APPLICATION OF MICRO PERFORATED PANEL ON THE SAFETY EARMUFF

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DECLARATION

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LIST OF ABBREVIATIONS

3D	3 Dimensional
ATB	Acoustic Test Bench
ATF	Acoustic Test Fixture
DOSH	Department of Occupational Safety and Health, Malaysia
HVAC	Heating, Ventilation and Air Conditioning
MEMS	Microelectromechanical System
MPP	Micro-perforated Panel
MPP-PHP	MPP-based Personal Hearing Protection
NEL	Noise Exposure Level
NIHL	Noise-Induced Hearing Loss
OSHA	Occupational Safety and Health Administration
PHP	Personal Hearing Protection
SAC	Sound Absorption Coefficient
STL	Sound Transmission Loss

ABSTRAK

Alat penutup telinga keselamatan adalah pelindung pendengaran peribadi yang biasa digunakan dalam industri untuk melindungi pekerja daripada kehilangan pendengaran. Salah satu kelemahan penutup telinga keselamatan adalah ia tidak sesuai digunakan di persekitaran yang panas, lembap, atau berdebu. Lapisan busa penutup telinga keselamatan, yang terbuat dari bahan berliang, cenderung hancur lebih masa. Panel berlubang mikro (MPP) dicadangkan sebagai pengganti bahan lapisan busa kerana ciri akustik, tahan lama dan ringan. Hasil eksperimen menunjukkan bahawa MPP mempunyai prestasi peyerapan bunyi (SAC) dan kehilangan penghantaran suara (STL) yang lebih baik berbanding busa dengan purata peningkatan 26.44 dB. MPP juga menunjukkan peningkatan dalam SAC dan ciri akustik mempunyai lebar jalur penyerapan, yang dapat dikendalikan oleh parameter ketebalan (t), diameter perforasi (d), kedalaman rongga (D) dan nisbah perforasi (σ). Ini menunjukkan bahawa ciri akustik MPP dapat dimodifikasi untuk memiliki SAC yang lebih baik pada frekuensi yang diinginkan, terutama untuk aplikasi frekuensi rendah hingga pertengahan. Analisis kehilangan transmisi suara dilakukan pada tahap penutup telinga, dengan MPP diterapkan dalam penutup telinga. Hasil menunjukkan bahawa lapisan busa hanya memberikan peningkatan pelemahan minimum kepada penutup telinga sementara penutup telinga MPP secara signifikan mengubah ciri akustik penutup telinga, dengan peningkatan purata pelemahan 12.63 dB. Keluk STL penutup telinga keselamatan berasaskan MPP (MPP-PHP) menunjukkan peningkatan besar dalam julat frekuensi pertengahan dan tinggi (500 Hz - 4000 Hz) dan sedikit peningkatan dalam julat frekuensi rendah (di bawah 500 Hz). Hasil eksperimen yang diperoleh menyimpulkan bahawa MPP-PHP adalah pengganti yang berpotensi untuk penutup telinga konvensional dan ciri akustik MPP-PHP dapat diubah berdasarkan aplikasi. Lebih banyak penyelidikan harus dilakukan untuk menilai prestasi akustik pelindung pendengaran peribadi berasaskan MPP.

ABSTRACT

Safety earmuff is a common personal hearing protectors used in the working industries to protect workers from hearing losses. One of the disadvantages of the safety earmuff is it is not suitable to be used in hot, humid, or dusty environment. The foam lining of the safety earmuff, which is made of porous material, tends to disintegrate overtime. Micro-Perforated Panel (MPP) is proposed as the substitution for the foam lining material due to its acoustic characteristic, durable and lightweight characteristic. Experimental result shows that the MPP has better SAC and STL performance compared to the foam with averaged 26.44 dB STL improvement. MPP also shows improvement in SAC and the acoustic characteristic has an absorption bandwidth, which can be controlled by the parameters thickness (t), perforation diameter (d), cavity depth (D) and perforation ratio (σ). This shows that the acoustic characteristic of MPP can be modified to have better SAC at the desired frequency, especially for low to mid frequency application. Sound transmission loss analysis is performed on the earcup level of the earmuff, with MPP applied onto the earcup. Result shows that the foam lining only provides minimal attenuation improvement to the earcup while MPP earcup significantly changes the acoustic characteristic of the earcup, with an average improvement of 12.63 dB attenuation. The STL curve of the MPP earcup shows a major improvement in the mid and high frequency range (500 Hz – 4000 Hz) and a slight improvement in the low frequency range (below 500 Hz). The experimental results obtained conclude that the MPP-PHP is a potential substitution for the conventional earmuff and the acoustic characteristic of the MPP-PHP can be varied based on the application. More research should be done to evaluate the acoustic performance of the MPP-based personal hearing protectors.

CHAPTER 1 INTRODUCTION

1.1 Project Overview

According to the OSHA's Occupational Noise Exposure Standard section 1910.95(i)(1), employers shall make hearing protectors available to all employees exposed to an 8-hour time-weighted average of 85 decibels or greater at no cost to the employees and hearing protector shall be replaced, as necessary[1]. The Department of Occupational Safety and Health, Malaysia (DOSH) also required employer to supply effective personal hearing protector (PHP) to be worn by employees, when engineering and administrative noise control measures do not reduce the exposure to noise below the excessive noise exposure level (NEL) of 82 dBA as specified in Occupational Safety and Health (Noise Exposure) Regulations 2019 section 11.1.1[2]. The PHP ensure that the workers will not suffer from noise-induced hearing loss (NIHL) during works.

Thus, PHP has been used as a protection of human hearing when working in loud noise environment. There are two types of PHP available, which are the safety earmuff and earplug, in which safety earmuff is the studied PHP in this project. There are four different sound transmission paths through the earmuff, which are the transmission through human bones and tissues, vibration of the earcup and transmission through the earcup and sound leakage through earcup gap, as depicted in Figure 1.1[3]. The acoustic performance of the earmuff is mainly contributed by four components which are the earcup, foam lining, cushion, and headband [4] as shown in Figure 1.2.

