ACOUSTIC PERFORMANCE STUDY OF 3D PRINTED MICRO-PERFORATED PANEL

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ACOUSTIC PERFORMANCE STUDY OF 3D PRINTED MICRO-PERFORATED PANEL

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DECLARATION

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LIST OF SYMBOLS

Z_{MPP}	Acoustic impedance of the micro-perforated panel
μ	Kinematic viscosity
p	Density of air
c_0	Speed of sound in the air
ω	Frequency of sound
t	Thickness of the panel
D	Air gap distance
d	Diameter of perforated hole
q	Perforation constant
Z_D	Acoustic impedance of the air gap
f	Frequency of sound in the air
Z_{total}	Total normalized specific acoustic impedance
α	Sound absorption coefficient
Re(Z)	Real part of the impedance
Im(Z)	Imaginary part of the impedance
C	Circularity of the hole
D_{min}	Minimum diameter of the hole
D_{max}	Maximum diameter of the hole
R_{min}	Minimum radius of the hole
R_{max}	Maximum radius of the hole
C_{entry}	Circularity at entry of the hole
C_{exit}	Circularity at exit of the hole
mm	SI unit of length millimeter
C_{ISO}	Circularity defined by ISO standard 9276-6/2006

LIST OF ABBREVIATIONS

MPP	Micro-Perforated Panel
ANN	Artificial Neural Network
AM	Additive Manufacturing
CAD	Computer Aided Design
MLR	Multiple Linear Regression
CO2	Carbon Dioxide
GUI	Graphical User Interface
FDM	Fused-Depositing Material
SAC	Sound Absorption Coefficient
MSE	Mean Square Error
R	Coefficient of Correlation

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ABSTRAK

Dalam kajian ini, konfigurasi optimum untuk menghasilkan panel berlubang mikro dengan bulatan lubang yang disasarkan telah dibincangkan melalui analisis pengukuran dan pembinaan rangkaian saraf tiruan. Pembuatan panel berlubang mikro menggunakan pembuatan bahan tambahan sebagai kaedah pilihan telah dicadangkan. Namun, kes terbaru ini telah mendapati bahawa kaedah tersebut boleh menyebabkan penghasilan lubang tidak seragam yang boleh menjejaskan prestasi sebenar. Dalam usaha untuk menyelesaikan masalah tersebut, beberapa sampel lubang perforasi telah dirancang menggunakan perisian SolidWorks dan dihasilkan dengan menggunakan mesin PolyJet. Parameter sampel (diameter lubang dan ketebalan sampel) diukur dan dianalisis berdasarkan pelencongan yang telah dihasilkan. Analisis tersebut menunjukkan bahawa ketebalan sampel yang lebih tinggi dan diameter lubang yang lebih rendah dapat menghasilkan pelencongan yang lebih konsisten dan lebih rendah daripada model yang telah dihasilkan. Gambar lubang telah ditangkap menggunakan mikroskop yang beresolusi tinggi (Alicona Infinite Focus). Gambar yang ditangkap telah diproses dalam algoritma pembahagian gambar potongan graf. Lingkaran setiap lubang diukur menggunakan gambar yang telah diproses dan dinilai berdasarkan hasil kebarangkalian mengikut lingkaran yang ditetapkan. Penilaian tersebut menunjukkan bahawa sampel dengan ketebalan yang tinggi dan diameter lubang yang rendah mempunyai kecenderungan yang lebih tinggi untuk menghasilkan lingkaran yang lebih baik. Parameter yang diukur dan parameter yang dibina telah dihasilkan dan dilatih dalam model rangkaian dua lapisan. Model tersebut disahkan dengan menjalankan ujian kebolehpercayaan. Model rangkaian yang dilatih mencapai hasil ramalan yang memuaskan kerana purata ketepatan bagi kedua-dua diameter lubang dan ramalan ketebalan sampel masing-masing adalah 1.5588% dan 0.3328%. Berdasarkan hasil eksperimen dan pemodelan analitik, didapati bahawa model rangkaian tersebut dapat meramalkan konfigurasi optimum untuk menghasilkan panel berlubang mikro dengan bulatan lubang yang terbaik.

ABSTRACT

In this study, the optimum configurations for producing micro-perforated panel with targeted hole roundness is discussed through measurement analysis and construction of artificial neural network. The development of micro-perforated panel using additive manufacturing as an alternative method have been proposed. However, recent cases have found that the method can cause imperfection holes which affect its actual performance. In a further attempt to solve the problem, several perforation hole samples were designed using SolidWorks software and fabricated by using PolyJet machine. The sample parameters (hole diameters and sample thickness) were measured and analysed the deviations produced. The analysis showed that higher sample thickness and lower hole diameters produced more consistent and lower deviations throughout the fabricated model. The perforation holes images were captured using high resolution microscope (Alicona Infinite Focus). The capture images were processed in graph-cut image segmentation algorithm. The circularity of each hole is measured using the processed images and evaluated based on the probability outcomes of specified circularities. The evaluation showed that lower thickness and lower hole diameter sample has a higher tendency to produce better hole circularity. The measured parameters and designed parameters were constructed and trained in two-layer feed forward network model. The model was verified by conducting a reliability test. The trained network model achieved satisfactory prediction results as the mean accuracy for both hole diameter and sample thickness predictions were 1.5588% and 0.3328%, respectively. Based on the experimental results and analytical modelling, it was found that the artificial neural network model can predict the optimum configurations for producing the MPP with the best hole roundness.

CHAPTER 1

INTRODUCTION

1.1 Overview

Micro-perforated panels (MPPs) are becoming one of the next generation sound absorption method due to their fiber-free and inflammable materials. A "Second generation MPP" which uses plastic or resin was recently introduced as an alternative material to the "First generation MPP" which produced using metal sheets [1]. Both generations comprising of thin panel with a lot of submillimetre perforations. MPP sound absorbers were first introduced by Maa [2], who found the theory to measure the acoustic properties of MPP absorbers and parameters such as perforation diameter, thickness of plate, perforation ratio and depth of air cavity which can be optimized to achieve the target frequency. MPPs are produced with small parameters like hole diameter and thickness which is smaller than 1mm [3].

There have been numerous studies regarding the perforation panel sound absorbers before MPP was discovered and theoretical investigations has been rapidly performed such as the study on acoustic impedance and sound absorption coefficients of perforated panel backing thin porous material and air space [4]. Two studies have demonstrated the importance of increasing backing material density via experimental measurements [5] and examination on the sound absorption characteristics of perforated aluminum panel backing with absorptive material conducted in 1997 [6]. From the literature review, it is important to investigate and identify the sound absorption coefficients of perforated panels in the acoustics research field. However, dimensional deviations during fabrication of MPP can greatly affect the targeted performances. Most of the related studies only focus on designing the sound absorbing constructions based on the experimental measurements to obtain desired sound absorption characteristics. Therefore, it is crucial to investigate the parameters for fabricating the MPP that offers the best hole roundness and shapes, especially when the fabrication process involved in using additive manufacturing (AM) method. This situation suggests that several correction factors for the deviations occurred on fabricated holes need to be identified [7].

