

Sound Transmission Loss of Double Layer Impervious Membranes with an Internal Microperforated Membrane

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ABSTRACT

Double layer impervious membranes are commonly used as building materials. This paper provides results of experiments that show the effect on sound transmission loss associated with the incorporation of a microperforated membrane (MPM) layer. Four types of MPMs with different perforation ratios are considered inserted between the two impervious membranes and the effects of the perforation ratio on the sound transmission loss of the combined system are investigated. The measurements employ two reverberation chambers and are conducted in accordance with the AS/NZS ISO 717.1 standard (2004). The test results show that an internal MPM is able to significantly increase the sound insulation of double layer impervious membranes. This double layer structure with an internal MPM is suitable for lightweight sound barriers and is promising and worthy of further study.

INTRODUCTION

Double layer membranes have been available for decades as building materials. They are highly valued for their light weight, their low carbon footprint as far as the environment is concerned, and their convenience for transportation and storage when not inflated. Although in practice portable double layer membrane structures are generally inflated, the membranes examined in this paper were not inflated.

When the acoustic environment is of interest in a building which consists of membrane structures, an understanding of the acoustic properties of these membrane structures becomes crucial. There are many publications on the acoustic properties of membrane structures (Bosmans et al. 1999; Guigou-Carter & Villot 2004; Kiyama et al. 1998), in particular their sound absorption and sound insulation. The latter is of particular interest in this paper. The experimental work of Mehra (2002) has demonstrated that, although pressurised inflatable membranes have effective sound insulation, their sound transmission losses are commonly lower than those of the more massive building materials which are used as traditional sound barriers.

Therefore, efforts have been made to enhance the sound insulation of membrane structures. Adding small weights to the membrane surfaces has been considered an effective method. Hashimoto *et al.* (1996; 1991) found that the sound insulation was improved by this strategy, especially in the low frequency range. Similarly, Yang *et al.* (2008) placed a small mass at the centre of a membrane-type acoustic meta-material. It has been indicated that the performance of this configuration could exceed the mass law and increase the sound insulation significantly in the low frequency range from 100 Hz to 1000 Hz. Zhang *et al.* (2012) furthered Yang *et al.*'s work by investigating the sound transmission losses of the same materials with different attached mass locations. The experiments and predictions demonstrated that the attached mass strongly affected the first transmission loss valley and peak in the sound transmission loss vs. frequency plot, while the second transmission loss valley depended on the properties of the membrane itself. However, adding additional small weights on the membranes, no matter if the membranes are common materials or meta-materials, increases the overall weight of the membrane structures.

Besides additional small weights, adding porous materials in the cavity between the double membrane layers is another way to improve the sound insulation of membrane structures. Porous materials are widely used as sound absorbing materials and can provide efficient sound absorption with low cost. In Vries's (2011) master thesis, various absorption materials, including mineral wool, foams, wood wool and glass wool, filled the cavities of triple layer membrane structures. From the experimental results, it can be concluded that filling the cavities between the membranes with porous materials could improve the sound insulation. These porous materials need to be sufficiently thick to maintain effective sound absorption, particularly in the low frequency range. Therefore, the overall thicknesses of the membrane structures are increased in addition to their mass. This detracts from the advantages of the membrane structures being lightweight and convenient for transportation and storage.

The microperforated panel (MPP) offers an alternative choice as a sound absorbing material. It is a thin panel (typically made of wood, plastic or metal) perforated with millions of holes with sub millimetre diameter. An MPP absorber (MPA) consists of an MPP, an acoustically rigid backing wall and an air cavity between them. The detailed research on MPPs (Maa 1975, 1998) indicates that microperforation provides high acoustic resistance and consequently MPAs can provide effective acoustic absorption, especially in the frequency range near their resonance frequency. However, traditional MPPs are rigid, therefore unsuitable for the membrane structures which are the focus of this paper.

Like MPPs, a microperforated membrane (MPM) is a thin membrane on which millions of holes with sub millimetre diameter are perforated. This material provides a significant advantage over microperforated panels due to the flexibility of the membrane. Kang & Fuchs (1999) derived expressions to predict the sound absorption of an MPM and found that they can absorb sound effectively. In Geetre's (2011) research, the sound insulation of MPMs was investigated. Experimental results confirmed their effectiveness in providing sound insulation in the high frequency range. However, the flexibility of the MPM also leads to its fragility. It is difficult to use an MPM as the surface material of a sound absorbing

or sound insulating structure where the surface is likely to be abraded.

This study aims to explore a realistic structure to improve the sound insulation of double layer membranes which maintain the advantages of being lightweight, flexible and easy to store. A double layer impervious membrane structure with an internal microperforated membrane is proposed. This proposed structure is able to maintain all the advantages of membrane structures, owing to the flexibility of the MPM. The MPM is assumed to act as a sound absorbing material in the cavity and to contribute to the enhancement of the sound insulation. This assumption is confirmed by the measurements of the sound transmission loss of the proposed structure. The details of this design and the measurements will be described in the following sections.

