THE EFFECT OF ACOUSTIC LEAKAGE ON THE SOUND ABSORPTION OF AN MPPSL

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The micro-perforated panel with shunted loudspeaker (MPPSL) absorber has been recently proposed, which provides a compact solution to broadband sound absorption by adjusting the electrical parameters in the shunted circuit. This paper investigates the leakage effect on the absorption of the MPPSL, where the absorption performance of an MPPSL under normal incidence with and without leakage is investigated based on the equivalent circuit model (EC) method instead of the modal analysis approach. Experiments are carried out to verify the proposed model, and both theoretical and experimental results show that another peak exists between the two resonance frequencies and the first resonance frequency shifts to lower frequency when leakage exists.

1. Introduction

A micro-perforated panel (MPP) consists of a thin sheet panel perforated with a lattice of sub-millimetre apertures which create high acoustic resistance and low acoustic mass reactance necessary for broadband sound absorption without further additional porous material.1 Because the light and fibreless MPPs can be made of various recyclable materials, they are becoming more and more widely used in noise control engineering today, especially in clean situations where strict hygiene required or in industrial environments where porous materials deteriorate.2 Furthermore, MPPs can be made of transparent plates or membranes, so they are also in demand by architects for sound quality control in auditoriums.3 MPP absorbers are tagged as the “next generation” absorbing materials due to their huge potential in comparison with conventional porous materials.4,5

A typical MPP absorber consists of a MPP fitted in front of a backing wall, with an air gap between them. The design principle of MPP absorber was proposed based on the equivalent circuit model (EC),1 which was further extended to consider the losses of the MPP’s panel vibration6 and the sound absorption of the back wall surface.6 The mode solution technique, based on the modal analysis solution of the classical plate equation coupled with the acoustic wave equation, is another general approach for the absorption formula, which can be used to study the coupling between a finite fixable MPP and the back cavity.2,7

In pursuit of better sound absorption performance, many methods were investigated, including double-leaf MPP, multi-layer MPPs8-10 arranged in series, MPPs backed by cavities with different depths in parallel or by an irregular cavity11,12, MPP with partitioning the air cavity and gluing the partition to the panels2,5,13, which can broaden the bandwidth to lower frequencies at the cost of large cavity depth. A big challenge for the design of the MPP absorber is to extend the absorption...
bandwidth to lower frequency and reduce the cavity depth simultaneously. Tao et al.\textsuperscript{14} have proposed the model of micro-perforated panel with shunted loudspeaker\textsuperscript{15} (MPPSL). The modal analysis approach was used to analyses MPPSL’s sound absorption, which demonstrated this model can achieve attractive low frequency performance meanwhile with small cavity depth by adjusting the electric circuit parameters.

The effect of small lateral air gaps on the normal incidence absorption coefficient of mono-layer and two layers porous materials is investigated. But a hybrid finite element-modal method is taken to study the coupling between the material and waveguide domains, instead of hard-controlling experimental mounting conditions.\textsuperscript{16} Selamet et al.\textsuperscript{17} have investigated the effect of leakage in Helmholtz resonators by varying levels of intentional leakage due to holes in the baffle and gaps between the baffle and the housing, which illustrates the critical need to account for such leakages at the design stage.\textsuperscript{17}

In this paper, the absorption performance of a MPPSL under normal incidence with leakage is investigated based on the equivalent circuit model (EC) method. A theory for describing the leakage effect between the loudspeaker and cavity is established, and then experiments are carried out to verify the theory.

