Comparison Sound Absorption Methods of Multilayer Micro-perforated Panels

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Abstract. Micro-perforated panel (MPP) absorbers as the next-generation sound absorbers are getting more widely use in aviation, automobiles, construction and other fields. It’s a complex problem to predict the acoustic performance using surface impedance methods. The acoustic absorption performance of micro-perforated panels were compared in terms of Transfer matrix method and Equivalent electric circuit approach (EECA). The calculated results show that transfer matrix method is more convenient and effective than the equivalent circuit approach especially to multiply layer micro-perforated absorbers.

1. Introduction
Micro-perforated panels (MPP) has been widely used in harsh and corrosive environment. The diameter of MPP is sub-millimeter providing enough acoustic resistance and low acoustic [1-2]. Ma[3] has developed a theoretical model for circular cross-sectional MPP structures. A single-layer mechanical impedances structure combining a MPP exhibits a sound peak at the low frequency. However, the absorption frequency band is narrow for a single layer MPP. Most researchers [4-6] focused on estimate the absorption performances of MPP absorbers by equivalent electro-acoustic approach (EECA). By means of the circuit analysis, the resultant surface acoustic impedance is derived, if there is multiple layer perforated panel system, the circuit analysis becomes very complicated. The transfer matrix method [7-8] has become very popular for multi-layer absorber’s analysis. This paper predicted the sound absorption performance of by transfer matrix method comparison with EECA. The results show that the transfer matrix method is more simple and effective than EECA for multiple layer micro-perforated absorbers.

2. Transfer matrix method
Let us consider a rigid single layer micro-perforated panel backing with an air-space which makes a simple resonator as shown in Figure 1. For the case of a perforated panel with grazing flow, there is a impedance model could be expressed in terms of the porosity, thickness, hole diameter and frequency, well established by Rao and Munjal[9] as follows

$$\zeta = \left[ 7.337 \times 10^{-3} + j \phi 2.2245 \times 10^{-5} (1 + 51r) (1 + 204d)f \right] / \phi$$

(1)

where \(\phi\) is porosity, \(t\) panel thickness in \(mm\), \(d\) hole diameter in \(mm\), \(f\) frequency in \(Hz\), and \(M\) Mach number.
According to the Chang et al. [10] prediction the absorption coefficients compared with experimental results for correction the factor. Therefore, impedance of the perforated panel could be expressed as:
\[ \zeta = \left[ 7.337 \times 10^{-3} + j \delta \right] \times 2.2245 \times 10^{-5} (1 + 51t) (1 + 204d) / \phi \]

(2)

For micro-perforated absorbers, it is not necessary to provide extra fibrous or porous materials.

Figure 1. Perforated panel and impedance \( \zeta \).

Figure 2. Four-pole parameters of an acoustic cavity.

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\[
\begin{bmatrix}
    p_1 \\
    u_1
\end{bmatrix}
= 
\begin{bmatrix}
    E_{11} & E_{12} \\
    E_{21} & E_{22}
\end{bmatrix}
\begin{bmatrix}
    p_2 \\
    u_2
\end{bmatrix}
\]

(3)

where \( E_{11}, E_{12}, E_{21} \) and \( E_{22} \) are the four-pole parameters.

In the case of a perforated panel, the unit transfer matrix can be expressed by

\[
[P] = \begin{bmatrix}
    P_{11} & P_{12} \\
    P_{21} & P_{22}
\end{bmatrix} = \begin{bmatrix} 1 & \rho c \zeta \\ 0 & 1 \end{bmatrix}
\]

(4)

where \( \rho \) is the density of air, \( c \) the speed of sound in air and \( \zeta \) is the normalized acoustic impedance of the panel defined by

\[
\rho c \zeta = \Delta p / u
\]

(5)

we can obtain the matrix elements as follow:

\[
\begin{bmatrix}
    p_1 \\
    u_1
\end{bmatrix} = 
\begin{bmatrix}
    \cos kD & j \rho c \sin kD \\
    j \rho c \sin kD & \cos kD
\end{bmatrix}
\begin{bmatrix}
    p_2 \\
    u_2
\end{bmatrix}
\]

(6)

For an airspace of depth \( D \), the unit transfer matrix can be expressed:

\[
[S] = \begin{bmatrix}
    S_{11} & S_{12} \\
    S_{21} & S_{22}
\end{bmatrix} = 
\begin{bmatrix}
    \cos kD & (j / \rho c) \sin kD \\
    (j / \rho c) \sin kD & \cos kD
\end{bmatrix}
\]

(7)

where \( j = \sqrt{-1} \) and \( k \) is the wave number.

Figure 3. Configuration of multi-layer micro-perforated panel.

To broaden the range frequency of absorption, it is effective to use more layers of micro-perforated panels. Figure 3. shows the multiple layer micro-perforated panels backing with associated cavities.
The overall transfer matrix $[T]$ for a multi-layer perforated panel system can be obtained by multiplying all the unit transfer matrices as follows:

$$[T] = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = [P]_1 [S]_1 ... [P]_n [S]_n$$  \hspace{1cm} (8)

Then the state variables on the surface of the left and panel, number 1, can be expressed in terms of the overall transfer matrix and the variables at the right end number $n+1$, as follows:

$$\begin{bmatrix} p_1 \\ u_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p_{n+1} \\ u_{n+1} \end{bmatrix}$$  \hspace{1cm} (9)

Since the particle velocity $u_{n+1} = 0$ on a rigid plate, the acoustic pressure reflection coefficient $R$ can be expressed by the transfer matrix elements as

$$R = \frac{T_{11} - \rho c T_{21}}{T_{11} + \rho c T_{21}}$$  \hspace{1cm} (10)

