Transmission Loss Analysis of Simple Expansion Tube with Micro – perforated Cylindrical Panel

MI Alisah\textsuperscript{1}, LE Ooi\textsuperscript{1*}, Z M Ripin\textsuperscript{1}, CS Ho\textsuperscript{2}, AF Yahaya\textsuperscript{2}

\textsuperscript{1}TheVibrationLab, School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia.
\textsuperscript{2}Dyson Manufacturing Sdn Bhd, Plot 208, Jalan Cyber 14, Senai Industrial Estate IV, 81400 Senai, Johor, Malaysia.

\textsuperscript{*}Corresponding author: ooiluean@usm.my

Abstract. This study presents a development of simple expansion tube attach with micro-perforated cylindrical panel (MPCP) to improve the acoustic performance. A simulation based boundary element method (BEM) was carried out using PLM Simcenter 3D. The model was constructed in three dimensional in CAD NX Nastran 12 application and then meshing into small elements. The acoustic properties and boundary condition were defined for the simulation purpose. The model was then fabricated by 3D printer material and verified with the transmission loss measurement utilized the two-load method. In comparison, the transmission loss of simple expansion tube with and without MPCP show a good agreement of BEM analysis and experimental result. The addition of the MPCP inside the expansion tube improved the transmission loss by 2-10 dB in wider frequency band compared to the simple expansion tube. Finally, the air cavity depth of the expansion tube is varied to study it effect. Its showed that, the larger air cavity depth caused the transmission loss peak shift to a lower frequency range.

1. Introduction
Simple expansion tubes are widely used in vehicle and industrial for a noise control application. The noise control can be accomplished by applying a porous or fibrous materials inside the muffler [1,2]. However, for the case of high air flux application and clean absorbent, it is not possible to use fibrous or porous materials [3]. A micro-perforated panel (MPP) is a suitable candidate in this kind of application where it can be used inside the simple expansion tube to boost the transmission loss at the desired frequency. Subsequently, MPP is considered to be non-combustible and recyclable, and is suitable for applications in a high temperature environment [4]. Typically, MPP it is made of a metal plate with the perforations diameter in sub-millimeters, and where the air cavity between the plate and the backing wall forms the absorber system [3].

The MPP has been extensively studied by previous researchers. Some have proposed proposed double layer MPP [5,6] and triple layer MPP [7] in order to improve the acoustic performance. However, this flat panel-like shape restricts their practical use in actual rooms or buildings. To overcome these limitations, micro-perforated cylindrical panel (MPCP) have been proposed [8]. The study shows that the noise attenuation of the muffler improved significantly with a broadens frequency after integrating the MPCP.

Transmission loss (TL) is an important parameter for the evaluating the performance of the muffler. TL is studied the discrepancy in the sound power between the incident wave entering and the transmitted...
wave exiting the muffler when the muffler termination is anechoic [9]. In this study, TL is compute both
by simulation through BEM analysis and measurement of two-load method.

The MPCP was integrated inside the simple expansion chamber tube and the result on the sound
transmission loss was simulated and validated. The effect of air cavity depth of the MPCP was also studied
in order to determine its TL performance.

2. Theoretical Background

TL measurement via two-load approach is accomplished by performing the measurements with two
different conditions at the end of the tube, which are rigid and anechoic termination as shown in figure 1.
As shown in Figure 1, the sound signal is generated by the sound source at the end of tube, and four
microphones are positioned along the tube with the simple expansion tube placed between 2nd and 3rd
microphones. The resulting sound field in the tube consists of one component travelling toward the
specimen and one reflected component. The sound pressure at the microphone 1, 2, 3, and 4 can be
expressed as [3]

\[ P_1 = A e^{i(\omega t - kl_1)} + B e^{i(\omega t + kl_1)} \]  
\[ P_2 = A e^{i(\omega t - kl_2)} + B e^{i(\omega t + kl_2)} \]  
\[ P_3 = C e^{i(\omega t - kl_3)} + D e^{i(\omega t + kl_3)} \]  
\[ P_4 = C e^{i(\omega t - kl_4)} + D e^{i(\omega t + kl_4)} \]

where A and B are amplitudes of the incident and reflected sound wave respectively at the inlet tube, C and
D are amplitudes of the incident and reflected sound wave respectively at the outlet tube, \( l_1 \) is distance from
the specimen to microphone 1, \( l_2 \) is distance from the specimen to microphone 2, \( l_3 \) is distance from the
specimen to microphone 3, \( l_4 \) is distance from the specimen to microphone 4, k is wave number, and t is
the time.

