Investigation on the Acoustic Absorption of Flexible Micro-Perforated Panel with Ultra-Micro Perforations

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Abstract. Flexible micro-perforated panel has unique advantages in noise reduction due to its good flexibility compared with traditional rigid micro-perforated panel. In this paper, flexible micro-perforated panel was prepared by computer numerical control (CNC) milling machine. Three kinds of plastics including polyvinylchloride (PVC), polyethylene terephthalate (PET), and polyimide (PI) were taken as the matrix materials to prepare flexible micro-perforated panel. It has been found that flexible micro-perforated panel made of PET possessing good porosity and proper density, elastic modulus and poisson ratio exhibited the best acoustic absorption properties. The effects of various structural parameters including perforation diameter, perforation ratio, thickness and air gap have also been investigated, which would be helpful to the optimization of acoustic absorption properties.

1. Introduction
Micro-perforated panel (MPP) has been widely used in acoustics design for many years, and it has the advantages of tunable sound absorption peak frequency and robust noise reduction properties. The perforation diameter of micro-perforated panel was reduced to sub-millimeter dimension, thus to provide enough acoustic resistance and low acoustic mass reactance for desired acoustic absorption behavior. The theory model of micro-perforated panel acoustic absorber was firstly proposed by Maa [1], who has developed the general model to predict the acoustic absorption coefficients [2, 3]. The acoustic behavior is related to various structural parameters including perforation diameter, hole distance, panel thickness, and the depth of back air gap. Compared with traditional rigid micro-perforated panel, flexible micro-perforated panel has good flexibility and deformability. Therefore, it could well meet the demand of particular noise reduction of equipment with complicated geometrical shapes. Flexible micro-perforated panel has gradually become the research hot spot in recent years.

To investigate the vibro-acoustic effects of flexible micro-perforated panel, Lee and Swenson [4] have studied the acoustic absorption behavior of compact sound absorber. The results indicated that panel vibration plays an important role in the acoustic properties of the absorber. Hereafter, various models have been proposed to characterize the vibro-acoustic effects on the acoustic absorption of flexible micro-perforated panel, where Maa’s transfer impedance definition of aperture in parallel was taken [5-7]. On the other hand, various acoustic absorption structures based on flexible
micro-perforated panel have been developed, such as hybrid passive-active noise control system [8],
multiple layers of flexible micro-perforated panel for enhanced acoustic absorption [9], and flexible
micro-perforated panel absorber made of piezoelectric film [10]. According to Maa’s model [11],
micro-perforated panel with diminished perforation diameters could effectively increase the energy
dissipation of viscous flow and thus improve the acoustic absorption properties. To the best
knowledge of us, there is few studies concerning the acoustic behavior of flexible micro-perforated
panel with micro-scale perforations (approximate 100 μm). It is feasible for conventional processing
methods to make micro-perforated panel with perforation diameters more than 200 μm. However, it is
still a challenge to fabricate flexible micro-perforated panel with such small sized perforations of
approximate 100 μm. Furthermore, the effects of different structural parameters on the acoustic
absorption of flexible micro-perforated panel has not been reported.

In the present work, computer numerical control (CNC) milling machine was taken to prepare
flexible micro-perforated panel. Three kinds of plastics including polyvinylchloride (PVC),
polyethylene terephthalate (PET), and polyimide (PI) were utilized as the raw materials of flexible
micro-perforated panels. The purpose of this study is to investigate the effects of different plastic
materials on acoustic absorption behavior. In addition, we have further studied the role of perforation
diameter, perforation ratio, thickness and air gap distance in the determination of acoustic absorption
properties.

