An Experimental Study of The Improvement of Noise Reduction Performance of Plenum Window with Different Sonic Crystal Arrays Installed

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ABSTRACT

An experiment was conducted to study the acoustic insulation improvement of plenum window after installation of two-column sonic crystal (SC) arrays within the window cavity. The arrays are formed using rigid cylindrical scatterers. The *square*, *rectangular* and *triangular (with an irregular hexagonal unit cell)* lattices of SC with two different diameters were included in the experiment. The lattice constant is dependent on the size of cavity gap (G). Results demonstrate that among all the cases experimented, the largest A-weighted insertion loss (IL) of 2.76 dBA is attained at array with a rectangular lattice and a larger diameter of scatterers, with lattice constants of *(a,b)=(G/3,G/2)*. The array with a square lattice and a smaller diameter together with a lattice constant of *a=G/2,* gives the lowest IL of merely 0.05 dBA. With size of diameter fixed, rectangular lattice of SC having larger diameter is found to perform the best. Apart from the ‘complete’ SC, the effect of ‘half’ form of it, arranged as with the same lattice and same lattice constant as that of the abovementioned ‘weakest’ performing array, was also investigated for comparison with its counterpart. Intriguingly, results reveal that the ‘half’ form achieves a better improvement in the current experiment.

1. INTRODUCTION

Acoustic Metamaterials (AM), such as Sonic Crystal (SC), have been widely studied by scholars from different fields around the world due to the demonstration of its special, unique, and intriguing acoustical behaviours [1][2][3]. Together with the investigation, numerous applications of AM have also been discovered, such as noise filtering, sound barrier, waveguide, acoustic cloaking, acoustic focusing, etc [4][5][6][7][8] and implemented in various industries. Yet, to the best of authors’ knowledge, attempts of applying SC on buildings are rarely seen [9][10][11], especially on the plenum

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window [12][13], which has been proved to be effective in noise reduction and meanwhile guaranteeing sufficient air ventilation. Therefore, the current work aims to study the acoustic insulation improvement of plenum window after installation of two-column SC arrays within the window cavity. The arrays are formed using rigid cylindrical scatterers. The current conference paper also partly acts as an extension of a previous one [14].

2. EXPERIMENT SETUP AND METHODS

The size of cavity gap of the window used in the current experiment is 158 mm and the two different lengths of diameter (d) of cylinders implemented here are 32 mm and 19 mm respectively. The maximum number of columns of the installed finite SC arrays is 2, due to a practical consideration of ventilation [12]. Also, the one-third octave band centre frequency range covered is between 400 Hz and 20 kHz. Apart from these, the general experimental setup, measurement procedures as well as other values of geometrical and physical parameters (e.g., model size and scaling, material properties, etc.) remain the same as those considered in reference [14]. In the previous work, however, only a square lattice with lattice constant of G/3 was considered. Some more new lattices of the installed finite SC arrays are thereby further introduced in the current work, namely a rectangular lattice, a triangular lattice, and a new square lattice partially composed of half cylinders. These arrangements partially having half cylinders are included in the experiment for the purpose of comparison with those formed by complete cylinders and with the same lattice.

Table 1 – Summary of the installed finite SC arrays

Arrangement code	Lattice type	Lattice constant (Direction 1) (a) (In unit of m)	Lattice constant (Direction 2) (b) (In unit of m)	Inclusion of half cylinders (Yes/No)
(c)(i)	Square lattice	$\frac{G}{2}$	$\frac{G}{2}$	No
(d)(i)	Square lattice	$\frac{G}{3}$	$\frac{G}{3}$	No
(e)(i)	Triangular lattice (Irregular Hexagonal)	$\frac{G}{2}$	$\frac{\sqrt{5}G}{4}$	Yes
(f)(i)	Triangular lattice (Irregular Hexagonal)	$\frac{G}{3}$	$\frac{\sqrt{5}G}{6}$	Yes
(g)(v)	Square lattice	$\frac{G}{2}$	$\frac{G}{2}$	Yes
(h)(v)	Rectangular lattice	$\frac{G}{3}$	$\frac{G}{2}$	Yes

It should be noted that for the triangular (irregular hexagonal) lattice, namely (e)(i) and (f)(i), since the lattice constant is calculated along a slant direction, it results in a form of square root, as shown in the column of ‘Direction 2’ of Table 1.