For normal incidence, the sound absorption coefficient is defined by

$$\alpha = 1 - |R|^2$$  \hspace{1cm} (11)

3. Equivalent Electric Circuit Approach

In acoustic system analysis, the equivalent electric circuit approach (ECA) is one of the most popular approaches. The ECA method is very useful to analyse the acoustic propagation through a series parallel assembly acoustic perforation elements. Ma [3] found a simple approximate formula for the acoustic impedance of the micro-perforated panel $Z_{\text{panel}}$, which is:

$$R = 32 \eta t \left( \sqrt{1 + x^2 / 32} + \sqrt{2xd / 8t} \right) / \phi d^2$$  \hspace{1cm} (12)

$$M = t \rho \left( 1 + 1 / \sqrt{9 + x^2 / 2 + 0.85d / t} \right) / p$$  \hspace{1cm} (13)

$$x = \left( d \sqrt{\rho \omega / \eta} \right) / 2$$  \hspace{1cm} (14)

$$Z_{\text{panel}} = R + j \omega M$$  \hspace{1cm} (15)

where $\eta$ is dynamic viscosity of air$(= 17.9 \mu Pa s)$, $\rho$ is air density, $c$ the sound speed in air and $\omega$ the angular frequency of the sound, $\phi$ the perforation ratio, $d$ the hole diameter, $t$ the panel thickness. $R$ and $M$ are acoustic resistance and acoustic mass, respectively.

The impedance of airspace is

$$Z_D = -j \rho c \cot(\omega D / c)$$  \hspace{1cm} (16)

where $D$ is the thickness of the airspace. The configuration of single layer micro-perforated panel backing with airspace can be described by the equivalent electric circuit shown in Figure 4.

![Figure 4. Perforated panel structure and equivalent](image_url)
Figure 5 shows the structure of double micro-perforated panel absorber and equivalent electrical circuit and the subscripts 1 and 2 indicate the two resonator elements.

According to the equivalent circuit in Fig.5, the resultant acoustic impedance \( Z \) of the parallel circuit is

\[
Z = R_1 + j\omega M_1 + \frac{(R_2 + j\omega M_2 + Z_{D2})Z_{D1}}{R_2 + j\omega M_2 + Z_{D2} + Z_{D1}}
\]

(18)

where \( Z_{D1} \) and \( Z_{D2} \) are the acoustic impedances of the airspaces, respectively.

By substituting Eq.(18) to Eq.(12), the sound absorption coefficient of double layer MPM structure is obtained. All of the equations are solved by Matlab software since program becomes simply with complex number computation function.

4. Results and discussions

For comparing the effect of two methods, the normal incidence absorption coefficients are calculated using the transfer matrix(TFM) method and the equivalent electro-acoustic(ECA) method, respectively. In this part simulation, the parameter are as listed in Table.1

| Parameter   | Panel I   | Panel II  |
|-------------|-----------|-----------|
| Porosity \( \phi \) | 1%-3%     | 2%        |
| Thickness \( h \) | 2-6 mm    | 3 mm      |
| Hole diameter \( d \) | 0.8 mm    | 0.8 mm    |
| Airspace thickness \( D \) | 7 mm      | 7 mm      |

Figure 6. Comparison absorption coefficient by TFM method with ECA approach

Figure 7. Variation of the panel thickness of the single layer MPP absorber

Figure 6. reveals that the results solved by transfer matrix method also agree well with those computed by electro-acoustic analogy approach. Its absorption performance is limited to the resonance frequency region. Some more predictions are used to demonstrate the effect of important parameters.

Figure 7. shows the effects of the panel thickness on sound absorption coefficients of single layer micro-perforated panel. In this case, except for panel thickness \( t \), all the parameters are the same as in
the first case in previous case. It is seen from Fig.7 that reducing thickness of perforated panel increase the higher acoustic resonance frequency.

Figure 8. compares the sound absorption performance of single layer MPP by changing the porosity. In this case, except for panel porosity \( \phi \), all the parameters are the same as in the first case. It is seen from Fig.8 that the absorption coefficients calculated by transfer matrix method agree with the values by EECA method except the porosity over the 1%. The lower porosity of the micro-perforated panel has a lower acoustic resonance frequency and higher acoustic absorption performance. This is because the acoustic impedance of the panel increases with inversion proportion to the porosity, decrease in porosity results in increase of impedance of the system.

In order to make an efficient sound absorbing performance, double layer micro-perforated absorber is used, where each compartment is composed of one layer micro-perforated panel and airspace. Herein, the normal incidence absorption coefficients of the double layer micro-perforated panel absorber are discussed.

![Figure 8. Variation of the porosity of the single layer MPP absorber](image1)

![Figure 9. Variation of the porosity of the double layer MPP absorber](image2)

Figure 9. reveals that the acoustic resonance frequencies of the double layer absorbers are more broadband than those of the single layer absorbers. The highest acoustic resonance frequencies of those double layer absorbers are mostly higher than single layer compartments. The reason is that when the incident frequency is equal to the acoustic resonance frequency of the double layer structure, the air medium existing in the absorber will vibrate with the incident sound and the incident sound energy will be largely absorbed. They are suitable for any reverberation or noise control applications.

5. Conclusions

In this paper, the applicability and accuracy of the acoustic absorption performance analysis by transfer matrix method have been successfully demonstrated. As expected, the micro-perforated constructions can supply highly efficient sound absorbing performance without any porous materials. Besides, several the influence factors on sound absorption performance are also discussed include the thickness, holes diameter, porosity of the perforated panel and length of airspace. This provides a reliable reference for the design structure of the multi-layer micro-perforated panel absorbers.

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