DOUBLE LAYER IMPERVIOUS MEMBRANE WITH AN INTERNAL MICROPERFORATED MEMBRANE

To create a membrane-type structure with enhanced sound insulation, an MPM was inserted into the cavity between two impervious membrane layers, instead of conventional porous materials. An MPM is able to absorb sound energy effectively, as is the case with the MPP. The experimental and analytical work of Kang and Fuchs (1999) on the sound absorption of microperforated membranes indicates that the impedance of the MPM depends on the impedance caused by the microperforation and the acoustic impedance of the membrane itself without perforation. Therefore, it is reasonable to presume that the internal MPM contributes to the sound insulation of membrane structures. The geometry of the model of the proposed structure is shown in Figure 1.

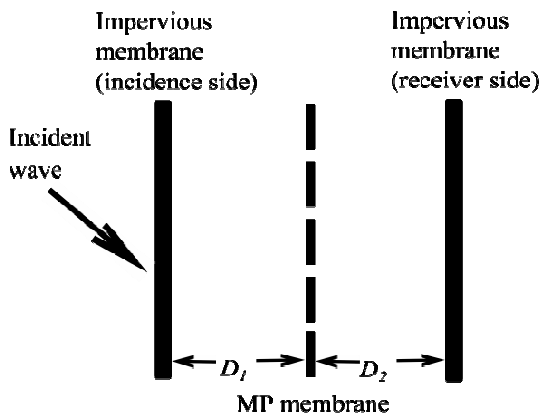


Figure 1. Geometry of the model of double layer impervious membranes with an internal microperforated membrane. Variable D_1 denotes the depth of the cavity between the impervious membrane on the incidence side and the MPM and D_2 the depth of the cavity between the MPM and the impervious membrane on the receiver side. In this study, $D_1 = D_2 = 70$ mm.

In previous research on both MPP and MPMs, it is clear that the sound absorption abilities of MPP and MPMs are dependent on the parameters that characterise the structure, such as the hole diameter, the thickness of the panel or membrane and the perforation ratio. Four types of MPMs are utilised in this study and their parameters are listed in Table 1. The measurements and the experimental results are discussed in the following sections.

Table 1. Structural parameters of MPMs tested

| Membranes tested | Material | Surface density (g/m ²) | Thickness (mm) | Perforation ratio (%) | Hole diameter (mm) |
|----------------------|----------|-------------------------------------|----------------|-----------------------|--------------------|
| MP membranes | | | | | |
| A 10 | PVC | 243.6 | 0.17 | 1.4 | 0.1 |
| A 20 | PVC | 250.3 | 0.17 | 2.5 | 0.15 |
| A 30 | PVC | 244.8 | 0.17 | 4.4 | 0.2 |
| A 40 | PVC | 250.6 | 0.17 | 0.8 | 0.5 |
| Impervious membranes | | | | | |
| Source side | PVC | 485 | 0.42 | N/A | N/A |
| Receiver side | PVC | 485 | 0.42 | N/A | N/A |

MEASUREMENTS OF SOUND TRANSMISSION LOSS

To quantify the level of sound insulation, sound transmission loss (STL) or sound reduction index is defined as

$$STL = 10 \log_{10} \left(\frac{1}{\tau} \right) = 10 \log_{10} \left(\frac{I_i}{I_t} \right), \quad (1)$$

where τ is the sound transmission coefficient, I_i the incident sound intensity and I_t the transmitted sound intensity. All the sound transmission experiments have been done in the two reverberation rooms at the University of Adelaide of dimension shown in Table 2. The sound pressure levels (SPLs) of the source room and the receiver room were averaged over three minutes at the centre frequencies of one-third octave frequency bands from 50 Hz to 10 kHz. The calculation of STLs was in accordance with the standard AS/NZS ISO 717.1 (2004). The analysis of the collected data is presented in the Experimental Results section.

Table 2. Dimension of the reverberation rooms

| Rooms | Length (m) | Width (m) | Height (m) | Surface area (m ²) | Volume (m ³) |
|---------------|------------|-----------|------------|--------------------------------|--------------------------|
| Source room | 6.085 | 5.175 | 3.355 | 135.5 | 105.6 |
| Receiver room | 6.840 | 5.565 | 4.720 | 193.2 | 179.7 |
| Test window | 1.510 | 1.005 | N/A | 1.52 | N/A |

EXPERIMENTAL RESULTS

Figure 2 shows the sound insulation properties of double layer impervious membranes with and without the MPM present. Commonly, STL is used to quantify the sound reduction of structures. When the experiments are conducted in reverberation rooms as the case is in this paper, there are errors caused by the effects of the opening in which the test samples are mounted. Theoretically, the sound transmission loss of an open window is assumed to be zero. However, Martin (2008) found that the sound transmission loss of a finite open window is not zero in practice, but has small finite value varying with frequency. This is especially problematic when small apertures are used. Therefore, the measured STL of a test sample mounted in a finite window is the sum of the test-sample STL and the open-window STL and errors occur. To avoid these errors, sound insertion loss (IL) is utilised instead of sound transmission loss (STL). Sound insertion

loss (IL) is defined (Ingard 1994) as the difference of the sound pressure levels with and without the partition at a fixed position in the receiver side. In this study, the sound insertion loss (IL) is considered as the difference of the sound transmission loss with and without test samples. Therefore, the utilisation of the sound insertion loss (IL) here can remove the effect of the open window on the test results and increase their accuracy and reliability.