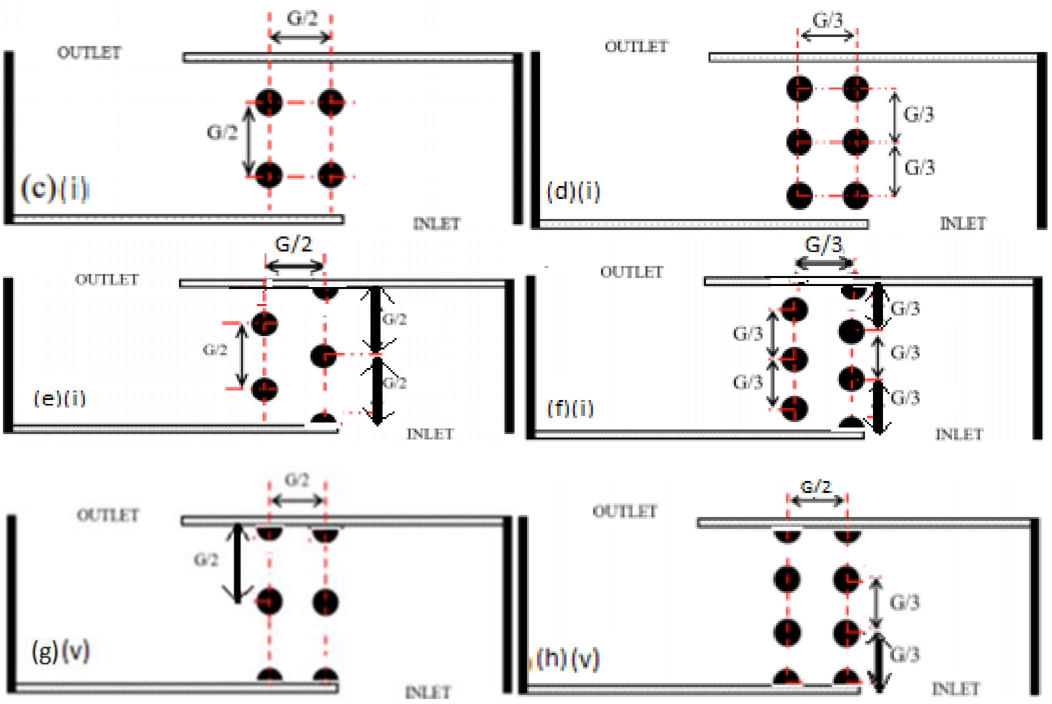

Figure 1 – Geometry of the arrangement of SC arrays installed within the cavity gap (Pictures drawn based on reference [15])

Due to the close connection with theory of SC, unit cells corresponding to all lattices considered in the current work are also demonstrated in the following, together with their first irreducible Brillouin zones respectively. As at here only experiment data are going to be discussed, in deep study of the effect of band structure, especially its band gap, on the noise reduction performance of these finite SC arrays, will be covered together in next publication.

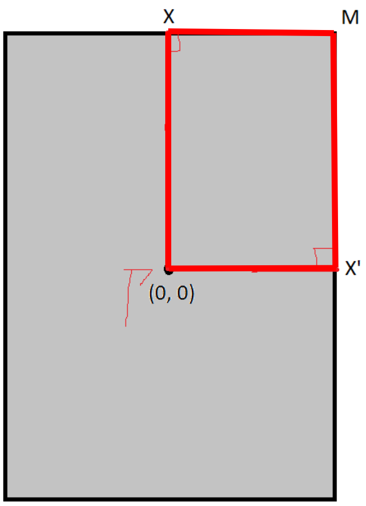

Figure 2 – Example of a unit cell of rectangular lattice and its first irreducible Brillouin zone (The region bounded by red lines)