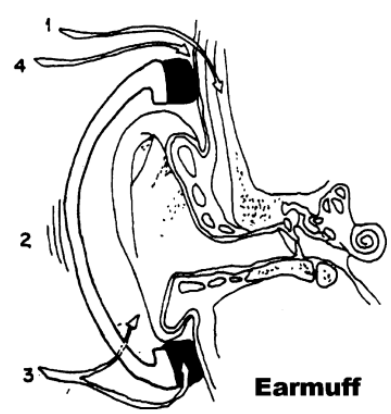

Figure 1.1 Sound Transmission Path through the Earmuff

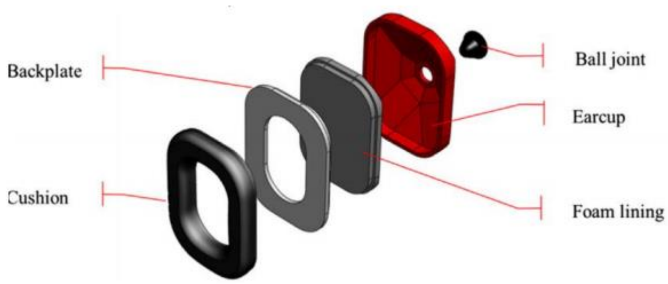

Figure 1.2 Earmuff Structure and Components

Although regulations have been set to wear PHP when working in loud noise environment, but it can still be observed that it is not enforced in certain industries especially in the grass trimming industries. Large number of grass trimming workers have found out to suffer from NIHL[5]. Reasons speculated are due to the discomfort caused when wearing earmuff for long period of time, especially at hot and humid outdoor environment [6]. Besides, standard compliant safety earmuff is costly while budgeted safety earmuff does not comply to the noise standard and only provide little attenuation[7]. Thus, grass trimming workers are unlikely to wear the PHP due to the cost incurred, discomfort caused, little attenuation provided.

Therefore, this project attempts to improve the budgeted safety by introducing microperforated panel (MPP) to replace the foam lining for the benefits of cheap labours in the industry. MPP is a thin sheet of panel with submillimetre holes perforated on top, which has proven to provide sound absorption effectively at low frequency range [8], [9]. Besides, the acoustic performance of the MPP is insensitive of the material used, thus light-weight material can be selected when fabricating the MPP[10]. The effect of dust accumulation on MPP is also minimal compared to the foam lining[11]. These reasons make MPP a potential alternative for the foam lining of the safety earmuff especially for the grass trimming industry as the grass trimmer functions at low frequency range[12].

Many studies have been conducted to investigate the sound absorption performance of MPP at various application. However, limited studies are found to be conducted on the sound transmission performance of the flat MPP, and its application has been limited to silencer application.

Application of the MPP of the safety earmuff has a great potential to increase the sound attenuation and conformity of the safety earmuff, which will bring great contribution to the workers who continuously exposed to loud noise. Therefore, this project aims to study the attenuation performance of the safety earmuff when MPP is applied. The parameters affecting the sound absorption performance of MPP is investigated and the acoustic performance of MPP-based personal hearing protection (MPP-PHP) is evaluated and compared with conventional safety earmuff.

1.2 Project Goals

The objectives of the research project are as follow:

1. To develop a Safety Earmuff based on Micro Perforated Panel Application.

2. To developed and statistically analyse the acoustic characteristic of the MPP.

4. To evaluate the performance of MPP-based Safety Earmuff with conventional earmuff.

1.3 Problem Statement

Foam lining of the safety-earmuff is made of porous material, but the attenuation properties is poor at low frequency and the foam will deteriorate over time. To achieve better damping and attenuation, one way is to increase the mass of the foam lining but will lead to potential discomfort to wear. Hence, micro-perforated panel (MPP) is proposed to overcome the disadvantages. MPP can achieve better sound absorption and wider bandwidth than conventional porous material by alternating the parameters. Besides, the acoustic characteristic is insensitive to the material made, thus thin and light material can be used to make the MPP, which make it a good alternative to replace the foam lining. Numerous studies have been conducted on the sound absorption performance of the MPP, but studies of the sound proofing performance of it are still limited. Herein, the potentials of the MPP are investigated from the sound transmission standpoint. Parameters affecting the attenuation performance of the MPP is investigated and the feasibility of applying MPP to the safety earmuff is explored.

1.4 Scope of Project

The acoustic characteristics of the safety earmuff are investigated. SAC measurement is made on the porous absorber material and the MPP to evaluate the acoustic characteristic. Parameters affecting the acoustic performance of the MPP is investigated and designs of Earmuff-MPP and Earmuff-Impedance adapter is developed. Transmission loss of MPP-PHP is compared with the performance of original earmuff. The data obtained from the experiment is statistically analysed to evaluate the feasibility of applying MPP onto conventional earmuff.

CHAPTER 2 LITERATURE REVIEW

2.1 Industrial Noise

Study shows that the average value of the noise exposure level of different industry ranges between 89 dBA and 95 dBA and the total average of all industry is at 92 dBA, which is higher than both regulations stated by OSHA and DOSH[2], [13], [14]. Another conducted study has assessed that all of the studied companies have exposure noise over 85 dBA at the frequency range of 500 Hz – 4000 Hz, which is the most sensitive hearing range of human ears[15].

The noise-induced hearing loss (NIHL)in grass-trimming workers is investigated and the result shows that 82.6% of the subjects suffered from NIHL[5]. Same study also explained that the average hearing thresholds at low frequency (500Hz, 1kHz, 2kHz) is better than the high frequency (3kHz, 4kHz, 6kHz) due to the reflection enhancement of sound energy. Therefore, the application of the safety earmuff is scoped towards the grass-trimming industry in Malaysia rather than general application to investigate the feasibility of MPP-PHP.