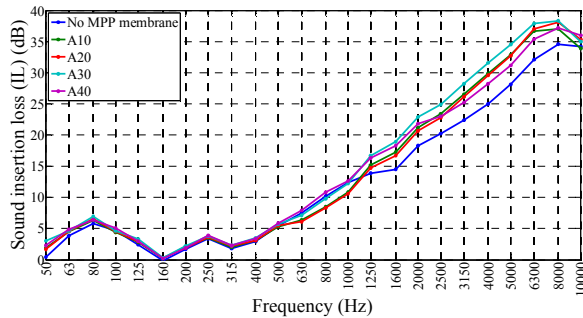


Figure 2. Sound insertion loss of double layer membrane structure with and without MPM. The blue solid curve is the sound insertion loss of double layer membrane structure without MPM; the green, red, cyan and purple solid curves are those with MPM A10, A20, A30 and A40, respectively.

It is clear in Figure 2 that the MPP insertion is able to enhance the sound insulation properties of double layer impervious membrane structures in the middle and high frequency range. In the low frequency range from 50 Hz to 500 Hz, all the curves are approximately equal. This implies that all four internal MPMs do not affect the sound insulation of the double layer membrane structure at low frequencies. From 630 Hz to 1 kHz, the insertion losses of the double layer structures with A10 (green curve) and A20 (red curve) are lower than those with no MPM (blue curve), while those with A30 (cyan curve) and A40 (purple curve) are close to those with no MPM (blue curve). The enhancement of MPP insertion starts from 1250 Hz.

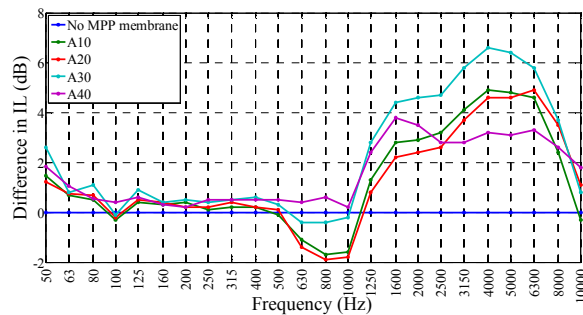


Figure 3. Increase of sound insertion loss. The blue curve is $IL_{\text{noMPP}} - IL_{\text{noMPP}}$; the green curve is $IL_{10} - IL_{\text{noMPP}}$; the red curve is $IL_{20} - IL_{\text{noMPP}}$; the cyan curve is $IL_{30} - IL_{\text{noMPP}}$; the purple curve is $IL_{40} - IL_{\text{noMPP}}$; where IL_{noMPP} denotes the sound insertion loss of double layer membrane structure without MPM insertion and IL_{10} , IL_{20} , IL_{30} and IL_{40} are those with MPM A10, A20, A30 and A40, respectively.

Figure 3 presents the differences of the ILs without the MPM and those with A10, A20, A30 and A40 membranes, respectively. From 1250 Hz to 10 kHz, the MPM A30, which has the highest perforation ratio, demonstrates the most significant enhancement of IL among all four MPMs. The maximum increase in IL from the A30 membrane is 6.6 dB at 4 kHz. In the same frequency range, the curve of A40 peaks at 3.8 dB of 1600. The curves of A10 and A20 share a similar

upward trend but the increase of A10 is greater than that of A20 from 1250 Hz to 5 kHz. The enhancement of A20 is more effective than that of A10 from 6300 Hz to 10 kHz.

It is concluded from the experimental results that the effectiveness of the proposed MPM insertion on the sound insulation of the double layer impervious membranes has been validated by the experimental results. The main effects of the MPM insertion consists of two aspects: 1) the enhancement of the MPM insertion occurs from 1250 Hz to 10 kHz; 2) the MPM with the highest perforation ratio provides the most significant increase of the IL among all MPMs considered.

DISCUSSION

This section focuses on the causes of the two effects of the MPM insertion on the sound insulation of the double impervious membranes. The effects of the membrane surface densities, the cavity between the double impervious layers and the MPM structural parameters are discussed.

Effect of the membrane surface densities

The surface densities of materials usually play a crucial part in their sound insulation properties. Based on the well-known mass law, the STL with normal incidence STL_n is expressed as (Fahy 1985)

$$STL_n = 10 \log_{10} \left[1 + \left(\frac{2\pi f \times m}{2 \rho_0 c_0} \right)^2 \right], \quad (2)$$

where m is the surface density of the membrane, f is the frequency, ρ_0 is the density of air and c_0 is the speed of sound in air. The STL with random incidence is given by (Fahy 1985)

$$STL_r = STL_n - 10 \log_{10}(0.23 \times STL_n), \quad (3)$$

The STL_r is only valid when it is over 15 dB (Ver & Beranek 2005). If there are several layers of completely decoupled materials, the overall STL is

$$STL_{\text{all}} = 10 \log_{10} \left[\frac{I_{1i}}{I_{1t}} \frac{I_{2i}}{I_{2t}} \dots \frac{I_{ni}}{I_{nt}} \right], \quad (4)$$

where I_{1i} to I_{ni} denote the incident sound intensities of each layer and I_{1t} to I_{nt} the transmitted sound intensities of each layer. According to Equation (1), Equation (4) is rewritten as

$$STL_{\text{all}} = STL_1 + STL_2 + \dots + STL_n, \quad (5)$$

where STL_1 to STL_n are the sound transmission losses of each decoupled layer.