2. Materials and methods

Micro-perforated panel could be considered as a lattice consists of short narrow tubes. The
perforations are separated by distances much larger than hole diameters, but rather small compared to
the wavelength of acoustic waves. The propagation of acoustic wave in the tube was defined by
Rayleigh and Crandall. Maa has further developed an approximate solution for micro-perforated panel
with sub-millimeter sized apertures [1]. The diagrammatic sketch and equivalent circuit of
micro-perforated panel (MPP) are shown in figure 1. According to Maa’s model, the acoustic wave in
the system is equivalent to a source of 2p pressure, and micro-perforated panel backed with an air gap
space could be seen as a resonant system. The acoustic behavior of such a system was determined by
the perforation diameter d, the panel thickness t, the distance between centers of adjacent perforations
b and the depth of the air gap D. The acoustic impedance of micro-perforated panel Z and impedance
of the air space ZD can be expressed as follows:

\[ Z = R + j \omega M \]  \hspace{1cm} (1)

\[ Z_D = -j \rho c \cdot \cot(\omega D / c) \]  \hspace{1cm} (2)

The normal incident acoustic absorption coefficient \( \alpha \) and maximum normal incidence acoustic
absorption coefficient \( \alpha_m \) of micro-perforated panel with air gap can be calculated by the equations as
follows [11, 12]:

\[ \alpha = \frac{4r}{(1 + r)^2 + (\omega m - \cot(\omega D / c))^2} \]  \hspace{1cm} (3)

\[ \alpha_m = \frac{4r}{(1 + r)^2} \]  \hspace{1cm} (4)

where \( r \) is the normalized specific acoustic resistance, \( m \) is the normalized acoustic mass respectively.
In addition, \( \rho \) is the density of air, \( c \) is the sound velocity in air, \( \eta \) is dynamic viscosity constant of air,
\( k \) is the perforated constant, \( \mu = \eta / \rho \) is kinematic viscosity constant of air. The equations are as
follows:

\[ r = \frac{32 \mu t}{\rho c d^2} \left( \sqrt{1 + \frac{k^2}{32}} + \frac{\sqrt{2k}}{8} \cdot \frac{d}{t} \right) \]  \hspace{1cm} (5)
\[ m = \frac{t}{\rho c} \left( 1 + \frac{1}{\sqrt{1 + k^2 / 2}} + 0.85 \frac{d}{t} \right) \]  

(6)

\[ k = \sqrt{\frac{2 \pi f}{\mu} \cdot \frac{d}{2}} \]  

(7)

Figure 1. (a) Schematic diagram and (b) equivalent circuit of micro-perforated panel (MPP) absorber.

In this study, the normal incidence absorption coefficient was measured by an impedance tube based on the standing wave method of ISO 10534-2 (Determination of sound absorption coefficients and impedance tubes, 1998). The schematic diagram of test equipment is shown in figure 2. The standard acoustic source of loudspeaker was placed at one end of the tube, and test sample was fixed at the other end. The acoustic field in the tube consists of incident and reflected waves. The maximum and minimum values of standing wave acoustic pressure can be collected by moving the pulley in the orbit. These measured results were repeated at least three times and the average values were taken.

Figure 2. Illustration of impedance tube test system for acoustic absorption coefficients.

Micro-perforated panels were made by computer numerical control (CNC) milling machine. The perforation diameters \( d \) of prepared micro-perforated panel was ranged from 0.085 mm to 0.15 mm, which have been measured by stereo microscopes. Three kinds of materials including
polyvinylchloride (PVC), polyethylene terephthalate (PET), and polyimide (PI) were taken to fabricate flexible micro-perforated panels.

3. Results and discussions

3.1. Effects of materials

In this section, polyvinylchloride (PVC), polyethylene terephthalate (PET), and polyimide (PI) were used to prepare flexible micro-perforated panels. All the fabricated micro-perforated panels have the consistent structural parameters, where the perforation diameter d is 0.1 mm, thickness t is 0.1 mm, hole spacing b is 0.633 mm, and perforation ratio p is 1.957 %. The acoustic absorption coefficient of obtained flexible micro-perforated panels were tested by impedance tube. The measured results were further compared with Maa’s model, as shown in figure 3. It could be observed that the absorption bandwidths of three specimens are moved to low frequency range. Considering that the flexible micro-perforated panel has better flexibility and deformability than the rigid MPP of Maa’s, the absorption peaks due to the panel’s vibration and the micro-perforation appear at the lower resonant frequencies. The measured results of PI sample exhibited the biggest deviation in comparison with the simulation results of Maa’s model, and the acoustic absorption property in high frequency is obviously decreased, which could be by reason of large viscosity and poor machinability. PVC and PET samples have the approximative absorption curves at the frequency range higher than 3000 Hz, while PET has better acoustic absorption properties when the frequency is lower than 3000 Hz. For instance, the acoustic absorption coefficient of PET is 10.6 % higher than that of PVC at 1500 Hz. By comparing the material properties of the two, it has been found that they have similar poisson ratio, but PET has better elastic modulus and bending performance, which account for this consequence. Therefore, it could be concluded that flexible micro-perforated panel made of PET has wider absorption bandwidth and better acoustic properties than PVC and PI samples.