2.2 Safety Earmuff

2.2.1 Attenuation Characteristic

Passive earmuff is composed of the ear cup, cushion, foam lining or insert, backplate and the headband [16]–[18], as shown in Figure 1.1. Whereas the transmission paths across the earmuff is depicted in Figure 1.2. Sound transmission through path 1 is by conduction through conduction of bones, path 2 is by pumping motion of the PHP, path 3 by transmission across PHP components, and path 4 is by leakage through small gaps.

It is found that the larger cup volume provide better attenuation[4]. The increasing force exerted on the headband shows slight improvement in the attenuation, but the increasing force may lead to potential discomfort[4], [17]. The backplate does not provide attenuation to the earcup. Studies also found out that foam insert provide better attenuation above 2kHz, and increasing the mass of the foam will allow better damping of resonances[4], [17]. The discovery of the acoustic characteristic of the foam lining also showed the potential of replacing the foam lining with MPP for low frequency application.

Besides, the lightness of the cushion material causes sound to leaks through the cushion at low frequency, but studies agreed that the earcup vibration effect dominated the sound leaked though cushion at low frequency [4], [17], [18]. Boyer found out that the vibroacoustic behaviour originates from the pumping motion of the earcup and the cushion at low frequency (< 800Hz) [18].

In this project, the targeted solution is to improve the transmission loss or attenuation performance of the PHP through the 3rd-transmission pathway in Figure 1.2, which can be done by replacing the foam lining with MPP.

2.2.2 Design and Development

The most common type of safety earmuff found is the passive safety earmuff. The attenuation characteristic of the passive safety earmuff relies on the materials used and the structure of the earmuff[19], [20].

Ahmadi investigated the attenuation and comfort performance of a 3D printed nanocomposite earmuff [21]. The study showed that double cup earmuff is undesired by the workers due to the weight. The developed nanoclay earmuff showed increased comfort and similar attenuation performance with common earmuff.

Babette investigated the speech intelligibility of uniform attenuating earmuff and result shows improvement in speech intelligibility compared to conventional PHP [22]. Besides, Yu also explored the performance of a dual-cup-dual-cushion earmuffs and improve attenuations are found at multiple frequency range[23].

Seichi introduced the active noise control system for active earmuff [24]. The active earmuff creates noise cancelling effect by producing anti-noise signal of same amplitude but 180° degree out of phase. The developed active earmuff shows a better noise attenuation compared to the conventional PHP but accompanies with heavier weight and restricted mobility. A recent study on active soundproof earmuff system shows improvement in attenuation performance by introducing a low pass filter to compensate passive noise insulation[25].

The project focused on improving the acoustic performance of passive safety earmuff to provide better hearing protection for the grass root community with a low-cost solution.

2.3 Micro-Perforated Panel Theory by Maa

MPP is first introduced by Dah Yu Maa during the 1970s. The concept of the MPP originates from the perforated panels. The construction of the MPP is consist of a thin panel with numbers of submillimetre holes perforated on it and the panel is backed by a panel or a wall, to form a back cavity[26]. The basic structure of the MPP and its equivalent acoustic circuit is shown in Figure 2.1.

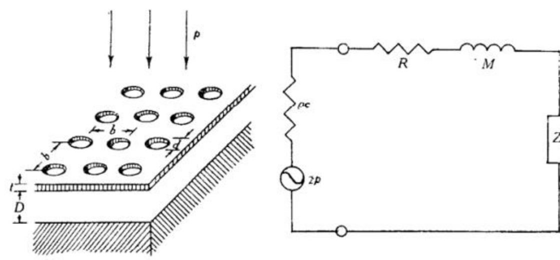

Figure 2.1 Basic structure of MPP and Equivalent Circuit

In the study presented, the acoustic specific acoustic impedance of a MPP is derived. The acoustic impedance of the MPP[26], relative to the impedance of air, is

$$Z_{MPP} = \ r + j\omega m,$$

But the relative acoustic resistance and relative acoustic mass are reintroduced in the other paper due to the approximation made. The exact solution of the relative acoustic resistance and relative acoustic mass are[8], [27], respectively,

$$r = \frac{32\, \eta\, t}{\sigma\, \rho_0\, c\, d^2}\ k_r\ ,$$

$$\omega m = \frac{\omega\, t}{\sigma\, c}\ k_m\ ,$$

where,

k_r = resistance constant

$$k_r = [1 + \frac{k^2}{32}]^{1/2} + \frac{\sqrt{2}}{32}\ k\ \frac{d}{t},$$

k_m = mass constant

$$k_m = 1 + [1 + \frac{k^2}{2}]^{-1/2} + 0.85\frac{d}{t}$$

k = perforate constant

$$k = r_0\sqrt{\rho_0\ \omega/\eta}$$

r_0 = radius of perforations

ω = angular frequency

t = thickness

η = coefficient of viscosity

It comes to realization that the acoustic characteristics of the MPP is heavily dependent on the acoustic resistance and the perforate constant, and there are four parameters that influences these values, which are the thickness of the perforated panel, diameter of perforations, perforation ratio and the depth of cavity. The above studies are important as it sets the fundamental knowledge to the later studies regarding MPP. The effect of these parameters on the acoustic performance of the MPP will be discussed in later sections.

2.3.1 Sound Absorption Coefficient of Micro-Perforated Panel

The application of the MPP is widely used in the sound absorption. The sound absorption coefficient, SAC is the ratio of the absorbed power to the incident power. It serves as a standard to measure the absorption performance of the MPP. The total MPP absorber impedance is [27]

$$Z_{total} = Z_{MPP} + Z_{cavity}$$

With the total impedance of the MPP absorber defined, the SAC of the MPP can be found. As discussed in the previous section, the specific acoustic impedance relative to the air impedance is defined. In Figure 2.1, the specific acoustic impedance of the air gap is denoted as Z_D. The specific acoustic impedance of the air gap and sound absorption coefficient (SAC) are different under different sound waves incident condition. The value of specific acoustic impedance and SAC are, respectively,

$$Z_D = -j\, cot\, \frac{\omega D}{c}$$

$$\alpha = \frac{4R}{(1+r)^2 + (\omega m - (\omega D/c))^2}$$

Whereas in diffuse sound field, the air cavity reacts differently[8]. When sound waves incident at an angle θ to the normal of the panel, the acoustic impedance and SAC of the air gap are, respectively,

$$Z_{D,\theta} = (r + j\,\omega\, m)\cos\theta - \ j\cot(\frac{\omega D}{c}\cos\theta)$$

$$\alpha_\theta = \frac{4\, r\cos\theta}{(1+r\cos\theta)^2 + (\omega m\cos\theta - \cot\frac{\omega D}{c}\cos\theta)^2}.$$