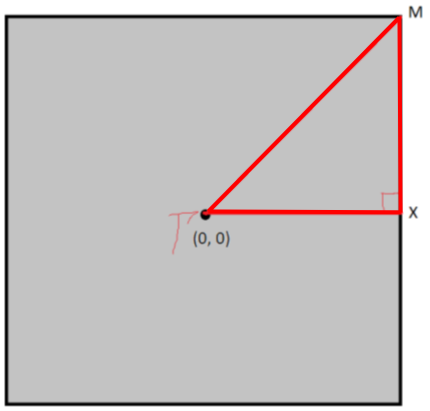

Figure 3 – Example of a unit cell of square lattice and its first irreducible Brillouin zone (The region bounded by red lines)

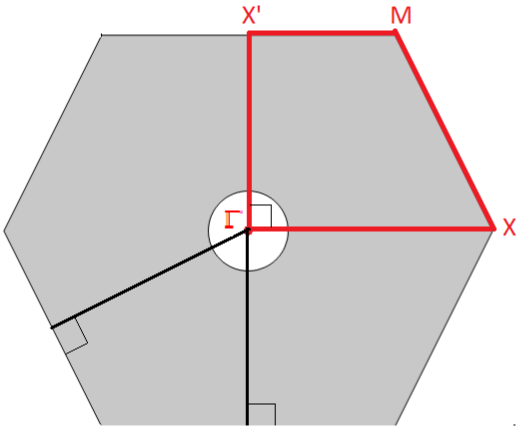

Figure 4 – Example of a unit cell of triangular (irregular hexagonal) lattice and its first irreducible Brillouin zone (The region bounded by red lines)

Performance of the plenum window installed with arrays is quantified by Transmission Loss (TL) and Insertion Loss (IL), which are defined as

$$TL_i = SPL_{i,reference} - SPL_{i,receiver} \qquad (dB)$$

$$IL_i = TL_{i,with} - TL_{i,without} \qquad (dB)$$

, where $SPL_{i,reference}$ and $SPL_{i,receiver}$ are the averaged sound pressure level at the i^{th} one-third octave band collected from the reference and receiver microphones respectively, the suffices *with* and *without* refer to the inclusion of arrays. Single number ratings, i.e., the A-weighted insertion loss $IL(A)$ and the A-weighted transmission loss $TL(A)$, are also calculated based on EN 1793-3 [17] to provide an indication of general performance and the formulae are given as

$$TL(A) = -10\log_{10}\left(\frac{\sum_{k=1}^{18} 10^{0.1(L_k - TL_k)}}{\sum_{k=1}^{18} 10^{L_k}}\right) \qquad (dBA)$$

$$IL(A) = -10\log_{10}\left(\frac{\sum_{k=1}^{18} 10^{0.1(L_k - IL_k)}}{\sum_{k=1}^{18} 10^{L_k}}\right) \qquad (dBA)$$

, where L_k is the normalized A-weighted sound pressure level of traffic noise in the k^{th} one-third octave band listed in EN 1793-3 [16][17].

3. RESULTS AND DISCUSSION

It can be seen from Table 2 and Table 3 that, generally, installation of finite SC arrays undoubtedly enhances the noise reduction performance of plenum window and the enhancement $IL(A)$ ranges from 0.05 dBA to 2.76 dBA, corresponding to the arrangement of (c)(i) with shorter diameter of cylindrical scatterers and that of (h)(v) with cylinders of longer diameter.