![Graph](image)

**Figure 3.** Comparison of Maa’s model with the measured normal absorption coefficient of different materials including PET, PVC and PI.
3.2. Effects of structural parameters
We have further studied the effects of different structural parameters on acoustic absorption properties. Firstly, four flexible micro-perforated panels with different perforation diameter were prepared. The structural parameters are listed in table 1. It can be seen that all the samples with the same thickness \( t \) of 0.1 mm and the consistent perforation ratio \( p \) of 1.957 %, while the diameter \( d \) ranged from 0.085 mm to 0.15 mm. The test results of absorption coefficient are shown in figure 4. The absorption peak is higher than 0.95 when the diameter is 0.085, 0.1 or 0.12 mm. However, the acoustic absorption peak is decreased obviously when the diameter is 0.15 mm. The absorption bandwidth is gradually increased with the decrease of diameter, and the flexible micro-perforated panel with 0.085 mm diameter has approximate 3 absorption octaves. Therefore, it could be concluded that flexible micro-perforated panel with reduced aperture diameter is benefit to broaden the absorption bandwidth and increase the absorption peak.

Table 1. Structural parameters of four flexible micro-perforated panels with different perforation diameters.

| Specimen | \( d \) (mm) | \( t \) (mm) | \( b \) (mm) | \( D \) (mm) | \( p \) (%) |
|----------|--------------|--------------|-------------|--------------|-------------|
| #1       | 0.085        | 0.1          | 0.538       | 15           | 1.957       |
| #2       | 0.1          | 0.1          | 0.633       | 15           | 1.957       |
| #3       | 0.12         | 0.1          | 0.76        | 15           | 1.957       |
| #4       | 0.15         | 0.1          | 0.95        | 15           | 1.957       |

Figure 4. Normal absorption coefficient of flexible micro-perforated panels with different diameters.

Flexible micro-perforated panels with different perforation ratio were also prepared; the structural parameters are listed in table 2. The perforation ratio of four samples ranged from 1.061 % to 4.55 %. As can be seen from figure 5, with the increase of perforation ratio, the maximum absorption
Coefficient is gradually decreased, and the absorption peak is moving to high frequency range. Therefore, the appropriate perforation ratio is benefit to increase acoustic absorption properties at high frequency range and broaden the absorption bandwidth. In this study, flexible micro-perforated panel with the perforation ratio of 1.957 % has the best acoustic absorption properties.

**Table 2. Structural parameters of four micro-perforated panels with different perforation ratio.**

| Specimen | d (mm) | t (mm) | b (mm) | D (mm) | p (%) |
|----------|--------|--------|--------|--------|-------|
| #1       | 0.1    | 0.1    | 0.86   | 15     | 1.061 |
| #2       | 0.1    | 0.1    | 0.633  | 15     | 1.957 |
| #3       | 0.1    | 0.1    | 0.52   | 15     | 2.903 |
| #4       | 0.1    | 0.1    | 0.42   | 15     | 4.55  |

**Figure 5.** Normal absorption coefficient of flexible micro-perforated panels with different perforation ratio.

The structural parameters of four micro-perforated panels with different thickness are shown in table 3. It can be seen that the thickness of all samples ranged from 0.1 to 0.3 mm. With the increase of thickness, the maximum absorption coefficient is gradually decreased, and absorption peak moved to the low frequency range. In addition, the absorption bandwidth is narrowing, as can be observed from figure 6. Therefore, it can be stated that flexible micro-perforated panel with thinner thickness is benefit to improve acoustic absorption.
Table 3. Structural parameters of four micro-perforated panels with different thickness.