Therefore, the STLs of the double layer impervious membranes with normal incidence can be predicted in two ways. Firstly, when the double layer structure is assumed to act like one layer with doubled mass, the STL is given by

$$STL_{\text{DMM(mass law)}} = 10 \log_{10} \left[1 + \left(\frac{2\pi f \times 2 \times m}{2 \rho_0 c_0} \right)^2 \right]. \quad (6)$$

This model is named as the doubled mass model (DMM).

Secondly, if the double membrane layers are assumed to be completely decoupled (CDM), two models are developed based on Equation (5). Let $STL_{\text{single(mass law)n}}$ denote the prediction of the sound transmission of the single layer impervious membrane with normal incidence. Equation (5) could be rewritten as

$$STL_{CDM(mass\ law)1} = 2 \times STL_{single(mass\ law)n}$$

$$= 20 \times \log_{10} \left[1 + \left(\frac{2\pi f \times m}{2 \rho_0 c_0} \right)^2 \right]. \quad (7)$$

Equation (7) is the prediction of the STL with normal incidence and for the random incidence correction it is necessary to utilise Equation (3). Alternatively, we could obtain the STL of the single layer impervious membrane with random incidence $STL_{single(mass\ law)r}$ directly by using Equations (2) and (3). Then the STL of the double layer structure is given by

$$STL_{CDM(mass\ law)2} = 2 \times STL_{single(mass\ law)r}, \quad (8)$$

where

$$STL_{single(mass\ law)r} = STL_{single(mass\ law)n} - 10 \log_{10}(0.23 \times STL_{single(mass\ law)n}). \quad (9)$$

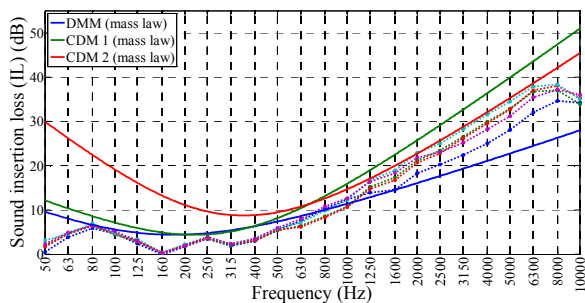


Figure 4. Prediction of the sound transmission loss of the double layer impervious membranes based on mass law (random incidence). The blue dotted curve is the experimental results of the sound insertion loss of double layer membrane structure without MPM; the green, red, cyan and purple dotted curves are those with MPM A10, A20, A30 and A40, respectively. The blue solid curve presents the DMM prediction of the sound transmission loss of double layer impervious membranes. The green and red solid curves are the predictions using the two CDM methods.

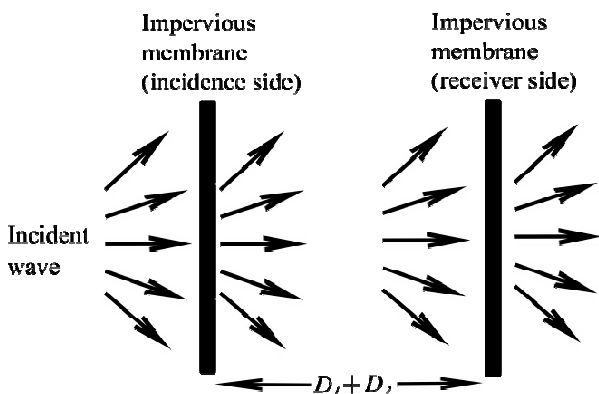


Figure 5. Sound field of the double layer impervious membranes without the MPMs.

Figure 4 presents the STL prediction of the double layer impervious membranes using the DMM method and the two CDM methods. As can be seen in Figure 4, with the A30 MPM present, in the middle and high frequency range the double layer membrane structure approaches the theoretically maximum IL offered by the two completely decoupled single layer membranes. The prediction results of the second CDM method have a great agreement with the experimental results

from 1250 Hz to 6300 Hz. This implies that the two impervious membranes act like two completely decoupled membranes in a diffuse field above 1250 Hz. As shown in Figure 5, without the MPMs the transmitted sound wave from the first impervious membrane could be considered as randomly incident upon the surface of the second impervious membrane.

When the MPMs are considered, a similar prediction of the STL of the double layer impervious membranes with the internal MPMs could be done using the DMM and CDM method. However, all four of the MPMs are lightweight and have almost the same surface densities. A comparison of the surface densities of the MPMs to those of the impervious membranes is shown in Table 2. Although the surface densities of the MPMs are almost identical, the experimental results show different STL enhancement of the structure with different MPM insertions. MPM A30 provides the most significant enhancement of IL amongst all four MPMs. This implies that the enhancement of the sound insulation is due to the differences in the perforation ratios of the MPMs.