2. Theory

A side view of the MPPSL is shown in Fig. 1(a) with a rectangular cross section with dimensions of $a$ and $b$ (on $x$-$y$ plane, not shown in the figure). A MPP is at $z = -(D_1+D_2)$ and a loudspeaker is at $z = -D_1$. The loudspeaker diaphragm divides the whole cavity into cavity I and cavity II with depth $D_1$ and $D_2$ separately. The loudspeaker together with cavity I and the electrical impedance $Z_E$ forms a shunted loudspeaker. Assume $p(x, y, t)$ is the sound pressure of the incident plane wave, $p_1(x, y, t)$ and $p_2(x, y, t)$ are the sound pressure just at the back of the MPP and the front of the loudspeaker diaphragm, and $v_1(x, y, t)$ and $v_2(x, y, t)$ stand for the particle velocity of the MPP and the loudspeaker diaphragm.\textsuperscript{14,18}

\begin{align}
Z_L &= \left( R_m S + j \omega M_m S + \frac{S}{j \omega C_{ss}} + \frac{B^2 l^2}{S(R_E + Z_E)} \right) \frac{ab}{S} + \frac{S}{j \omega C_{ss}} \frac{ab}{S} \quad (1)
\end{align}

\begin{figure}[h]
\centering
\begin{subfigure}{0.4\textwidth}
\centering
\includegraphics[width=\textwidth]{fig1a.png}
\caption{(a) Equivalent circuit model of the MPPSL (a) side view of the composite absorber MPPSL}
\end{subfigure} \quad \begin{subfigure}{0.4\textwidth}
\centering
\includegraphics[width=\textwidth]{fig1b.png}
\caption{(b) equivalent circuit model of the MPPSL}
\end{subfigure}
\end{figure}

Because the cross section of the proposed absorber is rectangular but the loudspeaker diaphragm is circular, the specific acoustic impedance at the loudspeaker diaphragm corrected can be described by\textsuperscript{14}

\[ Z_L = \left( R_m S + j \omega M_m S + \frac{S}{j \omega C_{ss}} + \frac{B^2 l^2}{S(R_E + Z_E)} \right) \frac{ab}{S} + \frac{S}{j \omega C_{ss}} \frac{ab}{S} \quad (1) \]
where, $R_E$ is the DC electrical resistance of the voice coil, $C_{as}$ is the acoustic compliance of the driver suspension, $M_{as}$ is the acoustic mass of the driver cone assembly including reactive air load, $R_{as}$ is the acoustic resistance of the driver suspension losses, $Z_E$ is the electrical impedance of the shunted circuit. $S$ is the effective surface area of the driver cone. $C_{ac}$ is the equivalent acoustic capacitance due to the back cavity with volume $V$ and $C_{ac} = V / \left( \rho_0 c_0^2 \right)$, where $\rho_0$ is the air density and $c_0$ is the sound speed in the air. Fig. 1(b) shows the equivalent circuit model of a MPPSL. The total relative acoustic impedance (in the unit of $\rho_0 c_0$) at the surface of MPP, can be obtained by

$$Z_{tot} = \frac{1}{\rho_0 c_0} \left( \frac{1}{R + j \omega M} + \frac{1}{j \omega m} \right)^{-1} + Z_D \rho_0 c_0$$

(2)

where, $j$ is the complex number, $\omega$ is the angular frequency, $d$ is the orifice diameter, $h$ is the panel thickness, $\eta$ is the coefficient of viscosity of the air, and $\sigma$ is perforation ratio, $R$ stands for the relative resistance of the MPP plate, while $M$ is the relative reactance of the MPP plate, $m$ is the surface density of the MPP leaf, $Z_D$ is the relative transfer impedance.

$Z_D$ in Eq. (2) can be derived from $Z_L$ by the impedance transfer method, expressed as:

$$Z_D = \frac{\rho_0 c_0 Z_L + j \rho_0 c_0 \tan(\omega D_2 / c_0)}{\rho_0 c_0 + j Z_1 \tan(\omega D_2 / c_0)}$$

(3)

Therefore, the absorption coefficient of the MPPSL can be calculated by

$$\alpha = \frac{4 \text{Re}(Z_{tot})}{\left(1 + \text{Re}(Z_{tot}) \right)^2 + \left(\text{Im}(Z_{tot}) \right)^2}$$

(4)

Fig. 2 shows a side view of the shunted loudspeaker (SL) considering acoustic leakage between the loudspeaker and cavity. The center of the leakage is at $z = -L_{bo}$ and the width of the leakage $l_b = L_b - D_1$. While the leakage length is $l_0$, the height length is $h_0$ and the cross-section area is $S_b$ (not shown in Fig. 2). Assume $p_i(x, y, t)$ is the incident plane wave, $p_t(x, y, t)$ is the reflected plane wave, $p_b(x, y, t)$ is the transmitted plane wave, $v_i(x, y, t)$ and $v_t(x, y, t)$ are both the sound pressure of the plane wave in the leakage ducts at the surface of the leakage center, and $v_1(x, y, t), v_i(x, y, t), v_t(x, y, t), v_b(x, y, t)$ and $v_{b1}(x, y, t)$ stand for the particle velocity at the surface of the leakage center accordingly.