Artificial neural networks (ANN) began to apply in a lot of academic research and used in many fields involving empirical data analysis for a variety of applications to solve complex problems. It is based on a collection of artificial neurons which create neurons model in a form of biological brain. In additive manufacturing field, a research has confirmed that ANN can be useful for estimating the process parameters that affect the characteristics of fabricated units [8]. The micro sized deviations produced in AM process is difficult to analyze due to several factors that need to be considered like random errors from the machine and model parameters [3]. Hence, ANN is applied to minimize the complexity and to obtain the optimum configurations for producing MPP with targeted perforation hole roundness and dimensions.

1.2 Project background

Recent development of the MPP is focusing on the wideband frequency study and achieve high transmission loss by optimizing the parameters of the MPPs, specifically on the project study which is the MPP holes circularity. The project study was supported by Jeong and Jeff (2012) which have concluded that lower frequency range can be tuned without a large increase in the air depth due to the ratio of hole diameter to thickness and surface porosity are optimizable [9]. Besides, a parametric optimization algorithm has been provided to determine the effective parameters on the circularity of holes on the MPPs [10]. However, there are a few studies related to optimizing the manufacturing process of the MPP specifically on AM technology. Researchers have been using AM as an alternative method to produce the MPP, but recent studies showed that the method can cause imperfection holes on nylon MPP which affect its actual performance [7] and the diameters of the perforations were not consistent and not precisely equal to the designed values [11].

Based on the literature review to date, there are some investigations has been done towards the production of MPP using 3D printers. Unfortunately, most of the studies do not provide detailed information regarding the production and optimization methods. Sakagami et al. [3] have mentioned several errors occurred during 3D printing process such as shrinkage and expansion of the sample due to the temperature on the sample surface and the error of thickness size due to new layer which is hot can melt the existing layer. Even so, there is no information regarding the method for identifying the configurations to produce the MPP. A perforated panel with a larger diameter and slanted holes was conducted by Carbajo et al. [12] and the samples produced were agreed to the theoretical result, but the manufacturing accuracy of the specimens were not clearly mentioned. Therefore, in this study, several investigations will be done to identify the causes of imperfection holes due to AM process and find the optimum configurations for producing the MPP with its targeted performance by employing ANN.

1.3 Problem statement

In the pioneering work on MPPs, recent development is focusing on the wideband frequency study and achieve high transmission loss by optimizing the acoustic properties of the next generation MPP. However, there are very limited literature provide the methods of producing accurate holes on MPPs using additive manufacturing. Hence, the main objective of the present paper is to investigate the parameters that affect MPP holes from Polyjet printer and its circularity. ANN is also applied to find the optimum configuration for producing the MPP so that the best hole circularity can be achieved.

1.4 Objectives

There are several objectives that must be achieved throughout this project:

1. To study the effective parameters of MPP.
2. To investigate the parameters that affect imperfection holes on MPP.
3. To identify the best method to calculate the deviations produced by the holes.
4. To find the optimum configuration for producing the MPP with its targeted hole roundness by using ANN.

1.5 Scope of work

In this project, the configurations of CAD model and its parameters that affect the imperfection holes is determined by fabricating multiple samples of submillimeter holes by using PolyJet printer. The circularity of each hole is calculated using image segmentations algorithm in MATLAB software. After the circularity is calculated, the parameters of the sample and its circularity are trained by using ANN in MATLAB to find the optimum configurations for producing the MPP with its targeted performance.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to micro-perforated panels

Micro-perforated panels (MPP) sound absorbers are made up of thin plate with many submillimeter holes which distributed evenly. Before MPP was introduced by Maa [2], an approximate analysis on perforated facings were conducted in year 1947 to study its acoustic behavior as absorptive materials [13]. The idea of perforated facing is similar with the MPP, but the diameter of the perforation holes is larger than 1mm. Later, Maa has proposed that the perforations can be reduced to submillimeter level so it can provide sufficient acoustic resistance while the low acoustic mass is retained [2]. In the pioneering work on MPPs, a research has conducted numerous practical application studies which later draw attention among the researchers to develop next generation sound absorber [14]. The first generation of MPP uses metal sheets which produce by using laser cut, etching, and drilling methods. Recently, the second generation of MPP made up of softer materials like plastic and resin were developed to achieve sustainability.

2.2 Effective parameters of micro-perforated panel

Since the idea of perforated facings as sound absorbers introduced, numerous studies have been investigated to analyze the acoustic properties and characteristics. Bolt and Ingard (1951) continue his investigation to study on acoustic impedance and sound absorption coefficients of perforated panel backing thin porous material and air space [4]. Later, two studies have demonstrated the importance of increasing backing material density via experimental measurements [5] and examination on the sound absorption characteristics of perforated aluminum panel backing with absorptive material were conducted in 1997 [6]. Then, Maa (1975) proposed an idea of micro perforations on a thin panel and proved that the problem of wide band, high coefficient sound absorber for severe circumstances can be solved. According to Maa [2], the acoustic impedance of the MPP, Z_{MPP} is derived by using a panel model that consists of an array of tubes and is expressed by equation (2.1) below [11].

$$Z_{MPP} = \frac{32\mu t}{pc_0 d^2}\left(\sqrt{1+\frac{q^2}{32}} + \frac{\sqrt{2q}}{8}\frac{d}{t}\right) + \frac{j\omega t}{pc_0}\left(1 + \frac{1}{\sqrt{9+\frac{q^2}{2}}} + 0.85\frac{d}{t}\right) \quad (2.1)$$

Where,

$$q = \sqrt{\frac{\omega}{\mu}}\frac{d}{2} \quad (2.2)$$

Where, μ = kinematic viscosity

p = density of air

c_0 = speed of sound in the air

ω = frequency of sound

d = diameter of perforated hole

q = perforation constant

t = thickness of the panel

MPP sound absorber backed with an air space behind it has the working principle of a resonant absorber. The absorption characteristics can be interpreted in a model illustration as shown in Figure 2.1. Maa stated that the sound wave impinges on the construction normally. The MPP can be expressed as parallel connections of many small tubes. If the distance between pores is large compared to their diameter, thus, the acoustic impedance of the panel is simply the impedance of individual tubes divided by the number of small tubes. Therefore, the pores are independent. At the same time, the sound reflection by the solid part of the panel between the pores can be neglected if the distance between pores is smaller compared to the sound wavelength.