![Schematic of two-load transmission loss measurement](image)

Figure 1. Schematic of two-load transmission loss measurement

The amplitudes of sound wave can be expressed in terms of the sound pressures (\( P_1, P_2, P_3, P_4 \)) for the four
microphones and shown as below
There are two sets amplitude of the sound waves are obtained as the two-load method of transmission loss measurement is performed with two different conditions as mention earlier. By inserting and solving the equation (5) to (8), the transmission loss coefficient, $\tau$, for the expansion tube [10] can be calculated by equation below

$$
\tau = \frac{A_1D_2 - A_2D_1}{C_1D_2 - C_2D_1}
$$

where $A_1$, $C_1$, and $D_1$ are the amplitude sound wave with rigid termination, and $A_2$, $C_2$, and $D_2$ are the amplitude sound wave with anechoic termination. Finally, the sound transmission loss of the specimen measured in the two-load method can be obtained in unit dB as equation (10) once the TL coefficient is determined.

$$
TL = -20\log_{10}(||\tau||)
$$

An ordinary MPP configuration and its equivalent electro-acoustical circuit is shown in Figure 2. As illustrated in Figure 2, there are four main design parameter in modelling the MPP which are the perforation diameter $d$, the plate thickness $t$, the perforation ratio $\sigma$, and the air cavity depth $D$.

![MPP configuration](image)

**Figure 2.** MPP configuration (a) electro-acoustical circuit equivalent (b) [6]

According to Maa [11], a perforation can be regarded as a short tube, and the specific acoustic impedance of a short tube is expressed as
\[ Z_1 = R + j\omega M \]  

(11)

where

\[ R = \frac{32nt}{d^2} \left[ \sqrt{\frac{k^2}{32} + \frac{\sqrt{2k}d}{8t}} \right] \]  

(12)

\[ \omega M = \omega \rho_0 t \left[ 1 + \frac{1}{\sqrt{9 + \frac{k^2}{2}}} + 0.85 \frac{d}{t} \right] \]  

(13)

\[ k = \frac{d}{2} \sqrt{\frac{\omega \rho_0}{n}} \]  

(14)

where \( R \) and \( \omega M \) are the specific acoustic resistance and specific acoustic reactance of the perforations respectively. While \( n \) is the dynamic viscosity, \( \rho_0 \) is the time-average density of air and \( \omega = 2\pi f \) is the angular frequency.

3. Methodology
The simple expansion tube is simulated using BEM analysis and then fabricated using 3D printer material based on the layout in figure 3 (a). The main body diameter \( D_e \) is 54 mm and 100 mm in length \( L \). The diameters for the inlet \( d_i \) and outlet tubes \( d_o \) are 34.8 mm. The application of MPCP inside the expansion tube that linked the inlet and outlet tube shows in Figure 3 (b).

(a)

(b)

Figure 3. Schematic diagram of simple expansion tube a) without MPCP b) with MPCP
The simple expansion tube without and with MPCP is later fabricated by 3D material with dimension as shown in figure 3. A parameter used for MPCP applied inside the simple expansion tube is listed in Design type 1 as shown in Table 1. Next, the design of simple expansion chamber with attached MPCP was used for parametric study. The perforation hole diameter, panel thickness and perforation ratio are remaining constant for the parametric study. The effect of the air cavity depth of the expansion tube with MPCP is studied for depth of 6 mm, 9 mm, 12 mm, and 16 mm respectively. Table 1 lists the parameter for four design of the expansion tube.

Table 1. Design parameter for the parametric study of simple expansion tube with attached MPCP

| Design type | 1   | 2   | 3   | 4   |
|-------------|-----|-----|-----|-----|
| Hole diameter (mm) | 0.9 | 0.9 | 0.9 | 0.9 |
| Panel thickness (mm) | 1.5 | 1.5 | 1.5 | 1.5 |
| Perforation ratio (%) | 1.8 | 1.8 | 1.8 | 1.8 |
| Air Cavity Depth (mm) | 6   | 9   | 12  | 16  |

3.1 Acoustic Simulation and transmission loss measurement

The acoustical simulation model is developed for both model by PLM Simcenter 3D based boundary element method (BEM). The result was then compared with experimental transmission loss measurement for validation. The geometry of the models was constructed in three dimensions in the CAD application environment using NX Nastran and then meshing into small element as illustrated in Figure 4.