Table 2 – Summary of $IL(A)$ (d=19 mm)

Arrangement code	A-weighted transmission loss $TL(A)$ (dBA) (Before installation)	A-weighted transmission loss $TL(A)$ (dBA) (After installation)	A-weighted insertion loss $IL(A)$ (dBA)
(c)(i)	8.63	8.44	0.05
(d)(i)	8.63	9.28	0.88
(e)(i)	8.63	9.32	0.96
(f)(i)	8.63	9.88	1.36
(g)(v)	8.63	9.77	1.23
(h)(v)	8.63	10.07	1.63

Table 3 – Summary of $IL(A)$ (d=32 mm)

Arrangement code	A-weighted transmission loss $TL(A)$ (dBA) (Before installation)	A-weighted transmission loss $TL(A)$ (dBA) (After installation)	A-weighted insertion loss $IL(A)$ (dBA)
(c)(i)	8.63	9.44	1.15
(d)(i)	8.63	9.51	1.23
(e)(i)	8.63	9.77	1.49
(f)(i)	8.63	9.68	1.44
(g)(v)	8.63	10.47	2.14
(h)(v)	8.63	11.06	2.76

3.1. Effect of size of cylindrical scatterer

In summary, obviously, with the arrangement and lattice being fixed, longer diameter of scatterers results in a more significant $IL(A)$ when compared to that achieved by the scatterers with shorter diameter. The difference could even be exceeding 1 dBA in some cases. For example, concerning arrangement (h)(v), $IL(A)$ attained by the shorter-diameter and longer-diameter scatterers are 1.63 dBA and 2.76 dBA respectively, resulting in a difference of 1.13 dBA. Even for the arrangement containing the least number of complete scatterers, i.e., (g)(v), the difference of $IL(A)$ obtained could be mounted on 0.91 dBA. It is uncertain at the current stage that whether the size of scatterers outweighs all the other remaining factors but, statistical analysis would be conducted in the future for a more profound understanding.

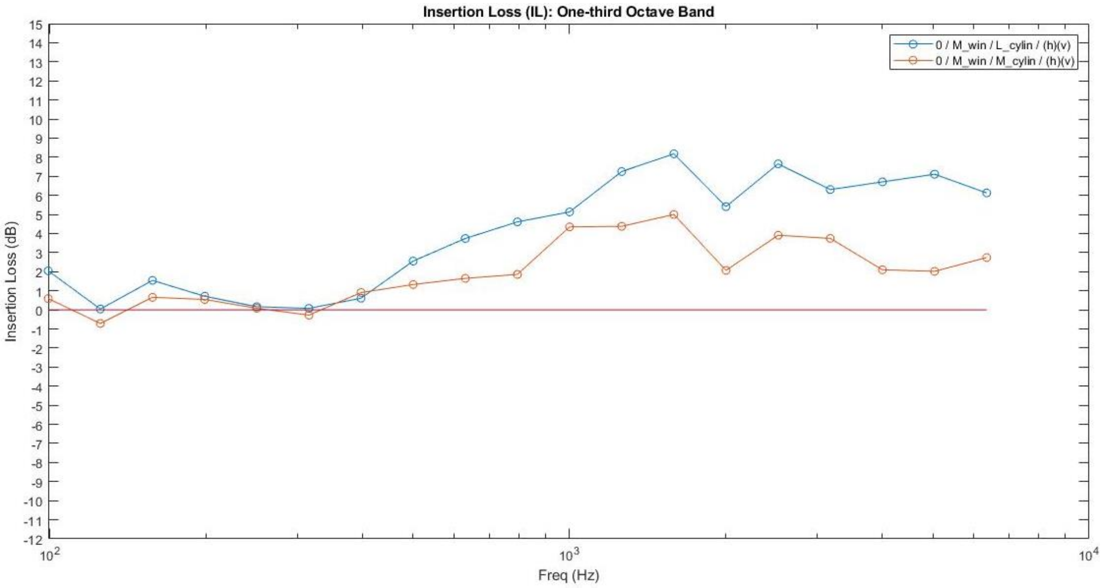

Figure 5 – *Insertion Loss (IL)* for arrangement (h)(v) on one-third octave band -
Blue line: with longer-diameter scatterers
Orange line: with shorter-diameter scatterers
Red line: reference line of *IL=0 dB*