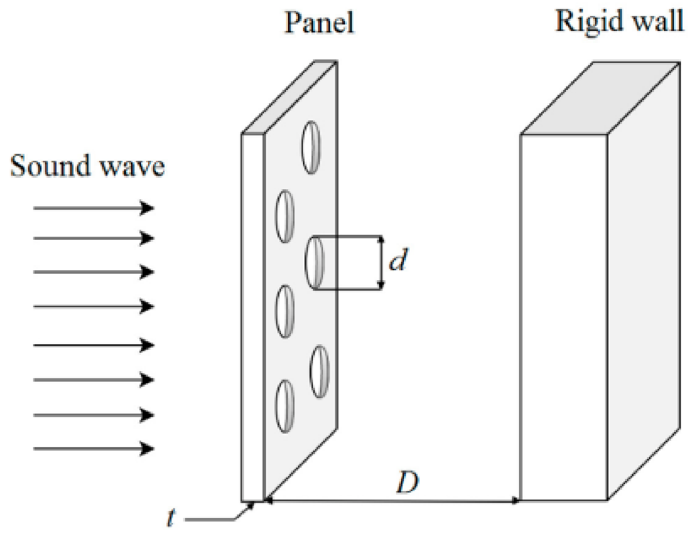

Figure 2.1: The schematic diagram of an MPP, which consists of a thin panel (*t*), an air gap (*D*), and a rigid wall [11].

The acoustic impedance of the air gap, Z_D is calculated by using the equation below.

$$Z_D = -j \cot \frac{2\pi f D}{c_0} \tag{2.3}$$

Where, *f* = frequency

D = air gap distance

The total normalized specific acoustic impedance, Z_{total} is calculated by summing up the acoustic impedance of the panel layer and the air gap.

$$Z_{total} = Z_{MPP} + Z_D \tag{2.4}$$

The sound absorption coefficient or SAC, α of the MPP can be calculated as shown in the equation below.

$$\alpha = \frac{4Re(Z_{Total})}{[1 + Re(Z_{Total})]^2 + [Im(Z_{Total})]^2} \tag{2.5}$$

Where Re(Z) represent the real part and Im(Z) represent the imaginary part of the impedance.

2.3 Design of micro-perforated panels sound absorber

MPP is known to its simple design and tunable capabilities to provide better sound absorption at low frequencies than typical foams and glass fiber [15]. MPP absorbers are most effective when the backing cavity depth is tuned to approximately one-quarter acoustic wavelength because the cavity depth dictates the frequency at which the acoustic particle velocity is maximum. A guide for designing the MPP absorbers has been established to guarantee an effective implementation [15]. The study has listed out several steps to design MPP; (1) Select an MPP and measure the transfer impedance. It is recommended to use nonlinear least squares curve fit to determine the effective MPP parameters based on Maa's theory. Next, (2) the environment where the MPP is placed must be consider because dust build-up inside the holes can deteriorate the acoustic performance of the MPP. (3) Partitioning the backing cavity so that the MPP behaves in a local reacting manner. MPP will be ineffective at attenuating grazing waves if it is not partitioned. Lastly, (4) varying the depth of the backing cavity is essential so that the low and broadband frequency attenuation can be improved. This project will not focus on implementation of the MPP, instead, the literature reviews have provided several information regarding the effective parameters that affect the performance of MPP like hole diameter and panel thickness.

2.4 Problems of producing perforation holes using 3D printer

Additive manufacturing (AM) is still developing until now and various of methods have been conducted to improve the quality of the product especially when constructing a micro size model or pattern. In the case of producing MPP, the parameters are relatively small which is lower than 1mm. Thus, a lot of problems have been stated in several articles regarding the production of MPP using 3D printing method [3], [7], [10]. A study conducted by Lili and Francesco [10] have stated the problems of producing holes on MPP using 3D printer which is; (1) the perforations in the printed structures were not perfectly circular in shape, (2) they were not consistent and not precisely equal as the designed values, (3) the unsmooth rims of the panels resulted in air spaces between the panels and the duct wall, and (4) irregular gaps between the circular panel and the tube wall occurred due to the thermal gradient during the SLS printing process.

Although 3D printing is not suitable for producing MPP, a trial production of MPPs using 3D printer has been published to investigate the manufacturing accuracy [3] and found several errors; (1) The samples are not necessarily the same size as designed in the CAD data used. Therefore, an adjustment to the size defined in the CAD data is possible; (2) shrinkage and expansion has been occurred during the production; and (3) error in its size was produced due to hot layer which can melt the existing layer. These problems also occurred in a recent study as it is found that the effect of burr results in non-circular or irregular shape of holes is due to the PolyJet manufacturing technique [7]. The study provided a comparison of microscopic image results between production of micro holes in MPP using 3D printed nylon and laser cut brass can be observed in Figure 2.2. The figure shows that both MPPs produced imperfectly circular holes as per used in Classic Maa theory calculation. The problem may occurred because the dimensional accuracy of printed parts primarily influenced by process parameters, material, and the geometry of parts [16]. Shrinkage may occur during the sintering of component which resulting smaller and uneven dimensions than the CAD model dimension.

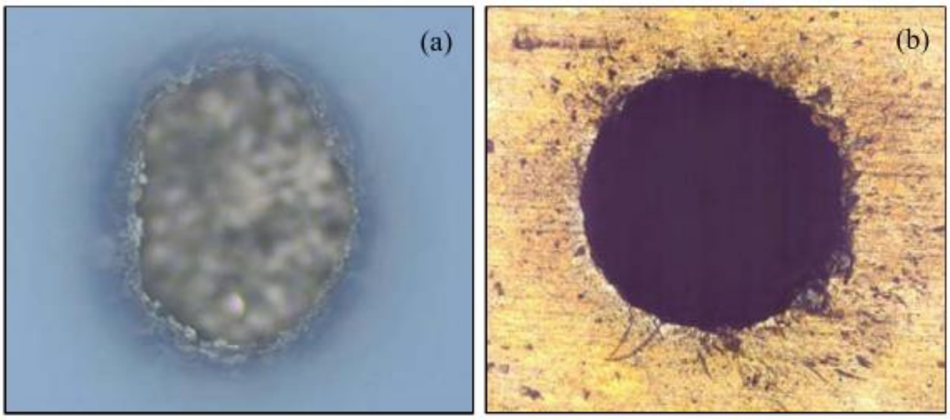

Figure 2.2: Scanned hole result for (a) 3D Printed Nylon MPP and (b) Laser Cut Brass MPP from InfiniteFocus Alicona Microscope [7].