| Specimen | d (mm) | t (mm) | b (mm) | D (mm) | p (%) |
|----------|--------|--------|--------|--------|-------|
| #1       | 0.1    | 0.1    | 0.633  | 15     | 1.957 |
| #2       | 0.1    | 0.15   | 0.633  | 15     | 1.957 |
| #3       | 0.1    | 0.2    | 0.633  | 15     | 1.957 |
| #4       | 0.1    | 0.3    | 0.633  | 15     | 1.957 |

Figure 6. Normal absorption coefficient of flexible micro-perforated panels with different thickness.

Furthermore, we have studied the acoustic absorption properties of flexible micro-perforated panels with different air gap distance, the detailed parameters are listed in table 4. It can be observed from figure 7 that all the four specimens have the similar absorption peak with different air gap distance. However, the increase of air gap distance is benefit to improve the acoustic absorption properties at low frequency range.

Table 4. Structural parameters of flexible micro-perforated panels with different air gap.

| Specimen | d (mm) | t (mm) | b (mm) | D (mm) | p (%) |
|----------|--------|--------|--------|--------|-------|
| #1       | 0.1    | 0.1    | 0.633  | 10     | 1.957 |
| #2       | 0.1    | 0.1    | 0.633  | 15     | 1.957 |
| #3       | 0.1    | 0.1    | 0.633  | 20     | 1.957 |
Figure 7. Normal absorption coefficient of flexible micro-perforated panels under different air gap distance.

4. Conclusions
In this work, we have mainly studied the acoustic absorption properties of flexible micro-perforated panel. It has been found that flexible micro-perforated panel appropriately fusing the structural resonances and the micro-perforation exhibited wider absorption bandwidth than the simulation values of Maa's model. Flexible micro-perforated panel made of PET has better mechanical behaviors such as excellent toughness and elasticity, thus show greater acoustic absorption properties than PVC and PI samples. The maximum absorption peak and absorption bandwidth were mainly determined by perforation diameter and perforation ratio. The reduced diameter is benefit to increase the acoustic absorption bandwidth, and flexible micro-perforated panel with 100 μm diameter exhibited approximate 3 octaves. Appropriate perforation ratio is also helpful to improve the acoustic absorption properties, while the air gap depth has little effect on the absorption bandwidth of the flexible. Flexible micro-perforated panel with thinner thickness can also improve the acoustic absorption properties.

References
[1] Maa D Y 1975 Sci Sin. 17 55-71.
[2] Maa D Y 1987 Noise Contr. Eng. J. 29(3) 77-84.
[3] Dah-You M 1998 J. Acoust. Soc. Am. 104 2861-6.
[4] Lee J and Swenson G W 1992 Noise Contr. Eng. J. 38(3) 109-17.
[5] Lee Y Y, Lee E W M and Ng C F 2005 J. Sound Vibr. 287(1) 227-43.
[6] Bravo T, Maury C and Pinhede C 2012 J. Acoust. Soc. Am. 131 3853-63.
[7] Wang Y H, Zhang C C, Ren L Q, Ichchou M, Galland M A and Bareille O 2014 *Comp. Struct.* **108** 400-8.

[8] Zheng W G, Huang Q B, Li S D and Guo Z Y 2011 *J. Low Frequency Noise Vib. Act. Contr.* **30** 313-28.

[9] Bravo T, Maury C and Pinhede C 2013 *J. Acoust. Soc. Am.* **134** 3663-73.

[10] Duan X H, Wang H Q, Li Z B, Zhu L K, Chen R and Kong D Y 2015 *Appl. Acoust.* **88** 84-9.

[11] Maa D Y 2006 Acta Acust. **31** 181-4.

[12] Maa D Y 1998 *J. Acoust. Soc. Am.* **104** 2861-6.

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