at 1kHz, 2kHz and 4kHz. Later, comparison of these results shall highlight the contribution of resonance frequencies toward α_n of DPCWP.

Table 3. Calculated resonance frequency for 33% perforation ratio

Perforation Ratio	Aperture		d (mm)	Resonance Frequency (Hz)		
				f_1	f_2	f_3
33%	I	x_1&y_1	185	919	1838	2757
		x_2&y_2	133	1278	2556	3835
		xy	258.8	657	1314	1971
	II	x	128.9	1319	2638	3957
		y	104	1635	3269	4904
		xy	92.8	1832	3664	5496
	III	x	104	1635	3269	4904
		y	128.9	1319	2638	3957
		xy	92.8	1832	3664	5496
	IV	x&y	104	1635	3269	4904
		xy_1	94	1809	3617	5426
		xy_2	147.1	1156	2311	3467
	V	x_1&y_1	83.5	2036	4072	6108
		x_2&y_2	34	5000	10000	15000
		xy	48.1	3534	7069	10603

Table 4. Calculated resonance frequency for 38% perforation ratio

Perforation Ratio	Aperture		d (mm)	Resonance Frequency (Hz)		
				f_1	f_2	f_3
38%	I	x_1&y_1	196.4	866	1731	2579
		x_2&y_2	141.4	1202	2405	3607
		xy	274.4	620	1239	1859
	II	x	137.2	1239	2478	3717
		y	110	1545	3091	4636
		xy	100	1700	3400	5100
	III	x	110	1545	3091	4636
		y	137.2	1239	2478	3717
		xy	99.7	1705	3410	5115
	IV	x&y	110	1545	3091	4636
		xy_1	100	1700	3400	5100
		xy_2	155.6	1093	2185	3278
	V	x_1&y_1	91.6	1856	3712	5568
		x_2&y_2	40	4250	8500	12750
		xy	56.6	3004	6007	9011

CONCLUSION

The DPCWP of star and diamond dominated geometric pattern at 33% and 38% perforation ratio shows its ability to act as reasonably good sound absorber. This as shown through numerical and experimental results discussed earlier. There are some α_n differences between the experimental and numerical. These α_n deviations requires further indepth analysis to further understand what really contribute to it. However, the trend of α_n are similar for both cases, where the α_n is higher at low frequency and decreasing as the frequency increase. Higher perforation ratio results in higher overall α_n.

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