Moreover, the internal condition such as high surface roughness can lead to hole imperfection due to formation of sharp burrs along the hole edge [17]. Figure 2.3 illustrated that the condition also produced a shallow depression of the plate’s surface as it approaches the edge of the hole. The printed hole diameter results showed inconsistent and asymmetrically distribution in every MPP samples. Shrinkage may occur during the sintering of the samples which resulting smaller and uneven dimensions than the CAD model dimension [16]. Most of the trial productions of MPP mentioned errors due to manufacturing process yet there are no specific solutions provided related to the problem. However, an alternative method has been introduced to quantify the deviations produced from the fabrication process based on resistance and correction factor [17]. This study will continue to investigate the parameters that affect the imperfection holes on MPP based on effective parameters of MPP and hole roundness analysis.

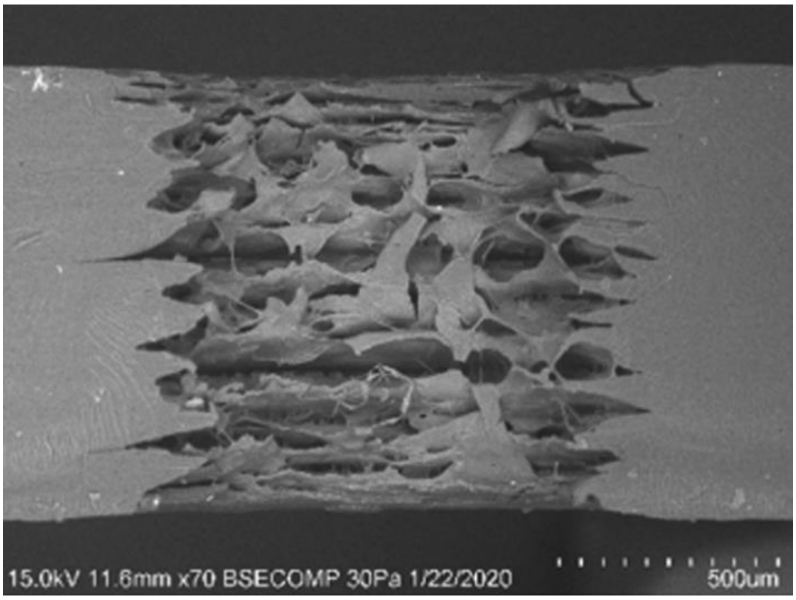

Figure 2.3: Inner wall surface of fabricated hole under the scanning electron microscope from front view [17].

2.5 Effect of imperfect perforation hole with theoretical model

In this section, an overview on the effect of imperfect fabricated perforation hole mainly due to AM process is reviewed to compare with the theoretical model. Several conditions have been stated for the MPP to achieve ideal MPP behavior [2], [18]. A uniform diameter and surface along the perforation hole must achieve because the viscous dissipation of a MPP occurred in internal part where the loss inside holes is present [18]. Numerous studies have shown that the result of 3D printed MPP disobey with the theoretical calculation [3], [7], [10], [17]. Hence, Guo et al. (2009) have proposed a modified calculation to account for the hole geometry [18]. The modification includes the effect of viscous energy loss inside the hole in case of circular hole.

Perfect sharp edge at the perforation hole has been proven to achieve better result which in accordance with Maa's theory in 1998 for sound propagation in circular perforations with end-corrections [19]. Guo's model also implies external resistance for a circular hole based on edge sharpness factor for both rounded and sharp edge hole [18]. Even so, the rounded edge hole in Guo's model agreed with Maa's theory in 1987 to compensate the high frequency range. From the studies, this project needs to consider the fabrication result that can affect hole roundness and edge sharpness of the hole. However, there is limited literature provided regarding achieving uniform surface along the hole and edge sharpness due to micro scale model and uncertainties produced by the AM processes.

2.6 Configurations of 3D printer and sample

Most available 3D printers in the market can print models with high accuracy and fine details using different kind of technologies and methods. 3D printers have their own configurations which can be controlled to meet the requirement of a specific model design. For the case of producing MPPs, a few articles have stated regarding the parameters of fused deposition modelling (FDM) machine [3]. Other than mentioning problems, there are several possible configurations which can be conducted in 3D printing process such as [3]; (1) Nozzle temperature can affect the temperature of the filament which causes excessive melt to existing layers. It is recommended to delay the time between the layers is proposed so that the filament can be cool down; (2) Accuracy of the MPP may depend on the production time, but it depends on the printer used; and (3) shrinkage and expansion can be controlled by maintaining the surface temperature of worktable. However, the configurations stated are specified for producing MPPs using FDM technology which may have different parameters from this study case.

In this study, the hole samples are printed using PolyJet printing technology. PolyJet is a form of rapid prototyping technology used to create small detailed prototypes and patterns by using the ultraviolet (UV) photopolymerization of the curable polymer resin [20], [21]. A study regarding producing MPP samples using Stereolithography (SLA) technology has been conducted to investigate the effects of the geometric parameters which include unit cell size, volume fraction and sample height on the acoustic absorption coefficients and the effective ranges of the frequency [21]. The study has concluded that high absorption coefficients can be achieved by a large volume fraction or a small unit cell size while the effective frequency ranges can be adjusted by the height. Based on the literature review, there are no configurations which can be controlled on SLA machines, instead the geometric parameters of the MPP are tuned to produce high absorption coefficient and effective ranges of the frequency samples. Thus, this project will involve in tuning the effective parameters of MPP to achieve a perfect hole circularity.

A similar study is conducted that related to reconfiguring the parameters of printed model and provided ways to achieve uniform printing quality [22]. They have included new method for calibrating a printer and adjustments of the model to achieve uniform print quality over the entire workspace. They suggested the following steps: (1) print the test specimens over the whole printer workspace. In this case, the authors printed multiple test cubes as a test model for calibration method; (2) measure the length of edge of printed test cubes; (3) the calculated values, along with the direction and position information as the input into pre-print software; (4) load the model into the software; (5) The software then configures and deforms the model preliminary according to the measured deviations between model and print. Missing values will be interpolated; and finally (6) print the adjusted model. Figure 2.4 below shows the comparison between normal printing method and printing with a preliminary configuration of the specimen to compensate the known printer inaccuracies. In this project, reconfiguring the parameters of printed samples is applied to reduce the measured deviations between the model and printed samples.

From the literature reviews, the controlled parameters used in this study is the thickness of the panel and the diameter of the holes. These parameters can be reconfigured and tuned in CAD software before the fabrication process. Therefore, the optimum configurations for producing the MPP using AM method is achievable by adjusting the parameters mentioned.