2.3.2 Acoustic Transmission Loss of Rigid Perforated Screen

A study has been conducted by Chen on the acoustic transmission loss of a rigid perforated screen. The transmission loss of 3 perforated plates with varied perforated radius, percentage and plate thickness is calculated theoretically through derived equations and verified through experiment. The transmission loss of sound wave and the transmission coefficients are, respectively

$$TL = 10\log\left|\frac{1}{\tau^2}\right|$$

$$\tau = \frac{P_{Transmitted}}{P_{Incident}}$$

The transmission loss of a perforated screen in terms of intensity transmission coefficient is derived as [28]

$$TL = -10\log\int_0^{\pi/2}\left|\left(\frac{1}{A\cos\theta+1}\right)^2\right|\sin 2\theta\, d\theta,$$

Where (1/A cos θ) = acoustic intensity transmission coefficient

2.3.3 MPP Parameters Analysis

To optimize the sound absorption performance of MPP during real-life application, the parameters affecting the acoustic characteristic of the MPP need to be investigated. As mentioned, the parameters that affect its behaviors are the panel thickness (t), perforation ratio (σ), cavity depth (D) and the perforation diameter (d). The equation of perforation ratio is [27]

$$\sigma = \frac{\pi d^2}{4b^2}$$

Where b = hole distance

The parametric study is conducted by alternating one parameter while the others remain constant. It is found that the absorption bandwidth become broader when the diameter of perforation (d) is reduced[27]. Next, studies found that the peak of SAC will moved to lower frequency when the perforation ratio (σ) decreased, and the absorption bandwidth became thinner[27], [29], [30]. This observation explained that the peak of the SAC can be shifted to desired frequency by alternating perforation ratio, with lower σ results to lower frequency for the SAC peak[30].

It was also found out that the SAC performance is less sensitive towards the plate thickness of the MPP, where the absorption bandwidth is slightly narrower, and the SAC peak shifted to lower frequencies when the plate thickness increased, but the effect is minimal [27], [31]. One of the studies explained that the cavity depth (D) has no significant effect to the absorption bandwidth and magnitude, while the others explained that the width of the maximum SAC increased with increasing depth, but all agreed that the absorption bandwidth will shift to lower frequency range with increasing depth[27], [29], [30].

Studies have also been conducted to study the effect of STL against the parameters. Chen conducted an experiment regarding the effect of parameters on the transmission loss effect but without the cavity depth [28]. Through the comparison of 9 samples, the author observed that the transmission loss is greater when the plate thickness is thicker when the other two parameters are kept the same. He also observed when the diameter of perforation increased, the transmission loss is lower. He later concluded that the transmission loss of the screen is strongly dependent of the perforation, as the transmission loss has significantly increased with lower perforation ratio.

Another study explained the STL effect with sub-division MPP[32]. The author observed the maximum value of STL increased and the curve shifted to higher frequency with increase perforation ratio. Next, the STL curve shifted to lower frequency and the value decrease as the thickness of the MPP increased. Increase in cavity depth results to the shift of the STL curve to lower frequency. The effect of perforation diameter is not explained in the study. Nonetheless, this study shows similar trend of the effect of the parameters towards the MPP STL performance with the SAC parameters study.

2.3.4 Configurations of Micro-Perforated Panel Absorber

The MPP model introduced by Maa considered simple case of micro-perforated panel backed by uniform air cavity depth. With the development of MPP, other MPP configurations have also been studied and a summary is made reviewing the MPP absorber arrangement technique [9].

An attempt has been done on MPP with ultra-micro perforations (<100 μm) using MEMS technology and result found out that the MPP can achieve high absorption in wide frequency bandwidth[33]. Tapered-perforation holes can affect the sound absorption characteristics of the MPP depending on the variations of the inlet and outlet holes [31]. Adding or replacing the air cavity with porous absorbent layer yields to a wider bandwidth with slight decreases in the absorption peak [29], [34].

Partitioning the air cavity of the MPP with honey-combed structure have been conducted by several researchers to investigate the absorption performance and transmission loss of the MPP. The papers concluded that the honey-comb partitioned MPP has improved the absorption performance and better transmission loss at mid and low frequency range [32], [35], [36].

MPP backed by irregular-shaped air cavity (trapezoidal shape) shows that the trapezoidal cavity with inclined MPP is able to produce more spectral peaks and better absorption performance at dips than the conventional MPP, but significantly altered the absorption pattern of the MPP [37]. MPP backed by Helmholtz Resonators of straight neck and hyperbolic neck can achieve better sound absorption at low frequency without needs of sacrificing absorption performance at mid and high frequencies [38].

Multi-layers MPP (ML-MPP) can be considered as the most common configuration of MPP used by researchers with different arrangement technique such as different cavity depth, different backed wall materials, series arrangement, parallel arrangement and dividing the air-cavity. The general observations of the ML-MPP from the studies are the wider absorption bandwidth is achieved with multiple spectral peaks as compared with the conventional MPP. Studies also showed that the average SAC and bandwidth have improved with the increase of number of layers of MPP [39], [40]. Simple single layer MPP is considered for this project as the main objective is to evaluate the feasibility of applying MPP onto safety earmuff. More configurations can be done in future work.

2.3.5 Vibro-Acoustic Properties of Micro-Perforated Panel

The MPP model proposed by Maa [8] only consisting of a simple MPP backed by a rigid back wall and study has also shown that the material selected to become the MPP does not affect the sound absorption performance of it [10]. It is true for most of the cases but for material density which is less than 2 kg/m^2, the absorption peak is lower than the immobile case and the absorption bandwidth may shift [41]. This indicates that the effect of vibro-acoustic properties of MPP on absorption performance need to be investigate clearly prior to the application.