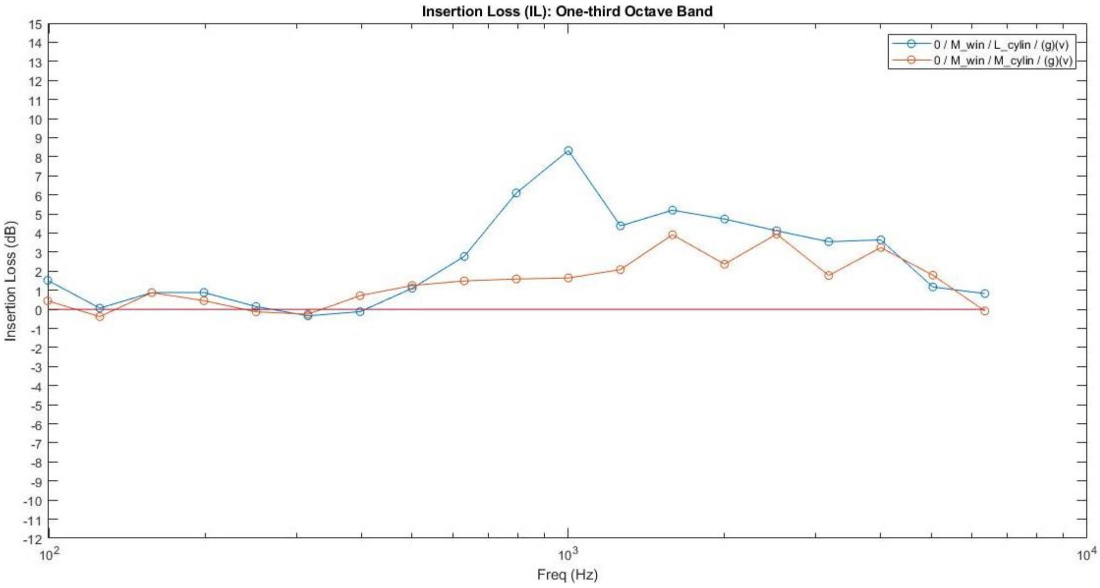

Figure 6 – *Insertion Loss (IL)* for arrangement (g)(v) on one-third octave band -
Blue line: with longer-diameter scatterers
Orange line: with shorter-diameter scatterers
Red line: reference line of *IL=0 dB*

3.2. Effect of arrangement of arrays

With the size of scatterer's diameter being fixed, the rectangular lattice, corresponding to arrangement (h)(v), achieves the highest $IL(A)$ among all the lattices considered in the current experiment. The difference in $IL(A)$ between it and the other lattices can sometimes even be up to 1.61 dBA. Even more, it seems that with the increase of size of scatterer's diameter, the difference becomes far more significant. Taking arrangement (c)(i) and (d)(i), which have a square lattice with lattice constant of $G/2$ and $G/3$ respectively, as examples.

The difference in $IL(A)$ between (h)(v) and each of them is 1.58 dBA and 0.75 dBA respectively for scatterer with shorter diameter, 1.61 dBA and 1.53 dBA respectively for scatterer with longer diameter.