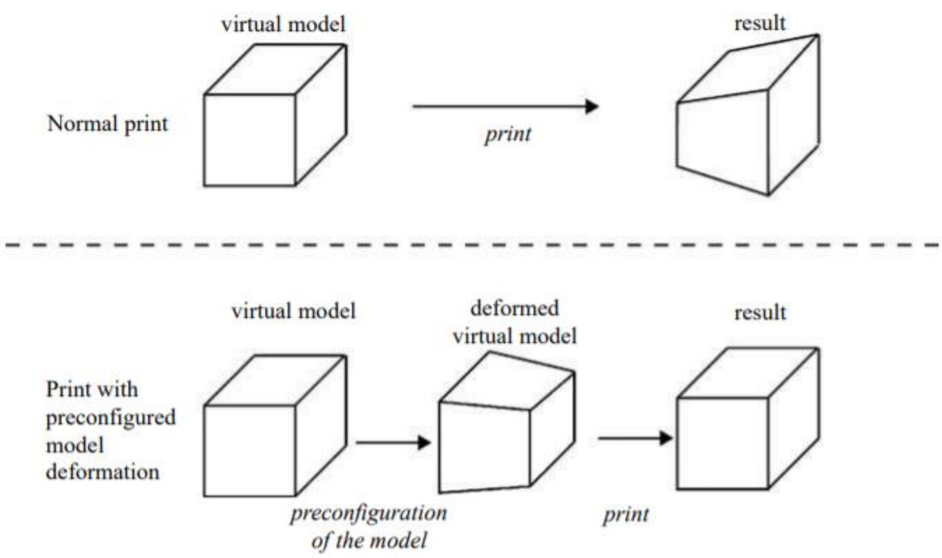

Figure 2.4: A comparison between normal printing method and printing with a preliminary configuration of the specimen to compensate the known printer inaccuracies [22].

2.7 Artificial Neural Network (ANN)

Artificial neural network (ANN) is a mathematical model has the functional form based on a simulation of the human brain system. ANN is often used in nonlinear models that have been widely applied to several applications like pattern recognition and system identification [23]. ANN model can adapt to recurrent changes and detect patterns in complex natural systems. Another feature is its self-learning capability [24]. A comparison on ANN model and multiple linear regression (MLR) have been published to determine the reliability of a correlation between estimation and measured absorption coefficient of perforated panels [25]. The study conducted a series of experimental measurements in the reverberation room to evaluate the sound absorption characteristics of three different type of perforated wooden panels and employed ANN and MLR models to compare both analytical results with the experimentation results. The analytical results produced by ANN exhibits satisfactory reliability of a correlation between estimation and the measured absorption coefficient while MLR cannot be applied to nonlinear cases as shown in Figure 2.5. In relation to this project, the study shows that ANN model can be useful tool for estimating the optimum configurations for producing the MPP.

Moreover, two recent studies have conducted optimizations for FDM process parameters and sample parameters using ANN approach [8], [26]. An optimization for the process parameters which is infill density, material density and extrusion temperature are trained using ANN and validated using genetic algorithm-artificial neural network (GA-ANN) to increase the tensile strength of FDM fabricated units [8]. From the study, three input process parameters (infill density, material density, and extrusion temperature) and output response (tensile strength) have been used to train the ANN model. The model uses Levenberg-Marquardt algorithm which attained the best overall R value of 0.97. Similar approach is conducted which used ANN model to predict the impact of drilling parameters (drill diameter, feed rate, and cutting speed) on the hole quality characteristics (surface roughness, circularity error, and cylindricity error) [26]. Both studies shows that ANN comprises a series of process parameters that influence the characteristics of the fabricated sample. As stated in previous sub-chapter, the MPP parameters have impact on the hole circularity production. Hence, the ANN method can be applied for this project to predict the optimum MPP parameters (hole diameter and panel thickness) on the quality of perforation holes on the MPP.

Development of ANN model requires suitable training algorithm based on the dataset used. Levenberg-Marquardt algorithm combines two numerical minimization algorithms, the gradient descent method and the Gauss-Newton method [27]. In the gradient descent method, the sum of the squared errors is reduced by updating the parameters in the steepest descent direction. If the algorithm used for linear parameters model, the least square objective is quadratic in the parameters. This objective may be minimized with respect to the parameters in one step via the solution to a linear matrix equation. The algorithm is used to train the network until the validation achieved the lowest mean square error (MSE) performance than the MSE of train and test performances [28].

The trained model can be tested using the same target data from the preprocessed ANN to determine its reliability to produce optimum configurations for MPP production. This method has been conducted to create a prediction comparison with the trained ANN model. This is because by comparing the ANN model prediction and the real output determines accuracy and reliability of the ANN model

[27]. The percentage error obtained from the trained network and the reliability of the model to predict the optimum configurations for producing the MPP can be achieved.

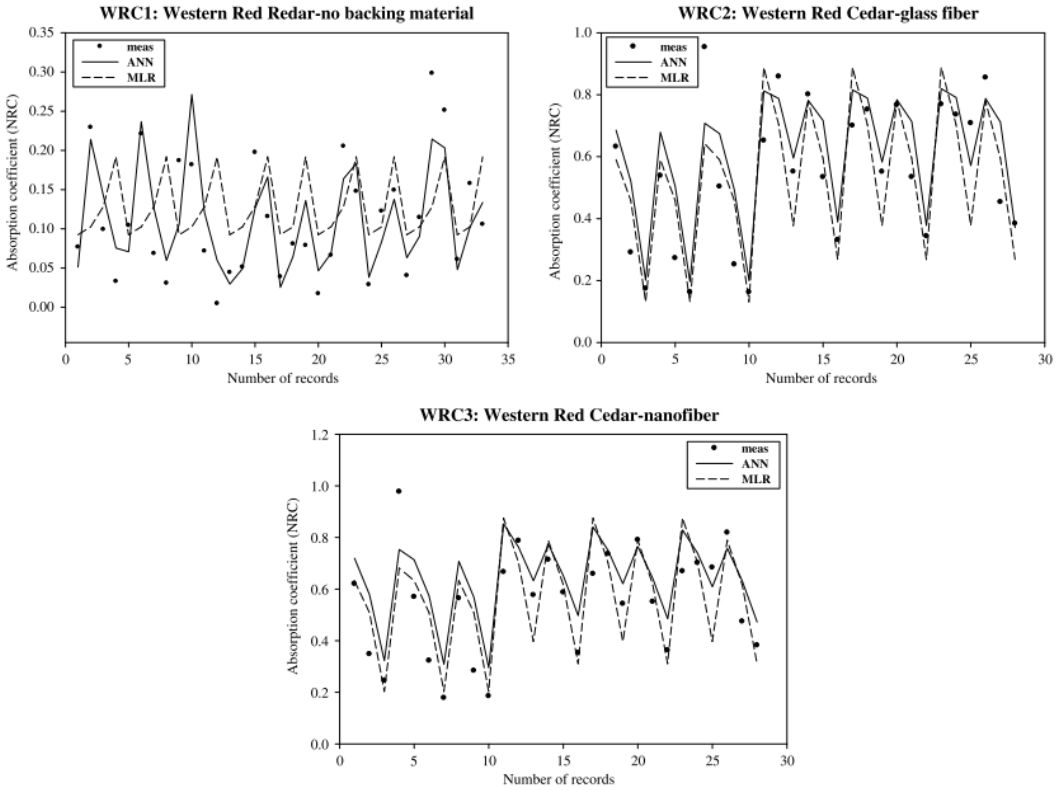

Figure 2.5: Comparison of absorption coefficient estimation models [25].