Multiple studies have been conducted to investigate the vibro-acoustic properties of thin micro-perforated panel and the studies found out that the panel vibrations tends to slightly lower the acoustic resistance of the MPP, which potentially result to decrease absorption peak, reduction and shift of absorption bandwidth[41], [42]s. Besides, extra absorption peaks or dips may be observed due to the structural resonance of impedance tube or air-frame relative velocity [42], [43].

Another study is conducted by Liu to investigate the acoustic properties of a 3D printed MPP which uses the Maa's theory governing equation for the numerical study[29]. The study noted that the experimental result fairly agrees with the theoretical model. Therefore, vibro-acoustic effect is not considered in this project as the vibro-acoustic effect is insignificant when a 3D printed MPP is used based on the literatures studied.

2.4 Material of MPP and Fabrication Method

It was mentioned that the first generations of MPPs were made of metal with laser cuts holes [11]. Other materials have also been used to develop the MPP, such as acrylics, plastic, silicon, polymer and etc. [10], [29], [31], [32]. Nonetheless, the absorption performance is not affected by the material chosen[10]. However, as mentioned in previous section, material too thin with very low density may affect the absorption performance of the MPP due to the vibro-acoustic properties [43].

A study has shown and explained several methods of fabricating the MPP [40] . Another study also explained the use of microelectromechanical system (MEMS) technology to fabricate MPP with ultra-micro perforations [33]. Two other studies successfully use 3D printing technology to fabricate the MPP and the experimental result obtained fit wells with the theoretical prediction[44], [45]. However, limitations of different 3D Printing methods need to be considered prior to parameter designing.

In this project, SLA 3D printing is selected as the fabrication method for the MPP. The reason is based on light-weight characteristic of the 3D printing material, cost consideration and the perforation accuracy can be achieved by 3D printing compared to other fabrication method. MEMS is excluded due to the high-cost fabrication.

2.5 Application of MPP

Current MPP develops more towards the sound absorption application, which is to reduce the internal noise. The MPP applied to the Sound Attenuating Cabinet is success as it can effectively reduce the noise value of air-cooled product[46]. The practical application of MPP at the train tunnel entrance hood also shows reduction in noise level[47]. Besides, study also shows the possible application of creating an MPP window[48]. Potential applications of MPP on aircraft are also studied. Studies show that although MPP has potential applications on aircraft, practical implementations are still limited[10], [49].

For sound proofing application, application of MPP on HVAC is investigated and the MPP shows positive trend on certain frequency band[50]. MPP is applied onto the silencer and different acoustic characteristic is achieved when the parameters are varied in these studies [51], [52].

2.6 Sound Measurement Technique

2.6.1 MPP Acoustic Measurement

For sound absorption application, the sound measurement is normally carried out in impedance tube. Studies use the impedance tube setup to verify this design parameters of the MPP [27], [29]. While for the transmission loss application, the acoustic measurement generally can be found conducted using 2 ways. While some studies have been found to use the reverberation box to measure the transmission loss inside an anechoic chamber[32], [28], but more studies have been found to use the impedance tube to measure the transmission loss [44], [53], [54]

2.6.2 Hearing Protector Measurement

Several studies have discussed the methods of the hearing protector attenuation measurement. The first technique is called the Real-Ear Attenuation at Threshold (REAT), which believed to be the most common and accurate technique as it accounts for all the relevant sound paths to the human ear[55]. The second technique discussed is called the Microphone-In-Real Method (MIRE), which a microphone is used and located inside the cavity of the PHP for attenuation measurement[56], [57]s. Adding another microphone at the outer cup yields another technique called the F-MIRE technique, which is discussed in the paper[58]. The next technique uses a cylindrical device to imitate the human head which is called the Acoustic Test Fixture (ATF) method, but the development is rarely new yet [59], [60]. The Acoustical Test Bench (ATB) Method is used in one of the studies in order to evaluate the influence of each earmuff components on the sound attenuation characteristic[4].

A measurement method similar to the ATB method is proposed in this project. As the sound transmission across the PHP components is the main focus, therefore, sound measurement is carried out using impedance tube to simplify the PHP measurement and neglect other PHP transmission paths influences.

CHAPTER 3 METHODOLOGY

3.1 Overview

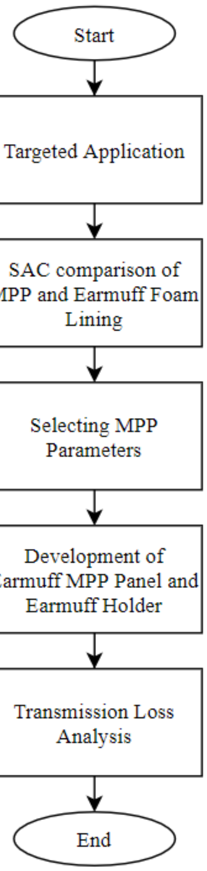

Figure 3.1 Methodology Flow Chart

Figure 3.1 shows the methodology flow chart for the project. First, the targeted application for the MPP-PHP is selected to compare the analysis result at the suitable frequency range. The sound absorption performance of the MPP is compared with the foam lining of the original earmuff to validate the objective of the project. Next, the MPP parameters are evaluated to ensure that the MPP can be applied onto the safety earmuff during the transmission loss analysis. Then, earmuff holder and MPP panel for earmuff application is modelled and printed out to carry out sound measurement on earcup level. Transmission loss analysis is then carried out to evaluate the performance of the MPP-PHP and compared to the original safety earmuff.

3.2 Targeted Application

The targeted application of the MPP-PHP is focused on the grass trimming industry in Malaysia. As found in one of the studies, approximate 85% of grass trimming workers suffered from NIHL due to lack of wearing PHP during trimming[5]. The mean of the NEL of the grass trimming machine is 95 dBA[5], which is higher that the safety NEL set by both OSHA (85 dBA) and DOSH (82 dBA) [1], [2]. Although reason of not wearing is not identified, but it can be speculated due to the discomfort of wearing PHP for outdoor works for long period of time.