Effect of the impedance of the impervious membranes

The sound transmission through a material is related to its acoustic impedance. The sound transmission coefficient of the membrane is expressed as (Kinsler et al. 1999)

$$\tau = \frac{I_t}{I_i} = \frac{4Z}{(1+Z)^2}, \quad (10)$$

where Z is the normalised acoustic impedance of the material. Hence, the STL can be predicted according to the definition of the STL and Equation (1) and is given by

$$STL = 10 \log_{10} \left[\frac{(1+Z)^2}{4Z} \right]. \quad (11)$$

Note that this STL is for normal incidence and the STL with random incidence can be obtained by Equation (3).

For a tension-free impervious membrane of infinite size, the normalised acoustic impedance is given by (Kang & Fuchs 1999)

$$Z_{impervious} = \frac{R+j\omega m}{\rho_0 c_0}, \quad (12)$$

where R is the acoustic resistance depends on the mounting conditions of the membrane as well as its construction, ω is the angular frequency and equal to $2\pi f$. Although the surface density is easily determined, the acoustic resistance offered by the impervious membrane is dependent on both the fabric construction and mounting arrangement therefore must be experimentally determined. For the impervious membrane tested, this was found to be $1500 \text{ Pa}\cdot\text{s}/\text{m}^3$ (see Appendix).

The STL prediction of the double layer impervious membranes can be calculated using the DMM and CDM methods, as is the case with the STL prediction using the mass law. In the DMM prediction, Equation (12) becomes

$$Z_{double\ impervious} = 2 \left(\frac{R+j\omega m}{\rho_0 c_0} \right). \quad (13)$$

Therefore, the STL using the DMM method is expressed as

$$STL_{DMM(impedance)} = 10 \log_{10} \left[\frac{\left(1 + 2 \left(\frac{R+j\omega m}{\rho_0 c_0} \right) \right)^2}{8 \left(\frac{R+j\omega m}{\rho_0 c_0} \right)} \right]. \quad (14)$$

Equation (3) is also used to obtain the random incidence correction.

Based on the CDM method, the sound transmission loss of a single layer impervious membrane is given by

$$STL_{\text{single(impedance)}_n} = 10 \log_{10} \left[\frac{\left(1 + \frac{R+j\omega m}{\rho_0 c_0}\right)^2}{4 \left(\frac{R+j\omega m}{\rho_0 c_0}\right)} \right]. \quad (15)$$

As is the case when the mass law is considered, there are also two ways to calculate the STL of the double layer structures based on the CDM method. Letting the $STL_{\text{single(mass law)}_n}$ in Equation (7) be $STL_{\text{single(impedance)}_n}$ and the STL using CDM method is obtained as

$$STL_{\text{CDM(impedance)}_1} = 20 \log_{10} \left[\frac{\left(1 + \frac{R+j\omega m}{\rho_0 c_0}\right)^2}{4 \left(\frac{R+j\omega m}{\rho_0 c_0}\right)} \right]. \quad (16)$$

Note that this prediction result is the STL with normal incidence and to obtain that with random incidence, Equation (3) is utilised as the last step. The other possibility is to calculate the STL of the single layer impervious membrane with random incidence and to double the calculation results. The prediction result is expressed as

$$STL_{\text{CDM(impedance)}_2} = 2 \times STL_{\text{single(impedance)}_r}, \quad (17)$$

where

$$STL_{\text{single(impedance)}_r} = STL_{\text{single(impedance)}_n} - 10 \log_{10}(0.23 \times STL_{\text{single(impedance)}_n}). \quad (18)$$

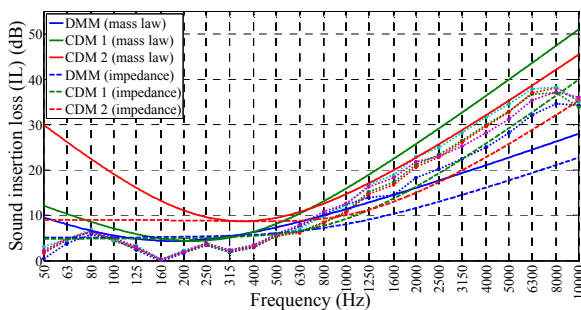


Figure 6. Prediction of the sound transmission loss of the double layer impervious membranes using the membrane impedance (random incidence). The blue dotted curve is the experimental results of the sound insertion loss of double layer membrane structure without MPM; the green, red, cyan and purple dotted curves are those with MPM A10, A20, A30 and A40, respectively. The blue, green and red solid curves present the DMM and CDM predictions of the sound transmission loss of double layer impervious membranes based on the mass law. The blue, green and red dashed curves are those predictions using the membrane impedance.

The STL results are shown in Figure 6 and are compared to the three predictions based on the mass law. As can be seen in Figure 6, the prediction of the STL using the first CDM method with the membrane impedance has good agreement with the experimental result of the IL of the double layer impervious membranes. This probably indicates that the transmitted sound wave from the first impervious membrane could be constrained by the MPMs (due to the perforation) and be normally incident on the surface of the second impervious membrane. Figure 7 presents the sound field of this

model. This result is similar to that observed for double layer walls with fibrous absorber in the wall space, where “the effect of the sound absorbing material in the airspace results in refraction of the oblique-incidence sound toward the normal” (Beranek & Ver 1992, p302).