2.8 Methods for determining hole roundness

One of the parameters of MPP is the perforations which must be study to obtain the desired performance. As stated previously, several problems can be occurred during 3D printing which related to the hole accuracy since the holes on MPP is in micro size. Therefore, most of the related papers conducted evaluation and measurement on the deviations of the circularity to obtain effective hole diameter and error of circularity [7], [29]. The circularity can be calculated to determine how close the hole to a true circle while the error of circularity is determined to analyze the hole quality produce by each MPP samples using the equations provided in equation (2.6) and equation (2.7), respectively.

$$Circularity, C = \frac{D_{min}}{D_{max}} \tag{2.6}$$

$$Error\ of\ circularity = R_{max} - R_{min} \quad (2.7)$$

Similar approach by Bharatish et al., but they focused on heat affected zone in pulsed CO2 laser drilling of alumina ceramics. Still, it can give some insights to measure the hole circularity shown in Figure 2.6. They determined the circularity of the hole at the entry and exit using equations minimum and maximum diameters at the entrance and exit of the hole, respectively, which provided in equation (2.8) and equation (2.9) below.

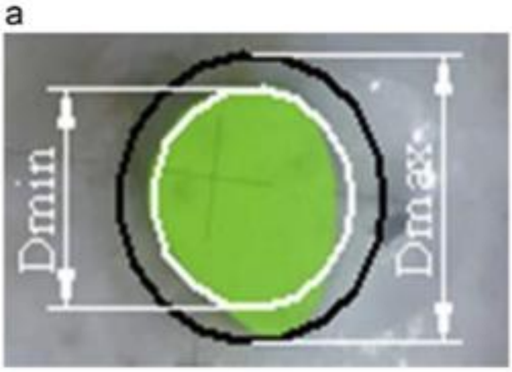

Figure 2.6: Hole perimeter analysis using segmentation algorithm [].

$$C_{entry} = \frac{D_{min}}{D_{max}} \quad (2.8)$$

$$C_{exit} = \frac{d_{min}}{d_{max}} \quad (2.9)$$

Recently, hole perimeter analysis in microscopic scale using segmentation algorithm has been carried out to calculate the actual hole area and the effective circular hole diameter as shown in Figure 2.7. The average value was considered in the subsequent calculations according to the actual frequency distribution of the effective diameters [10]. This method will be useful for this study to measure the circularity of microscopic scale holes. An article regarding image segmentation using GUI feature in MATLAB software have been conducted which presented the most suitable value of parameters for the segmentation of different types of imagery [30]. The parameters conducted are Edge Based Segmentation Algorithms, Thresholding Based Algorithms, Region Based Algorithms, Cluster Based Segmentation, and Graph Based Algorithms. From the study, the results of graph-based or graph-cut methods are better than the other methods and a better segmentation result can be achieved when the blurring is applied. The graph-cut is produced by segmenting of an object from the background and formulated into energy function which each pixel is a node connected by weighted edges [31]. However, the proposed system has its own limitation which is that the system is not suitable for different type of images by using a single algorithm [30]. Therefore, the images to apply the graph-cut algorithm must have fixed background and foreground colors.

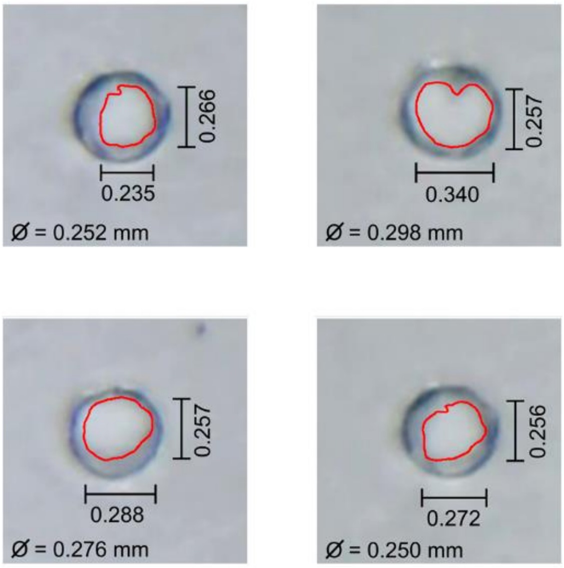

Figure 2.7: Hole perimeter analysis using segmentation algorithm [30].

The idea of circularity is how close is the particle geometry or 2D projection to a perfect circle [32]. The same article provided the two dimensional measurement of particle geometry which is circularity as defined in ISO standard 9276-6/2006 [33]. In comparison with other methods of evaluating the hole measurement, the circularity of a 2D image which defined by ISO standard can give a good interpretation as a ratio of area and perimeter of a circle. It is suitable to use in MATLAB program that calculate both area and perimeter of a segmented image in term of pixel counts rather than standard measuring system. Therefore, it is essential to apply the circularity measurement method in this project. Circularity value of 1 represents a perfect circle whereas value of lower than 1 means that the circle is imperfect.

2.9 Summary

This section will summarize all the information and studies obtained from the literature reviews. MPP sound absorber is evolving to become the next generation sound absorber which made up of softer materials like plastic and resin to achieve sustainability. MPP is acting like a resonant absorber which comprises of four effective parameters such as hole diameter, panel thickness, backed air space with rigid wall, and porosity. The parameters are optimizable to achieve high transmission loss. Several studies have proposed methods to design the MPP for its applications, but it is not the case for this project. Nonetheless, the proposed methods have provided the correlation between the effective parameters with the performance of an MPP. A few problems have been mentioned mainly on producing the perforation holes using AM process. Mostly the fabricated holes were resulting in irregular and inconsistent shape which can deviate from the theoretical calculations. Moreover, one study observed that internal condition of the hole does not fit with Maa's theory due to loss of viscous energy inside the hole.