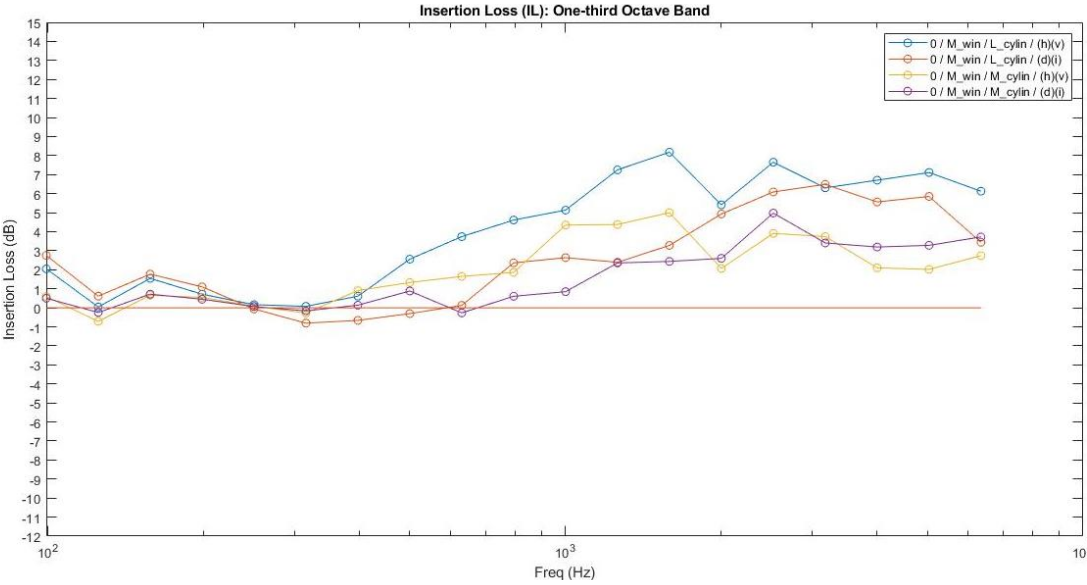

Figure 7 – Comparison of *Insertion Loss (IL)* on one-third octave band -
Blue line: (h)(v) with longer-diameter scatterers
Yellow line: (h)(v) with shorter-diameter scatterers
Orange line: (d)(i) with longer-diameter scatterers
Purple line: (d)(i) with shorter-diameter scatterers
Red line: reference line of *IL=0 dB*

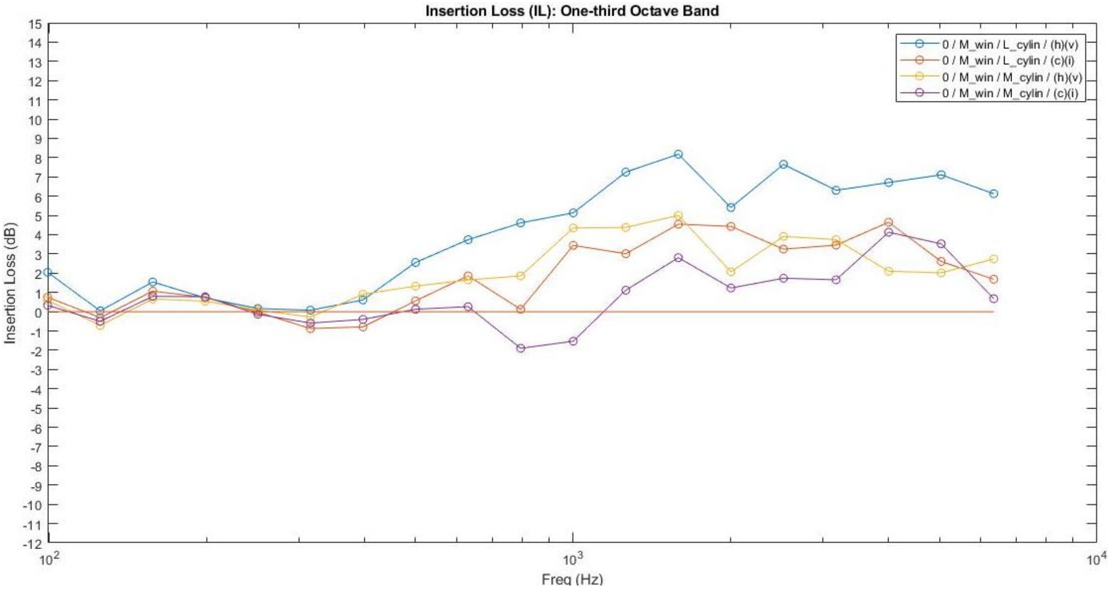

Figure 8 – Comparison of *Insertion Loss (IL)* on one-third octave band -
Blue line: (h)(v) with longer-diameter scatterers
Yellow line: (h)(v) with shorter-diameter scatterers
Orange line: (c)(i) with longer-diameter scatterers
Purple line: (c)(i) with shorter-diameter scatterers
Red line: reference line of *IL=0 dB*