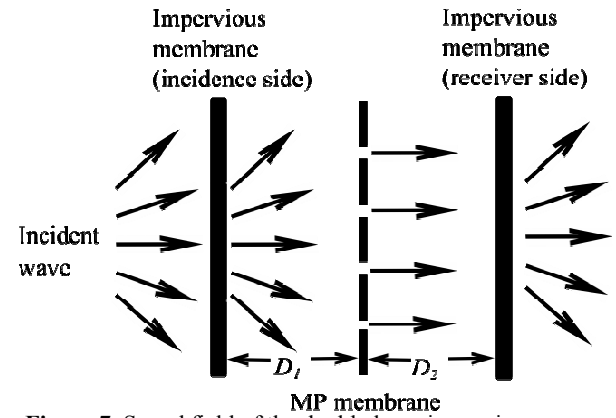


Figure 7. Sound field of the double layer impervious membranes with the internal microperforated membrane.

Effect of the cavity depth between the double impervious membrane layers

Note that the cavity depth $D_1 + D_2$ is equal to 140 mm and $D_1 = D_2$. The frequency of the fundamental acoustic cavity mode f_{cavity} is expressed as

$$f_{\text{cavity}} = \frac{c_0}{2 \times (D_1 + D_2)}, \quad (19)$$

where c_0 is the speed of sound in air. For the configuration tested, $f_{\text{cavity}} = 1225$ Hz which is exactly the frequency where the IL shown in Figures 2 to 3 shows a significant improvement due to the presence of the MPMs. This implies that the improvement with the MPM starts from the fundamental acoustic frequency of the cavities between the impervious membranes. Therefore, the benefit delivered by the MPM is associated with damping of the cavity modes that exist between the two impervious membranes.

Effect of the MPM structural parameters

As mentioned previously, both the perforation and the flexibility of the MPM contribute to its sound absorption. When the flexibility is included, the impedance of the MPM can be as (Kang & Fuchs 1999)

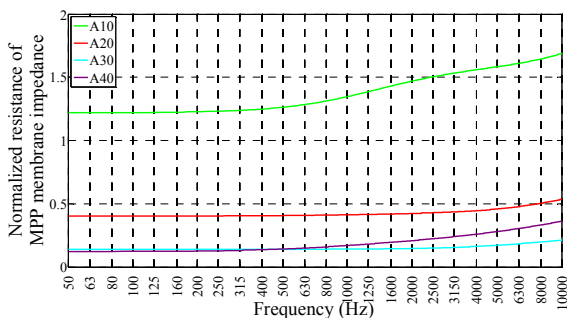
$$Z_{\text{MPM}} = \frac{Z_{\text{MPP}} \times Z_{\text{M}}}{Z_{\text{MPP}} + Z_{\text{M}}}, \quad (20)$$

where $Z_{\text{M}} = R + j\omega m_m$, m_m is the surface density of the MPM and Z_{MPP} denotes the normalised acoustic impedance related to the perforation. The variable Z_{MPP} could be considered as the normalised acoustic impedance of the MPP which has the same structural parameters with the MPM. The normalised acoustic impedance of MPP developed by Maa (1975) is

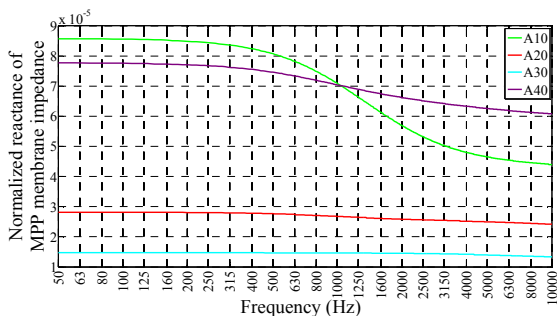
$$Z_{\text{MPP}} = \frac{\sqrt{2}\mu k}{pd} + \frac{j\omega\rho_0}{p} 0.85d + \frac{j\omega\rho_0 t}{p} \left[1 - \frac{2}{k\sqrt{-j}} \frac{J_1(k\sqrt{-j})}{J_0(k\sqrt{-j})} \right]^{-1}, \quad (21)$$

where $k = r_0\sqrt{\rho_0\omega/\mu}$ (*i.e.* the MPP constant), r_0 is the radius of the hole, J_0 is the Bessel function of the zeroth order and J_1 the Bessel function of the first order, t is the thickness of the panel or membrane, p denotes the perforation ratio and

μ is the air viscosity coefficient. The predictions of the MPM acoustic impedances are shown in Figure 8. The MPM A30 has the lowest resistance and reactance above 1250 Hz among the four MPMs considered here.