The normal hearing range of healthy human ears is 20 Hz to 20 kHz and the sensitive hearing range of human ear is within 500 Hz to 4 kHz. One of the studies stated that the working frequency of the grass trimming machine is around 50 Hz – 90 Hz and the other study stated the ranges fall between 16 Hz to 167 Hz, thus the working frequency can be assumed to be working at low frequency[61], [62].

3.3 CAD Modelling and 3D Printing

3.3.1 MPP Plate

MPP plate of different parameters are modelled for the SAC parameters study. The circular diameter of the MPP plate is set to be equal to the inner diameter of the impedance tube to carry out sound measurement, which is 34.8 mm. The MPP Plate Samples is as shown in Figure 3.2.

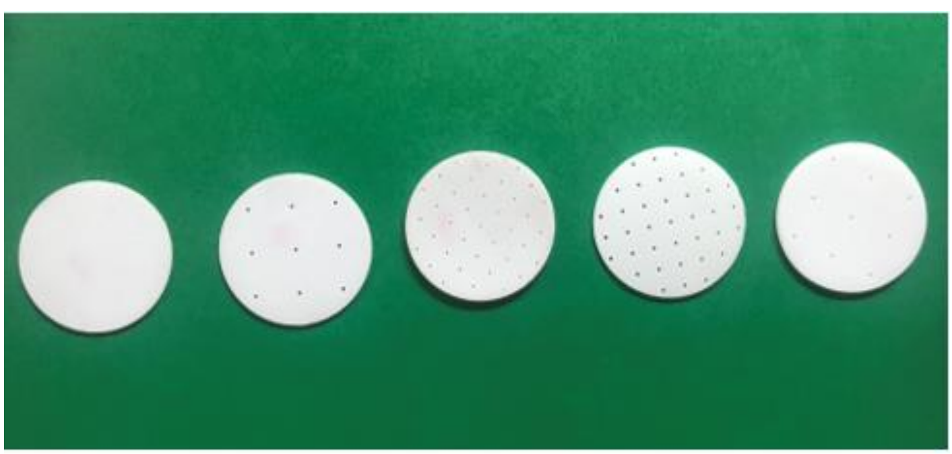

Figure 3.2 MPP Plates with Different Parameters

Noted that the back cavity of the MPP is modelled and printed separately. This is to reduce the 3D printing cost by simplifying the design. Besides, more configurations can be performed by attaching different MPP plates to different cavity depth. The MPP cavity samples are as shown in Figure 3.3.

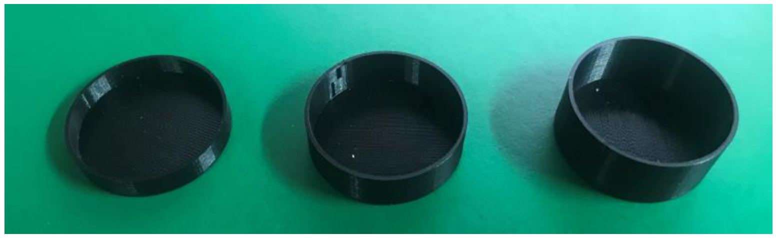

Figure 3.3 MPP Cavity with different Cavity Depth

There are 5 MPP plates and 3 MPP cavity printed with different parameters and cavity depth. The detailed parameters are listed in Table 3.1. The parameters are panel thickness (t), perforation ratio (σ), cavity depth (D) and the perforation diameter (d).

Sample	Parameters Description	Material / Printing
MPP - 1	d = 0.5 mm; σ = 0.636%; t = 1 mm;	Tough Resin (ABS-like)/ SLA
MPP - 2	d = 0.9 mm; σ = 0.636%; t = 1 mm;	Tough Resin (ABS-like)/ SLA
MPP - 3	d = 0.5 mm; σ = 0.785%; t = 1 mm;	Tough Resin (ABS-like)/ SLA
MPP - 4	d = 0.9 mm; σ = 0.636%; t = 1.5 mm;	Tough Resin (ABS-like)/ SLA
MPP - 5	d = 0.9 mm; σ = 2.54%; t = 1 mm;	Tough Resin (ABS-like)/ SLA
Cavity - 1	D = 5 mm	Standard PLA/ FDM
Cavity - 2	D = 9 mm	Standard PLA/ FDM
Cavity - 3	D = 13 mm	Standard PLA/ FDM

Table 3.1 Parameters table of MPP and Cavity Samples

After determining the parameters. The MPP models are converted into STL format and send for 3D printing. The printing material of the samples are as shown in Table 3.1. All the MPP samples are printed using ABS-like tough resin whereas the cavity samples are printed using standard PLA. The printing material selection is due to the limitation of the printing technology as conventional FDM printing could not achieve high precision when printing submillimetre dimensions. As the perforation diameter is an important parameter, thus SLA printing is chosen.

3.3.2 Earcup

The modelling of the earcup model is done based on the actual earcup purchased, as shown in Figure 3.4.

Figure 3.4 Actual Earcup

As the CAD model of the actual earcup is not provided, modelling is done through measuring and estimating the dimensions of the earcup, such as the curvature, loft radius, etc. Multiple iterations are done to model the earcup to be as close as the dimensions of the actual earcup so that the developed MPP Panel can fit perfectly inside the actual earcup. The final model of the earcup is as shown in Figure 3.5.

