SHUNTED LOUDSPEAKERS FOR TRANSFORMER NOISE ABSORPTION

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Transformer noise is mainly composed by the fundamental frequency component around 100 Hz and its harmonics. Sometimes it is difficult to apply traditional sound absorption treatments especially at the fundamental frequency and its second harmonic due to space constraints. Instead of radiating sound, loudspeakers can also be considered as an effective resonant absorber and its absorption performance can be adjusted by employing a shunt circuit at its terminals. This paper introduces a novel loudspeaker absorber with a shunt circuit, which is optimized based on the nonlinear model of the loudspeaker for the transformer noise absorption. Resistances, capacitances and inductances are used to adjust the electrical parameters of the loudspeaker in order to change its acoustic impedance. The proposed absorber shows excellent low frequency absorption performance at the transformer noise frequencies, but is much thinner than the traditional sound absorbers. Numerical simulations and the experiments are carried out to verify its feasibility.

1. Introduction

The noise of transformers, which are located in the residential areas, can sometimes be harmful to people’s health. The transformer noise comes mainly from the vibration of the core which is caused by the magnetostriiction of the silicon steel and the electromagnetic attraction. When frequency of the alternating current is 50 Hz, the frequency of the electromagnetic attraction will be 100 Hz. So the transformer noise is mainly composed by the fundamental frequency component around 100 Hz and its harmonics.

Many active methods have been proposed for transformer noise control. Some of them need a reference input, such as the waveform synthesis method, the adaptive notch filter and a specific algorithm for transformer noise control. Some of them only need the information of the fundamental frequency, or work with an internally synthesized reference signal. But they all need a signal processor to process the signal of the noise and drive the secondary source.

To reduce the transformer noise, acoustic enclosures can be built. Sound-absorbing materials or structures are generally used in enclosures. Shunted loudspeaker (SL), which means a loudspeaker with an electrical circuit connected to its terminals, is a new sound-absorbing structure. It was demonstrated that the acoustic impedance at a loudspeaker diaphragm can be adjusted by alternating the electric circuit parameters so that the SL can become an excellent sound absorber around its resonance frequency. The shunt technique has been compared to the active acoustic feedback technique for controlling the acoustic impedance of an electro-acoustic transducer, and the
equivalence between shunts and the active control has been developed. A shunted loudspeaker has been used to constitute a composite absorber with a micro-perforated panel in front.

This paper will give a design of the SL, which has an excellent absorption performance both at 100 Hz and 200 Hz. An analytical prediction model will be developed and the sound absorption of the SL will be shown by both numerical simulations and experiments.

2. Theory

The equivalent circuit model of a SL is shown in Fig. 1, in which $B$ is the magnetic flux density and $l$ is the voice coil length, $R_E$ is the DC electrical resistance of the voice coil, $L_E$ is the equivalent inductance 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, $p$ is the incident sound pressure, $U$ is the volume velocity, $Z_E$ is the electrical impedance of the shunted circuit, $S$ is the effective surface area of the driver cone, $C_p$ is the capacitance in the shunt circuit, and $L_p$ is the inductance in the shunt circuit. $C_{ac}$ is the equivalent acoustic capacitance due to the back cavity with volume $V$ and $C_{ac} = V / \rho_0 c_0^2 S^2$, where $\rho_0$ and $c_0$ are the air density and velocity.

\[
Z_L = R_{as}S + j \omega M_{as}S + \frac{C_{as} + C_{ac}}{j \omega C_{as} C_{ac}} S + \frac{B^2 l^2}{S(R_E + j \omega L_E + Z_E)}
\]  

(1)

When the $Z_E$ is infinite (the loudspeaker terminals is open circuit), the resonance frequency $f_L$ and the quality factor $Q_L$ of the shunted loudspeaker are given by

\[
f_L = \frac{1}{2\pi} \left( \frac{C_{as} + C_{ac}}{M_{as} C_{as} C_{ac}} \right)^{1/2}
\]

(2)

\[
Q_L = \frac{\omega L_{as}}{R_{as}S}
\]

(3)

When the circuit shown in Fig. 1 is connected to the loudspeaker, the acoustic impedance of the loudspeaker diaphragm can be described as
The value of $j\omega(L_E + L_p)$ is much lower than that of $1/j\omega C_p$. The resonance frequency $f_L$ of the shunted loudspeaker can be given as

$$f_L = \frac{1}{2\pi} \left[ \frac{C_p + C_{ac}}{M_{as} + B^2 l^2 / C_p + S^2 / C_{ac}} \right]^{1/2}$$ (5)

When the frequency gets higher, the value of $j\omega(L_E + L_p)$ becomes higher than that of $1/j\omega C_p$. The resonance frequency of the shunted loudspeaker can be given as

$$f_L = \frac{1}{2\pi} \left[ \frac{C_p + C_{ac}}{M_{as} C_p C_{ac} + B^2 l^2 / M_{as} S^2 (L_E + L_p)} \right]^{1/2}$$ (6)

When the inductance $L_p$ and the capacitance $C_p$ are chosen suitably so that the $f_L$ given in Eq. (6) is higher than the $f_L$ in Eq. (5), the SL has two resonance frequencies. Then the absorption coefficient of the SL which is given by Eq. (7) will have two peaks.