Figure 4. The meshing model of the MPCP in PLM Simcenter 3D.

In this simulation, the sound speed is 340 ms$^{-1}$ and the mass density is 1.225 kgm$^{-3}$. Two boundary conditions are applied at the inlet and outlet of the expansion tube. The noise source was modelled as the acoustic panel normal velocity with 1 ms$^{-1}$ at the inlet of the expansion chamber [12,13]. The anechoic termination condition at the outlet tube of model can be achieved by inserting the acoustic absorber impedance ($\rho_0 c$) value of 416.5 kgm$^{-2}$ s$^{-1}$ [14]. To compute TL, the sound pressure level of the inlet and outlet tubes of the model was determined based on the point set mesh primitive. The MPCP was defined as an absorbent panel with the impedance values determined based on equation (11) - (14), and fed into the simulation object container as a transfer admittance section of the PLM Simcenter 3D. The transmission loss measurement is based on determination of the transfer matrix using the two-load method as illustrated in Figure 1. Next, transmission loss measurement was set up as illustrated in Figure 1. The measurement set up consisted of four GRAS 46AE microphones, a speaker, a LMS SCADAS data acquisition unit, and a computer with the analysis software which is LMS Test Lab Sound Transmission Loss using impedance tube. The main tube is in the shape of cylinder, with diameter of 34.8 mm and 3 mm wall thickness.
4. Result and Discussion

Figure 5 shows the TL of the simple expansion tube for the frequency from 200 Hz to 5000 Hz. There are two transmission loss curves plotted which are BEM analysis and two-load measurement. The BEM simulation result is represented by black dotted line and solid red line is the measurement result. For frequency range of 400 Hz to 4000 Hz, it is realized that the two transmission loss curves have similar pattern where a dome-shaped with TL peak and valley observed at interval frequency. From this graph, the TL of BEM analysis maintained the same peak level of 3 dB. The transmission loss pattern obtained in this study is comparable and follow a similar trend as a results produced in the literature [14,15]. For frequency of 4000 Hz and above the peaks are slightly higher and shifted to the right for the measurement result. This is because of the inaccuracy of parameters, such as air density as reported in the study of Andersen (2008) [16]. In general, both results from the BEM analysis and two load measurement are comparatively similar and well correlated and BEM approach is considered valid for the simulation of TL of the expansion tube.

![Figure 5. Transmission loss of a simple expansion tube.](image-url)

Figure 6 shows the TL of BEM analysis and measurement results for both models. From the graph, the BEM analysis is represented by black dotted line curve for simple design, solid red dash line curve for expansion tube with MPCP, solid red line is the measurement result of simple design and solid blue line is measurement result of simple expansion tube with MPCP. It observed that the addition of the MPCP inside the expansion tube leads to the transmission loss improved by 2-10 dB compared to the simple expansion tube. The second hump and third existed with the peak transmission loss value of 12 dB and 14 dB respectively. Above 4000 Hz, it was found that the TL curve became wider and the humps were smoother. In overall, it is found that the transmission loss curve after applying the MPCP produces a higher peak over a wide frequency band compared to the simple expansion tube. The phenomenon is because the micro-perforated inside the expansion tube is playing an important role to increase the noise absorption for the overall investigation frequency range [13].
Figure 6. Transmission loss after applying MPCP

Figure 7 shows the parametric study for four different air cavity depth which are 6 mm, 9 mm, 12 mm and 16 mm. The result shows that as the air cavity depth of the MPCP is increased, it will produce higher transmission loss for the frequency range 400-1800 Hz. It is also observed that the peak attenuation of the transmission loss is shifted to low frequency as the air cavity depth value is increased. As reported in the literature by Li [17], the transmission loss pattern obtained in this BEM analysis was comparable the characteristic of the micro-perforated sound absorber, where the larger air cavity depth causes the transmission loss peak to shift to a lower frequency range.