Then, further analysis on AM configurations have been conducted to determine the controlled parameters during fabrication process. This project will account the panel thickness and hole diameter as the controlled parameters as suggested by previous studies. Most of previous studies determined irregular hole shape by using effective circular hole diameter method. Further research has found more effective way to determine hole roundness by using image segmentation method and circularity measurement using ISO standard is proposed to evaluate the hole condition. The controlled parameters are then applied in ANN along with the circularity measurement to predict the optimum configurations for producing the best hole roundness.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this project, the samples are produced into two categories, first batch sample and second batch samples. The first batch sample consists of one sample whereas the second batch samples consist of five samples. All samples were designed using SolidWorks software with defined parameters and fabricated using PolyJet machine with varying sample thickness and hole diameters. The first batch sample is produced to validate an initial hypothesis regarding the deviations due to AM process can be eliminated or reduced by determining a mean deviation from the parameters.

The first batch is designed with same thickness and varying hole diameters to determine the deviations produced from the fabrication process. The sample is measured by using Digital Profile Projector with accuracy of ±0.0001mm. The measured deviations will be used to design the second batch samples of varying parameters and measured using the same machine. After all samples were fabricated, the hole on each sample is captured individually using high resolution Alicona microscope. The images were imported in MATLAB software to process the image using graph-cut image segmentation method. A code provided in Appendix A is constructed to measure the area and perimeter of each hole in term of pixel unit for determining its circularity.

The measured parameters including circularity and designed parameters from the SolidWorks were employed in feed-forward propagation ANN model as input data and target data, respectively. This procedure is known as ANN preprocessing. The ANN model is trained multiple times until the validation result achieve lowest mean-squared error (MSE). After that, the trained model is tested using the preprocessing target data to validate the prediction accuracy. If the prediction accuracy is low (mean error is more than 5%), the trained ANN model is accepted and successful to determine the optimum configurations (best circularity or hole roundness) for producing MPP. Otherwise, the trained model is not valid and retrain process should be conducted. Note that this method is used to achieve best hole roundness on MPP by neglecting the surface roughness inside the hole. Figure 3.1 as illustrated below is a summarized flow chart for the methodology part.

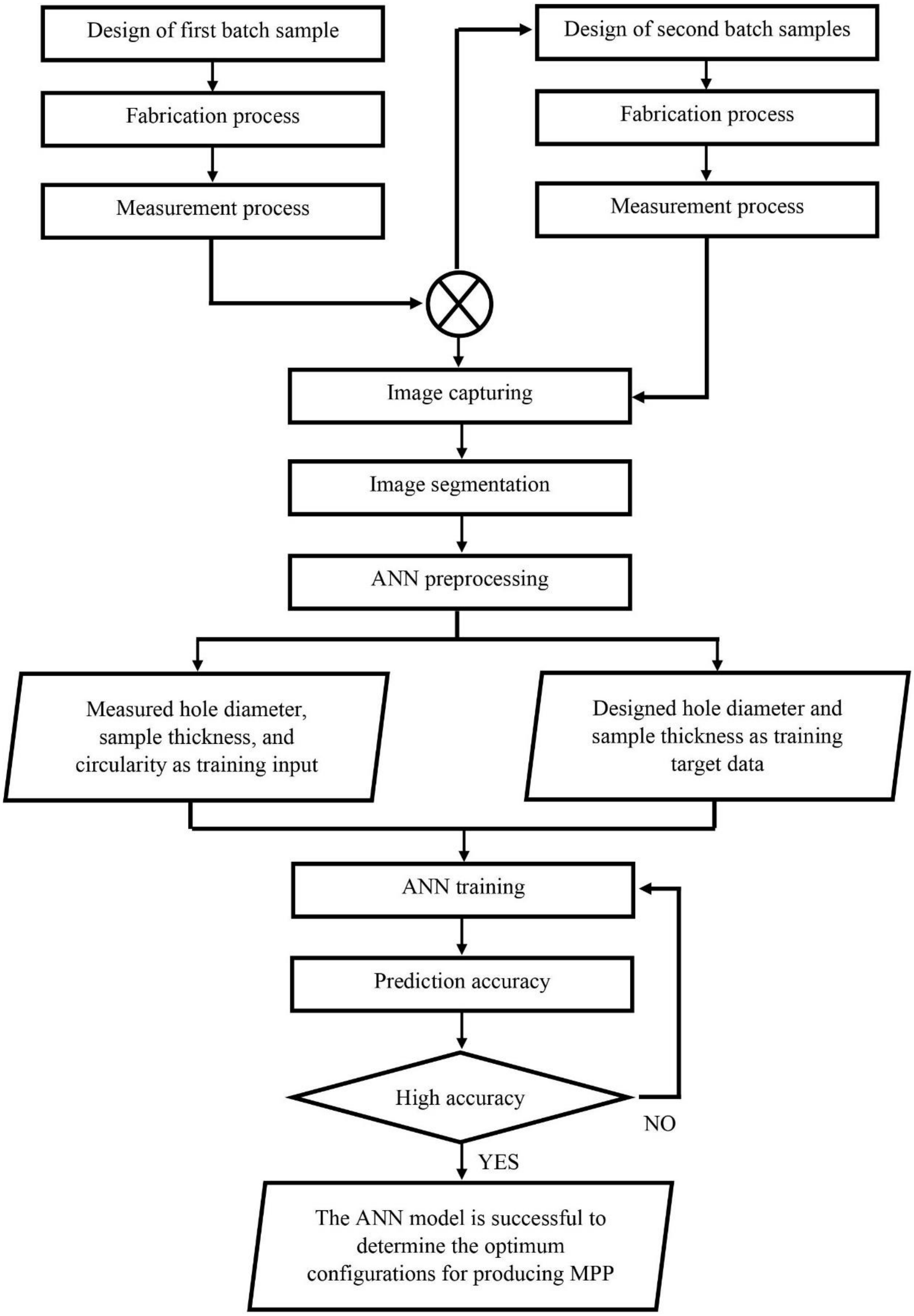

Figure 3.1: Project flow chart

3.2 Fabrication of samples

The first batch sample consists of one sample (Sample 1) with varying submillimeter holes diameter and constant thickness, whereas the second batch samples (Sample 2, 3, 4, 5, and 6) consist of five samples with different parameters (sample thickness and hole diameter). All samples were designed by using CAD software and converted to 'STL' file for fabrication process using PolyJet machine.

3.2.1 First batch sample

The first batch sample is designed using SolidWorks software with initial designed hole dimensions as shown in Table 3.1, which consists of 6 holes per designed diameter to investigate the deviations produced from the fabrication process. Each row of the holes comprised of two different space distances between each hole; top three holes have 5mm distance whereas bottom three holes have 10mm distance. The distance between holes is constructed to determine the effect of porosity on the production of imperfection holes. Therefore, the total number of designed holes on the sample is 36 holes.