3.3. Effect of completeness of cylinder

Intriguingly, arrangement including half cylinders outperforms those with complete cylinders and with the same lattice and size of diameter in the experiment. Arrangement (g)(v), which has the same lattice and lattice constant as (c)(i), performs better than the latter in $IL(A)$ with differences of 1.18 dBA (with scatterers of shorter diameter) and 0.99 dBA (with scatterers of longer diameter). It is uncertain that whether the phenomenon is simply resulted by randomness of sound source, multiple scattering between scatterers, finiteness of the arrangement of scatterers or other unknown factors. Thus, more profound investigation will be required in the future as theoretically the same results should be obtained given that the lattices are the same, disregarding the completeness of scatterers (this is also proved by using commercial simulation software, but the results are not included in the current paper).

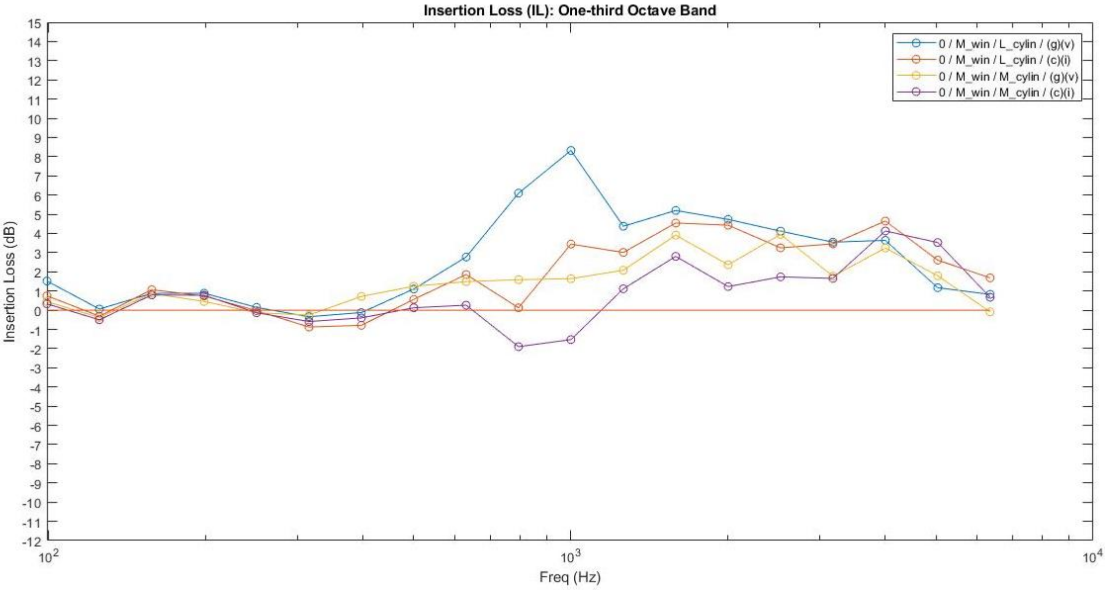

Figure 9 – Comparison of *Insertion Loss (IL)* on one-third octave band -
Blue line: (g)(v) with longer-diameter scatterers
Yellow line: (g)(v) with shorter-diameter scatterers
Orange line: (c)(i) with longer-diameter scatterers
Purple line: (c)(i) with shorter-diameter scatterers
Red line: reference line of *IL=0 dB*

4. CONCLUSIONS

It is suggested that, as from the experimental results, arrangement with half scatterers of longer diameter and with rectangular lattice could be considered as a suitable candidate for installation within the window cavity to improve its noise reduction performance. However, more studies regarding relationship between different factors included above will need to be conducted in the future for comprehension. Besides, as stated above, detailed and careful investigation will also be required to generally understand the intriguing differences in insertion loss caused between complete cylinders and half cylinders. Despite the limited improvement in noise reduction given by the installed SC arrays, putting its finite structure into consideration, the results are already not far away from satisfactory. Therefore, it is possible that more columns and rows of arrays will be installed for deeper understanding of the effect in the coming future. Besides, currently the theoretical development for the study is simultaneously in progress and the theoretical aspect of the current study will also be introduced in future publication. Lastly, optimization on geometrical parameters is further suggested to achieve better performance of the finite SC arrays.