Figure 7. Transmission loss of different air cavity depth of the expansion tube attached with MPCP.

5. Conclusion
The study of the effect of MPCP on the simple expansion tube has been done by acoustic simulation using PLM Simcenter 3D and two load method measurement. The result of both methods are comparatively similar and well correlated. The BEM analysis was able to simulate the expansion tube performance accurately for the higher frequency range. From the study, it is found that the addition of the MPCP inside the expansion tube leads to the transmission loss improved by 2-10 dB with a wider frequency band due to the effect of MPCP.
inside the expansion tube. Subsequently, the air cavity depth of the expansion tube also affected the TL curve.

6. References

[1] Delany, M. E., & Bazley, E. N. (1970). Acoustical properties of fibrous absorbent materials. *Applied acoustics*, 3(2), 105-116.

[2] Na, Y., Lancaster, J., Casali, J., & Cho, G. (2007). Sound absorption coefficients of micro-fiber fabrics by reverberation room method. *Textile Research Journal, 77*(5), 330-335.

[3] Tan, W. H., & Mohd Ripin, Z. (2013). Analysis of exhaust muffler with micro-perforated panel. *Journal of Vibroengineering, 15*(2), 558-573.

[4] Wu, M. Q. (1997). Micro-perforated panels for duct silencing. *Noise Control Engineering Journal, 45*(2), 69-77.

[5] Sakagami, K., Morimoto, M., & Koike, W. (2006). A numerical study of double-leaf microperforated panel absorbers. *Applied acoustics, 67*(7), 609-619.

[6] Sakagami, K., Nakamori, T., Morimoto, M., & Yairi, M. (2009). Double-leaf microperforated panel space absorbers: A revised theory and detailed analysis. *Applied Acoustics, 70*(5), 703-709.

[7] Sakagami, K., Yairi, M., & Morimoto, M. (2010). Multiple-leaf sound absorbers with microperforated panels: an overview. *Acoustics Australia, 38*(2), 76-81.

[8] Sakagami, K., Oshitani, T., Yairi, M., Toyoda, E., & Morimoto, M. (2012). An experimental study on a cylindrical microperforated panel space sound absorber. *Noise Control Engineering Journal, 60*(1), 22-28.

[9] Tao, Z., & Seybert, A. F. (2003). A review of current techniques for measuring muffler transmission loss. *SAE transactions*, 2096-2100.

[10] Yousefzadeh, B., Mahjoob, M., Mohammadi, N., & Shahsavari, A. (2008). An experimental study of sound transmission loss (STL) measurement techniques using an impedance tube. *Journal of the Acoustical Society of America, 123*(5), 3119.

[11] Maa, D. Y. (1975). Theory and design of microperforated panel sound-absorbing constructions. *Sci. Sin., 18*, 55-71.

[12] Vasile, O. (2010). Transmission Loss Assessment for a Muffler by Boundary Element Method Approach. *Analele Universitatii’Eftimie Murgu’, 17*(1).

[13] Tan, W. H., & Mohd Ripin, Z. (2013). Analysis of exhaust muffler with micro-perforated panel. *Journal of Vibroengineering, 15*(2), 558-573.

[14] Tan, W. H., Khor, T. S., & Zunaidi, N. H. (2016). Development of acoustical simulation model for muffler. *International Journal of GEOMATE, 11*(2), 2385-2390.

[15] Potente, D. (2005, November). General design principles for an automotive muffler. In *Proceedings of ACOUSTICS* (pp. 153-158).

[16] Andersen, K. S. (2008). Analyzing muffler performance using the transfer matrix method. In *Comsol Conference*.

[17] Li, G., & Mechefske, C. K. (2010). A comprehensive experimental study of micro-perforated panel acoustic absorbers in MRI scanners. *Magnetic Resonance Materials in Physics, Biology and Medicine, 23*(3), 177-185.

Acknowledgements

This study was completed with financial support from the Collaborative Research in Engineering, Science and Technology (CREST) research grant (304.PMEKANIK.6050379). Support from the Universiti Sains Malaysia (USM) and Dyson Development Sdn Bhd is also greatly acknowledged. The authors would also like to express their sincere gratitude to Mr. Baharom Awang and Mr. Wan Muhammad Amri for their assistance in the experimental work in the Vibration Lab.