The sample is fabricated using Objet30 Scholar which shown in Figure 3.2. The Objet30 Scholar is a PolyJet machine with a powerful 3D printing technology that produces smooth, accurate parts, prototypes, and tooling. The machine uses multiple print heads to deposit liquid plastic and curing approach which provides microscopic layer resolution and accuracy down to 0.014 mm. The material used to fabricate the sample is VeroWhite Plus RGD835. Hole diameters of 0.5mm and 0.6mm from the fabricated sample as shown in Figure 3.3 produced invalid hole results due to excess residue from the material is clogged completely inside the holes. Hence, both hole diameters are excluded from further analysis.

Table 3.1: Designed parameters of first batch sample.

Sample thickness (mm)	Hole diameter (mm)					
1.0	0.5	0.6	0.7	0.8	0.9	1.0

Figure 3.2: Objet30 Scholar 3D Printer

Figure 3.3: First batch sample (Sample 1)

3.2.2 Second batch samples

Five samples of multiple holes are designed with varying parameters and fabricated using same AM method. Each sample is made up of 25 holes in total with 5 holes of same hole diameter on every row. The designed parameters of the samples, as shown in Table 3.2, are constructed based on mean deviation obtained from the hole diameter measurement of the first batch sample which discussed in the next section. Furthermore, each hole is designed with same distances (10mm) between the holes. Two samples are rejected which is sample 5 and 6 because the thickness of the sample is too small and soft for MPP applications. Thus, both samples are neglected from further analysis. The accepted samples in Figure 3.4 shows Sample 2, Sample 3, and Sample 4, from left respectively.

Table 3.2: Designed parameters of second batch samples.

Sample	Sample thickness (mm)	Hole diameter (mm)				
1	0.6413	1.2587	1.1587	1.0587	0.9587	0.8587
2	0.5413	1.2587	1.1587	1.0587	0.9587	0.8587
3	0.4413	1.2587	1.1587	1.0587	0.9587	0.8587
4	0.3413	1.2587	1.1587	1.0587	0.9587	0.8587
5	0.2413	1.2587	1.1587	1.0587	0.9587	0.8587

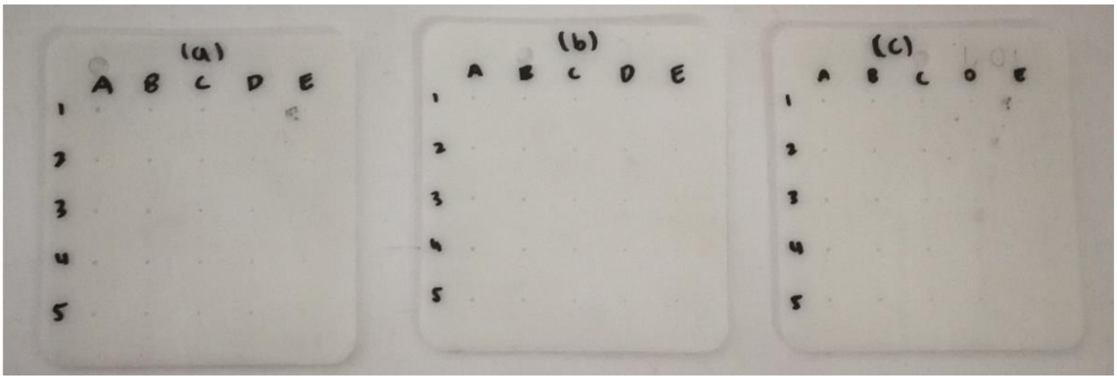

Figure 3.4: Accepted second batch samples.

3.3 Hole diameter and thickness measurement

The diameter of the holes on all samples are measured based on 6 measurement points as shown in Figure 3.5 to obtain the mean hole diameter by using Digital Profile Projector which is shown in Figure 3.6. The projector used least square circle method to determine the mean hole diameter with an accuracy of 0.001mm. The projector has a similar operation to coordinate measuring machine (CMM) which operated by positioning the pointer onto the hole contour that display on the screen. The thickness of the samples is measured by using vernier caliper as shown in Figure 3.7 with a sensitivity of 0.05mm.

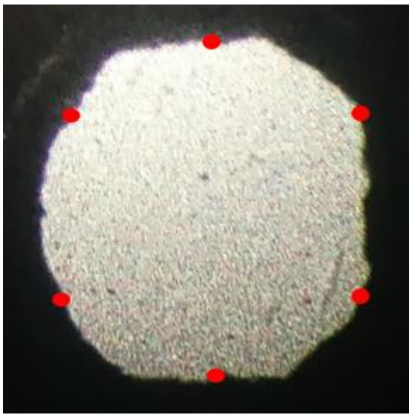

Figure 3.5: Six-point measurement on the hole

Figure 3.6: Digital Profile Projector

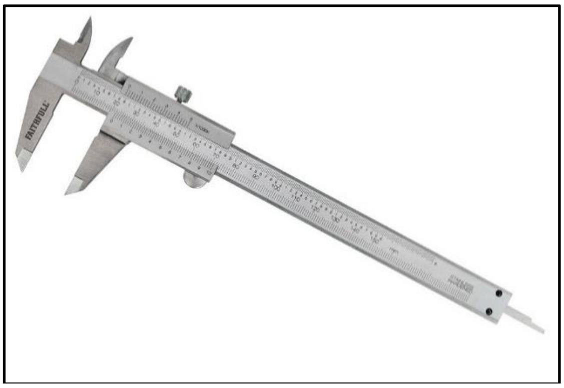

Figure 3.7: Vernier calliper

3.3.1 First batch sample measurement

The first batch sample is represented as Sample 1 and the perforation holes on this sample are labelled as hole number 1 to hole number 24 as listed in Table 3.3 below. The measured parameters for the first batch sample are tabulated in the table to compare the measurement results with the designed parameters for calculating mean deviation produced during the fabrication process. The mean deviation obtained from the measured hole diameter and panel thickness are 0.2587mm and 0.35mm, respectively. This method is conducted to perform the initial hypothesis stated in Section 3.1 by producing new samples to analyse the error from the AM method. Hence, the mean deviations calculated are applied in the CAD model for producing the second batch samples.

Table 3.3: Measured parameters of first batch sample.

Hole number	Designed hole diameter (mm)	Measured hole diameter (mm)	Designed thickness (mm)	Measured thickness (mm)
1	1.0	0.6529	1.00	1.35
2	1.0	0.6319		
3	1.0	0.6726		
4	1.0	0.6577		
5	1.0	0.6472		
6	1.0	0.6338		
7	0.9	0.5759		
8	0.9	0.5786		
9	0.9	0.5694		
10	0.9	0.5914		
11	0.9	0.5666		
12	0.9	0.5920		
13	0.8	0.4570		
14	0.8	0.4951		
15	0.8	0.4659		
16	0.8	0.4466		
17	0.8	0.4657		
18	0.8	0.4426		
19	0.7	0.3393		
20	0.7	0.3782		
21	0.7	0.3613		
22	0.7	0.3257		