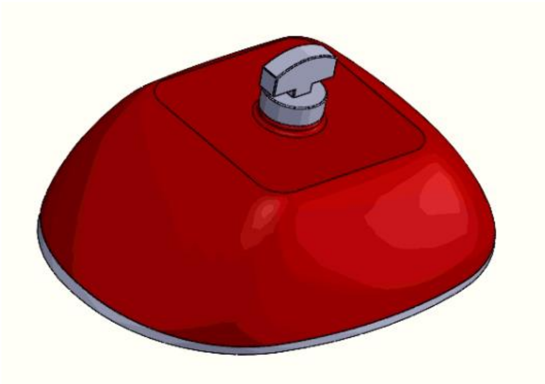

Figure 3.5 Modelled Earcup

3.3.3 Earcup Holder

After finalising the earcup model, the earcup holder is modelled, as shown in Figure 3.6. The purpose of the earcup holder is to hold the earcup in position during the impedance tube sound measurement. The earcup holder is separated into two parts, the inlet holder, and the outlet holder. As depicted in Figure 3.7, the holder inlet is connected to the up-stream of the impedance tube, which noise source is generated, while the holder outlet is connected to the down-stream of the impedance tube, where termination condition is applied. P_i represents the sound incidence from the noise source, while P_t is the transmitted sound.

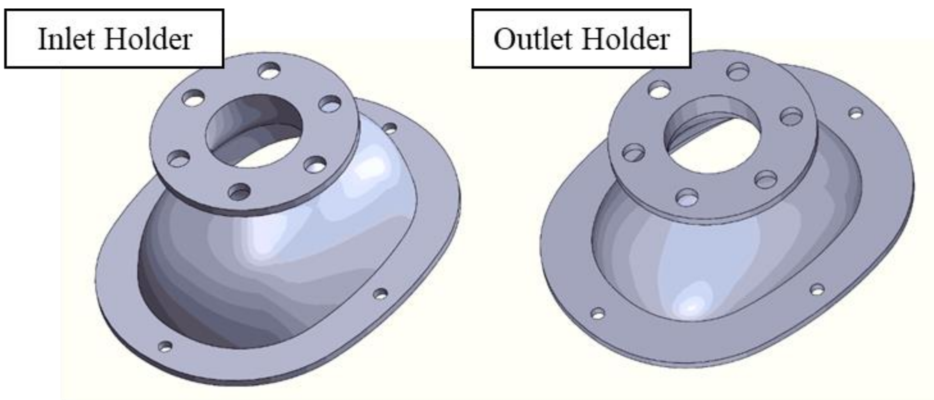

Figure 3.6 Inlet Holder and Outlet Holder of the Earcup Holder Model

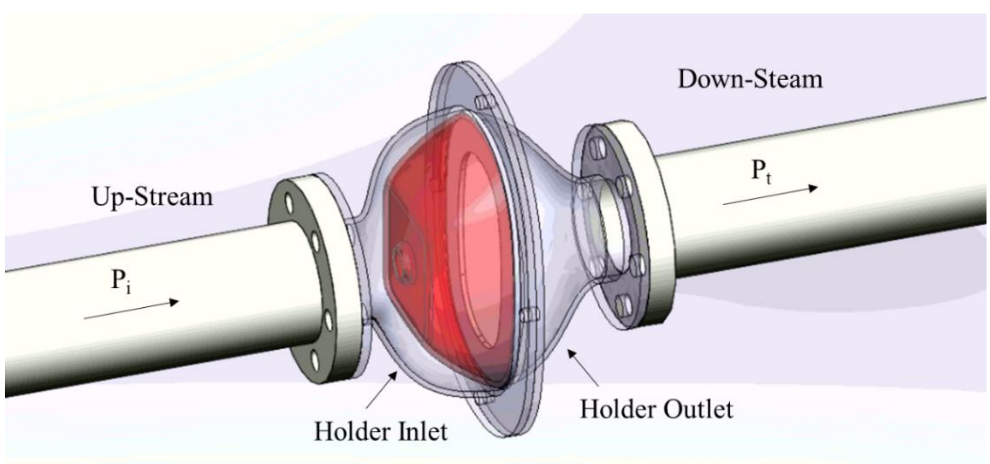

Figure 3.7 Earcup Holder Assembly with Impedance Tube.

The holder inlet is designed in a way that the earcup can fit perfectly inside and the outlet holder is designed to in a way that the edge of the earcup is touching with the edge of the inner cavity of the holder at minimal, as shown in Figure 3.8. Thus, a close cavity is formed where the earcup can fit inside the earcup holder and connects to the impedance tube for acoustic measurement. The earcup is fixed in position when assembled.

Besides, as depicted in Figure 3.8, the earcup holder is designed with curvature surfaces without any sharp edges or corners. This is to prevent any disruption of the sound transmission during the sound measurement as corners are known to cause vortex flux in fluid flow. Next, the earcup holders are clamped together with 4 mm nuts and bolt and connected to the impedance tube with 7 mm nuts and bolts.

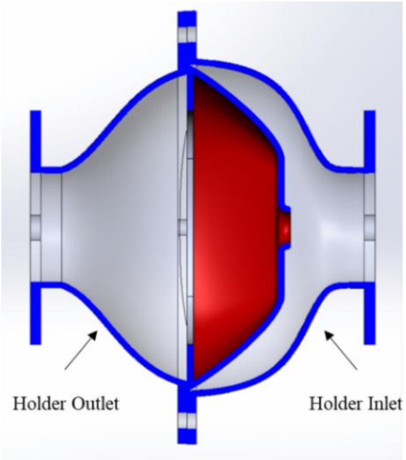

Figure 3.8 Cross-Sectional View of Earcup Holder Assembly

After finalising the design, the earcup model is sent for 3D printing using PLA material. The 3D printed earcup holder is as shown in Figure 3.9.

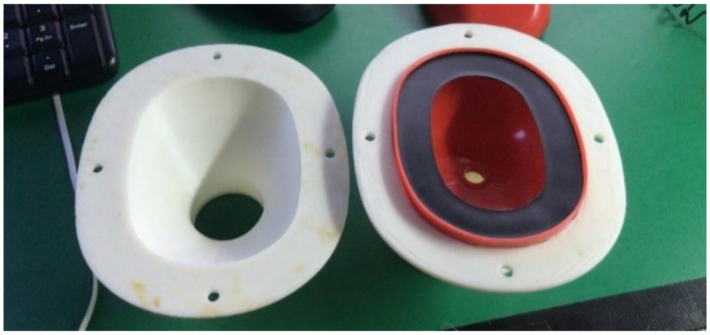

Figure 3.9 3D Printed Earcup Holder

3.3.4 MPP Earcup Panel

The earcup panel is modelled with the finalized parameters applied onto it, as shown in Figure 3.10. As shown in the figure, the earcup panel on the right contains submillimeter holes, which behaves like the MPP panel, while the panel on the left imitates the back wall of the MPP to form air cavity. The earcup MPP panel is modelled by slicing the earcup model (Figure 3.5) at the desired depth using the plane geometry and the unwanted bodies are removed.