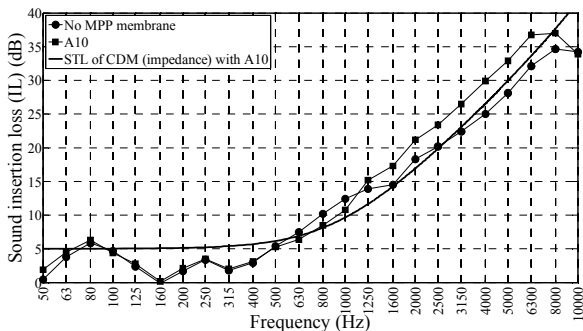
(a) Normalised resistance of MPMs



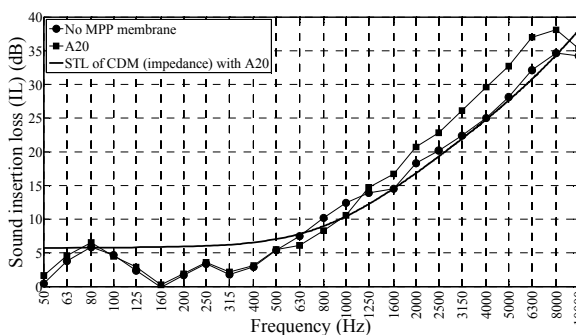
(b) Normalised reactance of MPMs

Figure 8. Normalised resistance and reactance of MPMs. The green, red, cyan and purple curves present the normalised resistances and reactance of MPM A10, A20, A30 and A40, respectively.

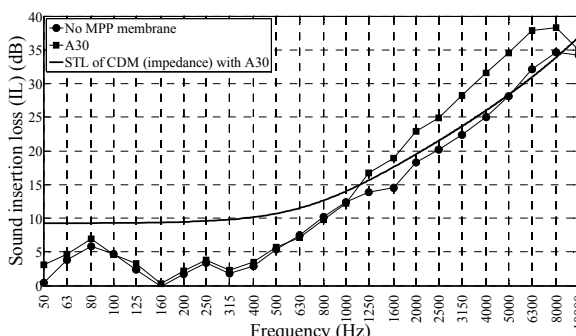
Using the completely decoupled model, the STLs of the double layer impervious membranes with the MPM insertion are predicted. Figure 9 presents the comparison between the experimental results and the prediction of the CDM method with Equation (20). Although the predictions are slightly lower than the experimental results, their main trends are very similar. The differences between the predictions and the experiments are caused by several aspects. The size of both the impervious membranes and the MPMs is assumed to be infinite when calculating the acoustic impedances. The stiffness of all the membranes is also neglected, as are the resonances of the enclosed cavities between the membranes. These will be investigated in the future research.



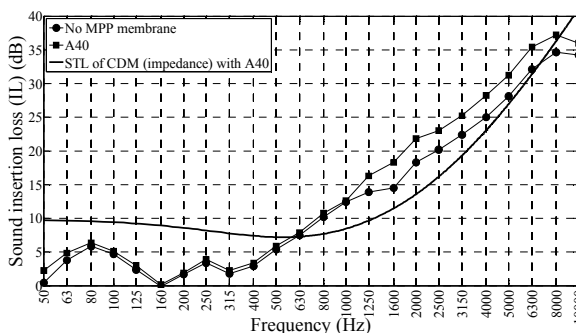
(a) With the internal MPM A10



(b) With the internal MPM A20



(c) With the internal MPM A30



(d) With the internal MPM A40

Figure 9. Prediction of the STL of the double layer impervious membranes with the internal MPMs using the membrane impedance and the CDM method (random incidence).

In general, the insertion of MPMs can increase the sound insulation properties of the double layer impervious membranes above the fundamental acoustic cavity mode, from 1250 Hz to 10 kHz. The surface densities and the sound absorption abilities of the MPMs contribute to the enhancement of the sound insulation. The improvement in the sound insulation of the double impervious membranes with the MPM insertion is related to the structural parameters of the MPMs, especially the perforation ratio. With the advantages mentioned previously of being lightweight, flexible and easy to store, the proposed double layer membrane structure incorporating an internal MPM is promising and worthy of further study.

CONCLUSIONS

A design of double layer impervious membranes with an internal MPM is proposed in this study to enhance the sound insulation of the double layer structure. Based on the previous research, it is assumed that the MPM could act as an internal sound absorbing layer and enhance the sound insula-

tion of the double layer structure. This assumption is validated by the test results. It is shown that the MPM contributes little to the transmission loss below the fundamental cavity mode (formed between the two impervious membranes). However, above the fundamental acoustic mode of the cavity, the transmission loss is increased significantly and remains enhanced over the frequency range tested. The mechanism for the enhancement is likely to be due to the increased damping of the acoustic modes within the cavity associated with the acoustic resistance across the inserted MPM. The proposed structure meets the needs of lightweight sound barriers. Further studies will be done on the detailed effects of the parameters of the MPM on the sound insulation of double layer impervious membrane structures.

REFERENCES

AS/NZS ISO 717.1 2004, *Acoustics-Rating of sound insulation in buildings and of building elements Part 1: Airborne sound insulation*.

Beranek, LL & Ver, IL 1992, *Noise and vibration control engineering principles and applications*, John Wiley & Sons Inc, p 302.