![Figure 2. Side view of the SL considering acoustic leakage](image-url)
At the surface of the leakage, the sound pressure and the particle velocity can be expressed as,

\[
\begin{align*}
    p_i &= p_0 e^{i\omega t}, \quad v_i = p_i / (\rho_0 c_0) \\
    p_r &= p_0 e^{i\omega t}, \quad v_r = -p_r / (\rho_0 c_0) \\
    p_t &= p_0 e^{i\omega t}, \quad v_t = p_t / (Z_{ps}S) \\
    p_{b1} &= p_{ab1} e^{j\omega t}, \quad v_{b1} = p_{b1} / (Z_{b1}S_b) \\
    p_{b2} &= p_{ab2} e^{j\omega t}, \quad v_{b2} = p_{b2} / (Z_{b2}S_b)
\end{align*}
\]

(5)

where,

\[
Z_t = \frac{1}{j \omega C_{ac}} = \frac{\rho_0 D_j}{j \omega V L_{bo}}
\]

(6)

Because the terminal of the lateral branch is open to the air, the acoustic impedance of the branch can be expressed as:

\[
Z_{b1} = Z_{b2} = Z_b = j \omega \rho_0 (l_0 + 0.85a_0) / (h_0 d_b)
\]

(7)

where, \(a_0 = \sqrt{h_0 l_b / \pi}\) represents the effective radius of the leakage part.

At the surface of the leakage center, the acoustic impedance can be derived from Eq. (8) and Eq. (9), which is expressed as Eq. (10).

\[
\begin{align*}
    p_i + p_r &= p_t = p_{b1} = p_{b2} \\
    U_i + U_r &= U_t = U_{b1} + U_{b2} \\
    Z_{bo} &= (1 / Z_t + 2 / Z_b)^{-1}
\end{align*}
\]

(10)

The specific acoustic impedance at the loudspeaker diaphragm can be described from Eq. (1) and Eq. (10) by the impedance transfer method, expressed as:

\[
Z_L = \left( R_{as} S + j \omega M_{as} S + \frac{S B^2 \xi^2}{j \omega C_{as}} \right) \frac{ab + j \rho \xi_0 Z_{bo} + j \rho \xi_0 \tan(\omega (L_b - L_{bo}) / c_0)}{ab \rho \xi_0 + j Z_{bo} \tan(\omega (L_b - L_{bo}) / c_0)}
\]

(11)

Therefore, the total relative acoustic impedance (in the unit of \(\rho_0 c_0\)) at the surface of the MPP, can be obtained by substituting Eq. (11) into Eq. (3) and Eq. (2). Then, substituting the result into Eq. (4) can get the absorption coefficient.

3. Simulations and experiments

Table 1 shows the TS parameters of one 2.6 inch loudspeaker driver measured with CLIOwin7, and Table 2 shows parameters of the MPP. The electrical circuit in each unit consists of a resistance 6 \(\Omega\) and a 4700 \(\mu\)F capacitance.

Experiments were conducted in an acoustic impedance tube to verify the prediction model in Section 2. Fig. 3 shows the experimental setup, where a source loudspeaker is placed at one end of the tube while the MPPSL construction is settled at the other hand. The cross section of the duct in Fig. 3 is about 8.5 cm \(\times\) 8.5 cm. The total length of the MPPSL is 26 cm. The sound absorption was measured using the two-microphone transfer function method according to ISO 10534-2 \(^{30}\) with a B&K PULSE 3560D.