$$\alpha = \frac{4 \text{Re}(Z_L)}{[\rho_c c_0 + \text{Re}(Z_L)]^2 + [\text{Im}(Z_L)]^2}$$ (7)

### 3. Numerical simulations

The Thiele-Small (TS) parameters of the loudspeaker used in the simulations are given in Tab. 1. The sound absorption coefficient of the SL is calculated based on Eq. (1) and Eq. (7) in three configurations: open circuit, short circuit, shunted with a $-30$ Ω resistance, a 21 μF capacitance and a 33 mH inductance. The results are shown in Fig. 2. When the loudspeaker terminals are short-circuited, the resistance is changed to DC resistance from infinite. So the resonance frequency changes from about 130 Hz to 150 Hz, and the absorption peak becomes broader. When a $-30$ Ω resistance, a 21 μF capacitance and a 33 mH inductance are connected to the loudspeaker, the second peak appears. The peaks are at the frequency of 100 and 200 Hz, and the sound absorption coefficients are above 0.95. The acoustic impedance of the loudspeaker diaphragm is corrected by $Z_L S/ab$, because the cross section of the duct in the experiment is rectangular, but the loudspeaker diaphragm is circular.

According to Eq. (2), Eq. (5), and Eq. (6), the first peak is mainly determined by $C_p$, and the second peak is mainly determined by $L_p$. When $C_p$ gets larger, the first $f_L$ becomes lower. And the second $f_L$ becomes higher, when $L_p$ gets smaller. $C_p$ and $L_p$ are continuously adjusted until the two peaks are in the right positions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC resistance</td>
<td>$R_E$</td>
<td>31.1</td>
<td>Ω</td>
</tr>
<tr>
<td>Voice coil inductance</td>
<td>$L_E$</td>
<td>9.84</td>
<td>mH</td>
</tr>
<tr>
<td>Force factor</td>
<td>$Bl$</td>
<td>17.02</td>
<td>T·m</td>
</tr>
<tr>
<td>Moving mass</td>
<td>$M_{ms}$</td>
<td>15.95</td>
<td>g</td>
</tr>
<tr>
<td>Mechanical resistance</td>
<td>$R_m$</td>
<td>2.14</td>
<td>kg/s</td>
</tr>
</tbody>
</table>

Table 1. The TS parameters of the loudspeaker adopted in the simulations.
Mechanical compliance \( C_{ms} \) & 0.23 & mm/N \\
Effective area \( S \) & 1.5e-2 & m\(^2\) \\
Back cavity volume \( V \) & 5.53e-3 & m\(^3\) \\
Cross section length & width \( a & b \) & 170 & mm \\

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4. Experiments

Experiments were carried out in an acoustic impedance duct to verify the prediction model developed in Sec. 2. The experimental setup is shown in Fig. 3. A source loudspeaker is placed at the left end of the duct, while the SL is placed at the right side. The cross section of the duct is 17 cm \( \times \) 17 cm. The sound absorption was measured by a B\&K Pulse 3560D using the two-microphone transfer function method according to ISO 10534-2. \(^{12}\)

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Figure 2. Calculated sound absorption of a shunted loudspeaker.

Figure 3. Experiment setup (1) shunt circuit, (2) loudspeaker, (3) cavity, (4) duct, (5) source loudspeaker, (6) amplifier, (7) Pulse 3560D, (8) microphones.
A negative impedance converter (NIC) shown in Fig. 4 was used to get the negative resistance, where $V_{cc+}$ and $V_{cc-}$ are the supply voltage of the operational amplifier, $U_i$ and $U_o$ are the input and output voltage, $R_1$ and $R_2$ are the electrical resistance, $Z$ is an electrical impedance. The input electrical impedance is $Z_i = U_i / I = -R/Z R_2$. OP27 is chosen as the operational amplifier, and the resistance of $R_1$ and $R_2$ are 1000 $\Omega$.

![Negative Impedance Converter Diagram](image)

**Figure 4.** A negative impedance converter.

Fig. 5 shows the absorption coefficients of SL with the same configurations as those in Fig. 2. The SL has absorption peaks in the frequencies of 100 Hz and 200 Hz. The absorption coefficient of the first peak is about 0.98 and the second one is about 0.91. The second peak is smaller and slightly thinner than the predicted values in Sec. 3. This may be caused by the differences between the loudspeaker parameters used in the prediction and the actual ones.

![Sound Absorption Graph](image)

**Figure 5.** Measured sound absorption of the shunted loudspeaker.
5. Conclusions

A loudspeaker shunted with an electrical circuit was designed to absorb the transformer noise, whose energy is concentrated at 100 and 200 Hz. An equivalent circuit model is given to calculate the impedance at the diaphragm of the shunted loudspeaker, which is regulated by the circuit parameters. The results are validated by experiments. The SL has excellent absorption performance at 100 and 200 Hz. Two absorption peaks are achieved, whose sound absorption coefficient are above 0.9. Further works will focus on making it easier to adjust the resonance frequencies and designing the shunted loudspeakers with three absorption peaks.

ACKNOWLEDGEMENT

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

REFERENCES