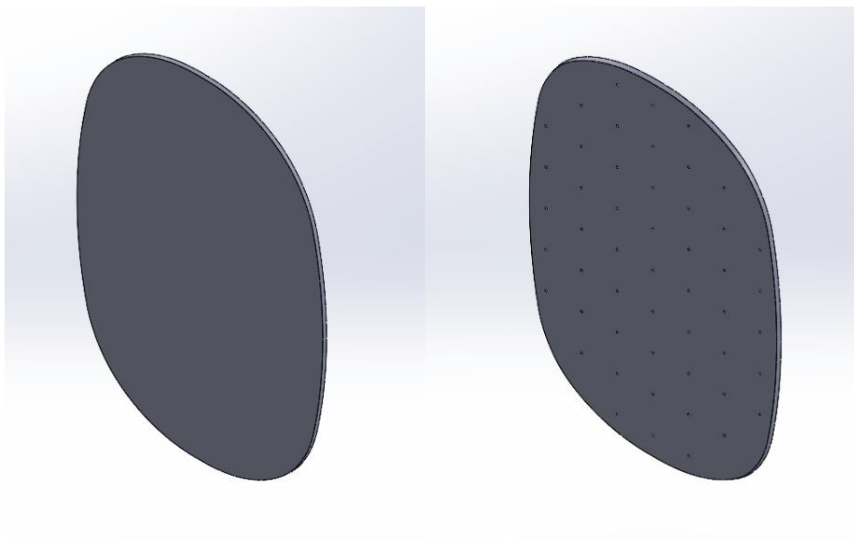

Figure 3.10 Modelled Earcup Panel: MPP (right) and backwall (left)

3.4 Sound Absorption Coefficient Measurement of MPP and Earmuff Foam

The SAC measurement is carried out in the Vibration Lab, School of Mechanical Engineering, USM. The measurement device and software used is the impedance tube and the SIEMENS LMS Test Lab. The apparatus setup is as shown in the Figure 3.11.

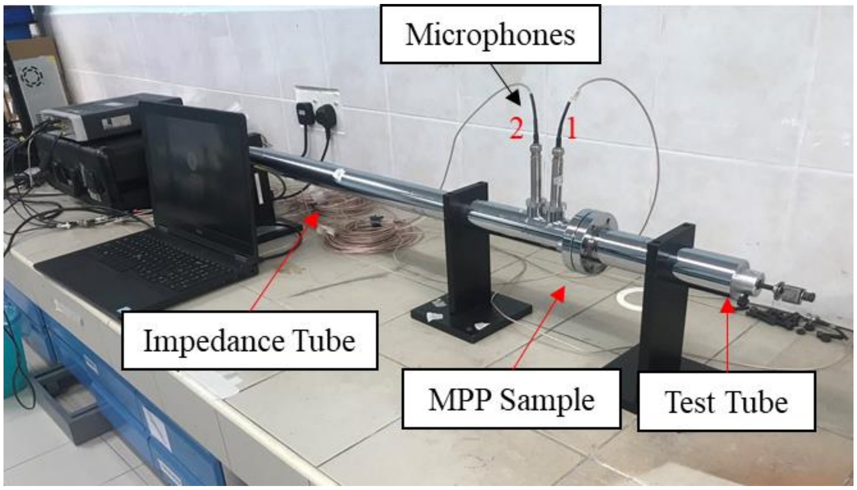

Figure 3.11 Impedance Tube Setup for Sound Absorption at Vibration Laboratory of University Science Malaysia

Figure 3.12 shows a simple sketch diagram of the impedance tube. Referring to Figure 3.11 and Figure 3.12, the sound source travels across the impedance tube and reflects when incident on the MPP sample. The two microphones then picked up the sound pressure inside the tube and the SAC is measured. The MPP sample is fixed on the test tube and the parameter cavity depth (D), is adjusted by controlling the depth of the test tube.

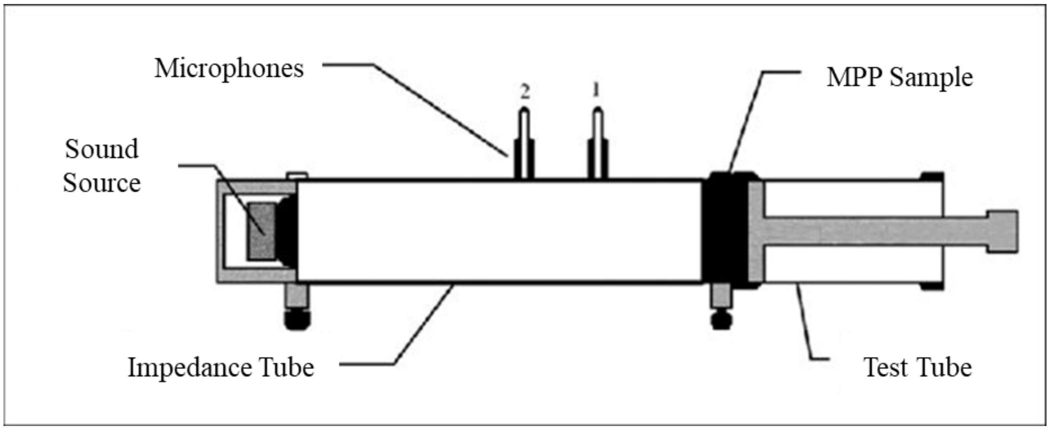

Figure 3.12 Sketch Diagram of Impedance Tube Sound Absorption Test System