Bosmans, I, Lauriks, W, Lombaert, G, Mermans, J & Vermeir, G 1999, 'Sound absorption of stretched ceilings with an impervious synthetic membrane', *Journal of the Acoustical Society of America*, vol. 106, pp. 233-239.

Fahy, FJ 1985, *Sound and Structural Vibration: Radiation, Transmission and Response*, 1st edn, Academic Press.

Geetere, L 2011, *Bouwakoestische prestaties van meerlaagse membraansystemen*, Wetenschappelijk en Technisch Centrum voor het Bouwbedrijf.

Guigou-Carter, C & Villot, M 2004, 'Study of acoustically efficient membrane based multilayered systems', *Inter-Noise2004*, pp. 1-8.

Hashimoto, N, Katsura, M & Nishikawa, Y 1996, 'Experimental study on sound insulation of membranes with small weights for application to membrane structures', *Applied Acoustics*, vol. 48, no. 1, pp. 71-84.

Hashimoto, N, Katsura, M, Yasuoka, M & Fujii, H 1991, 'Sound insulation of a rectangular thin membrane with additional weights', *Applied Acoustics*, vol. 33, no. 1, pp. 21-43.

Ingard, KU 1994, *Notes on Sound Absorption Technology*, Poughkeepsie, NY: Noise Control Foundation, 1994.

Kang, J & Fuchs, H 1999, 'Predicting the absorption of open weave textiles and micro-perforated membranes backed by an air space', *Journal of Sound and Vibration*, vol. 220, no. 5, pp. 905-920.

Kinsler, LE, Frey, AR, Coppens, AB & Sanders, JV 1999, *Fundamentals of acoustics*, 4 edn, Wiley-VCH.

Kiyama, M, Sakagami, K, Tanigawa, M & Morimoto, M 1998, 'A basic study on acoustic properties of double-leaf membranes', *Applied Acoustics*, vol. 54, no. 3, pp. 239-254.

Maa, DY 1975, 'Theory and design of microperforated panel sound absorbing constructions', *Scientia Sinica*, vol. 18, no. 1, pp. 55-71.

Maa, DY 1998, 'Potential of microperforated panel absorber', *Journal of the Acoustical Society of America*, vol. 104, pp. 2861-2866.

Martin, B 2008, 'What is the sound transmission loss of an open window?', Australian Acoustical Society. Conference (2008: Geelong, Victoria).

Mehra, SR 2002, 'Aufblasbarer schallschutz mit bauteilen aus folien und membranen', *Bautechnik*, vol. 79, pp. 794-797.

Ver, I & Beranek, L 2005, *Noise & Vibration Control Engineering: Principles & Applications*, John Wiley & Sons.

Vries, J 2011, 'Triple-layer membrane structures sound Insulation performance and practical solutions', Faculty of Civil Engineering and Geo Sciences, Master's thesis thesis, Master thesis, Delft University of Technology.

Yang, Z, Mei, J, Yang, M, Chan, NH & Sheng, P 2008, 'Membrane-type acoustic metamaterial with negative dynamic mass', *Physical Review Letters*, vol. 101, no. 20, p. 204301.

Zhang, Y, Wen, J, Xiao, Y, Wen, X & Wang, J 2012, 'Theoretical investigation of the sound attenuation of membrane-type acoustic metamaterials', *Physics Letters A*, pp. 1489-1494.

APPENDIX: CALCULATION OF ACOUSTIC RESISTANCE OF THE MEMBRANES

The variable R in Equation (12) denotes the acoustic resistance of the membrane and is dependent on the mounting conditions. Since it is difficult to measure R in the STL experiments, the prediction of the STL of the single layer impervious membrane is utilised to determine its value. Figure 10 is the prediction for the STL of the single layer impervious membrane using its acoustic impedance. Three different values of R were used and R equal to 1500 provided the best agreement between the predicted and experimental results. Additionally, when the value of R is varied, only the low frequency response is affected. This trend is realistic because the boundary conditions should mainly affect the STL in the low frequency range. Therefore, since the mounting conditions of all the impervious membranes and the MPMs are consistent, R is assumed to be 1500 Pa·s/m³ in all the calculation methods presented.

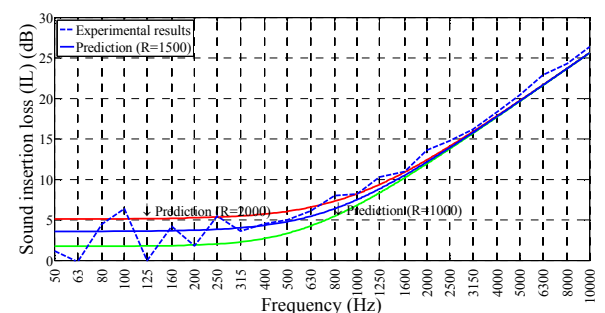


Figure 10. Comparison of the prediction and the experimental results of the STLs of the single layer impervious membrane. The dashed line is the experimental result, the blue solid curve is the prediction based on the membrane impedance when R is equal to 1500 Pa·s/m³. The green and red solid curves are those when R are equal to 1000 Pa·s/m³ and 2000 Pa·s/m³, respectively.