The prediction model of the acoustic leakage between the loudspeaker and cavity is expressed in Section 2. The results are plotted in Fig. 4, in which \(l_b\) represents the width of the leakage duct. It
is found that the sound absorption coefficient of a MPPSL without acoustic leakage (as shown in Fig. 4(a)) is above 0.5 over the frequency ranging from 61 Hz to 350 Hz, and there are two absorption peaks below 400 Hz. The first resonance frequency is found to shift from 93 Hz to 61 Hz when leakage exists (as shown in Fig. 4(b)-(f)).

**Table 1. Loudspeaker parameters adopted in the simulations**

<table>
<thead>
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<th>PARAMETER</th>
<th>NOTATION</th>
<th>NOTATION</th>
<th>UNIT</th>
</tr>
</thead>
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<tr>
<td>DC resistance</td>
<td>$R_E$</td>
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<td>Ω</td>
</tr>
<tr>
<td>Force factor</td>
<td>$BL$</td>
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<td>T · m</td>
</tr>
<tr>
<td>Moving mass</td>
<td>$M_{ms}$</td>
<td>6.1</td>
<td>g</td>
</tr>
<tr>
<td>Mechanical resistance</td>
<td>$R_{ms}$</td>
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<td>kg/s</td>
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<tr>
<td>Mechanical compliance</td>
<td>$C_{ms}$</td>
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<td>mm/N</td>
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<td>m²</td>
</tr>
<tr>
<td>Back cavity volume</td>
<td>$V$</td>
<td>1.3e-3</td>
<td>m³</td>
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<td>Cross section length</td>
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<td>mm</td>
</tr>
<tr>
<td>Cross section length</td>
<td>$b$</td>
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<td>mm</td>
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**Table 2. MPP parameters considered for the simulations**

<table>
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<th>PARAMETER</th>
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<td>Young’s modulus</td>
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<td>--</td>
</tr>
<tr>
<td>Density</td>
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<td>Loss factor</td>
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</tr>
<tr>
<td>Viscosity coefficient</td>
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<tr>
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<tr>
<td>Perforation rate</td>
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<tr>
<td>Loudspeaker location</td>
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<tr>
<td>MPP location</td>
<td>$D_2$</td>
<td>80</td>
<td>mm</td>
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</tbody>
</table>

**Figure 3.** Measurement setup of the absorption coefficients of the MPPSL in an impedance tube (when there is acoustic leakage)
It is found that when $l_b < 2$ cm (as shown in Fig. 4(b)-(d)) another peak exists between the two resonance frequencies, and the peak frequency shifts to the second resonance frequency as the leakage width broadens, while the trough between the first and the new peak frequency is a little bit deep. Fig. 4(e)-(f) show that the new peak vanishes and the trough between the two resonances is small when $l_b \geq 2$ cm. The analysis indicates that leakage model is very meaningful for lower frequency absorption especially below 100 Hz.

![Figure 4. Comparison of the measured and predicted sound absorption coefficients of a MPPSL when there is a acoustic leak(a) $l_b =0$ (b) $l_b =1$ mm (c) $l_b =2$ mm (d) $l_b =5$mm (e) $l_b =2$ cm (f) $l_b =19$ cm](image-url)
4. Conclusions

The absorption performance of a MPPSL under normal incidence with leakage is investigated based on the equivalent circuit model (EC) method. A theory for describing the leakage effect between the loudspeaker and cavity is established, and then experiments are carried out to verify the results. It is found that when \( l_b < 2 \text{ cm} \), another peak exists between the two resonance frequencies, and the peak frequency shifts to the second resonance frequency as the leakage width broadens, while the trough between the first and the new peak is a little bit deep. The new peak vanishes and the trough between the two resonances is small when \( l_b \geq 2 \text{ cm} \). The first resonance frequency is found to shift from 93 Hz to 61 Hz when leakage exists, which makes leakage model meaningful for lower frequency absorption especially below 100 Hz.

ACKNOWLEDGEMENT

The work is supported by the National Natural Science Foundation of China (11104141).

REFERENCES