5. ACKNOWLEDGEMENTS:

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6. REFERENCES:

[1] Martínez-Sala, Rosa, J. Sancho, Juan V. Sánchez, Vicente Gómez, Jaime Llinares, and Francisco Meseguer. "Sound attenuation by sculpture." *nature* 378, no. 6554 (1995): 241-241.

[2] Sigalas, M. M., and E. N. Economou. "Attenuation of multiple-scattered sound." *EPL (Europhysics Letters)* 36, no. 4 (1996): 241.

[3] Sigalas, M. M. "Defect states of acoustic waves in a two-dimensional lattice of solid cylinders." *Journal of Applied Physics* 84, no. 6 (1998): 3026-3030.

[4] Yang, Z., H. M. Dai, N. H. Chan, G. C. Ma, and Ping Sheng. "Acoustic metamaterial panels for sound attenuation in the 50–1000 Hz regime." *Applied Physics Letters* 96, no. 4 (2010): 041906.

[5] Martínez-Sala, Rosa, Constanza Rubio, Luis M. García-Raffi, Juan V. Sánchez-Pérez, Enrique A. Sánchez-Pérez, and J. Llinares. "Control of noise by trees arranged like sonic crystals." *Journal of sound and vibration* 291, no. 1-2 (2006): 100-106.

[6] Miyashita, Toyokatsu. "Sonic crystals and sonic wave-guides." *Measurement Science and Technology* 16, no. 5 (2005): R47.

[7] Torrent, Daniel, and José Sánchez-Dehesa. "Acoustic cloaking in two dimensions: a feasible approach." *New Journal of Physics* 10, no. 6 (2008): 063015.

[8] Gupta, Bikash C., and Zhen Ye. "Theoretical analysis of the focusing of acoustic waves by two-dimensional sonic crystals." *Physical Review E* 67, no. 3 (2003): 036603.

[9] Fusaro, Gioia, Xiang Yu, Zhenbo Lu, Fangsen Cui, and Jian Kang. "A metawindow with optimised acoustic and ventilation performance." *Applied Sciences* 11, no. 7 (2021): 3168.

[10] Lee, Hsiao Mun, Long Bin Tan, Kian Meng Lim, and Heow Pueh Lee. "Experimental study of the acoustical performance of a sonic crystal window in a reverberant sound field." *Building Acoustics* 24, no. 1 (2017): 5-20.

[11] Lee, Hsiao Mun, Long Bin Tan, Kian Meng Lim, and Heow Pueh Lee. "Sound quality experiments in a student hostel with newly designed sonic crystal window." *Acoustics Australia* 45, no. 3 (2017): 505-514.

[12] Tang, Shiu Keung. "Reduction of sound transmission across plenum windows by incorporating an array of rigid cylinders." *Journal of Sound and Vibration* 415 (2018): 25-40.

[13] Tong, Y. G., Shiu Keung Tang, J. Kang, A. Fung, and M. K. L. Yeung. "Full scale field study of sound transmission across plenum windows." *Applied Acoustics* 89 (2015): 244-253.

[14] Li, Xiaolong, and Shiu-Keung Tang. "Sound Insulation of Plenum Windows Installed with Rigid Cylinder Array." In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, vol. 259, no. 8, pp. 1103-1109. Institute of Noise Control Engineering, 2019.

[15] Li, Xiaolong. "Prediction and enhancement of the sound transmission loss across plenum windows." (2020).

[16] Garai, Massimo, and Paolo Guidorzi. "European methodology for testing the airborne sound insulation characteristics of noise barriers in situ: Experimental verification and comparison with laboratory data." *The Journal of the Acoustical Society of America* 108, no. 3 (2000): 1054-1067.

[17] BS EN 1793-3, Road traffic noise reducing devices - Test method for determining - Part 3: Normalized traffic noise spectrum, British Standard Institution, London, (1998)