Room Noise Filtering by Shunted Loudspeaker

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ABSTRACT

There are a variety of needs in room acoustics, such as the control of ventilation noise, adjustment of reverberation time and selective enhancement of echos over some frequency bands. All these call for a tunable sound absorber. This work describes an electro-acoustic method to design such an absorber, which is here described as an acoustic filter. The absorber consists of a moving-coil loudspeaker diaphragm backed by a cavity. When incident noise pushes the diaphragm, it moves and its structural damping consumes some sound energy. An RLC shunt circuit is attached to the moving coil giving an electrically induced mechanical impedance that alters the acoustic behaviour of the shunted loudspeaker. By manipulating component values of the shunt RLC circuit, the absorber drains noise at flexibly chosen frequency bands and at any assigned absorption levels, much like designing an electronic filter. The essential part of the theory is validated by experiment.

1. INTRODUCTION

Low-frequency noise is prevalent in our living environment and it is difficult to control by passive means. Ventilation noise is a typical noise source in most buildings, for which a sample spectrum is shown in Fig. 1. Such noise is detrimental to our quality of life in work place and at home [1]. In terms of passive noise control, there are two elements, namely

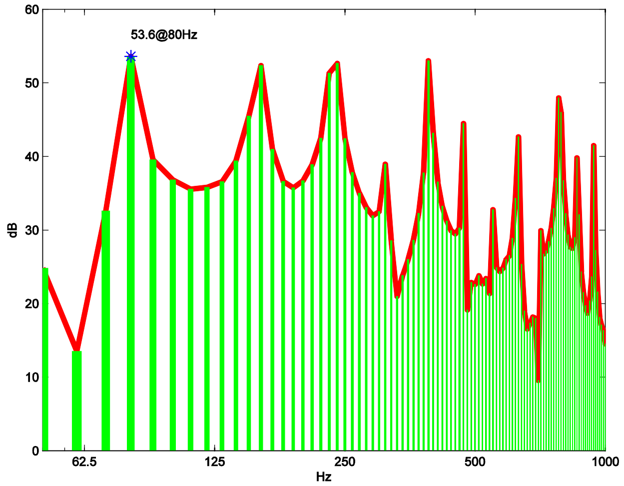

Figure 1. Typical ventilation noise spectrum

sound reflection and absorption. Reflection is effective in applications like duct noise, but absorption [2, 3] works in all situations. Many materials and passive devices are developed mechanically but they are hardly adjustable. Traditional designs using porous materials have good acoustic performance but these materials may irritate the room occupants. They are also ineffective in some applications. For example, concert hall should keep echoes of high frequency for clarity, while at the same time there may be a need to get rid of noise in a certain frequency band at a specific level of absorption. This work aims to develop an easily adjustable noise absorber through electro-mechanical coupling. Such coupling occurs when a moving coil cuts through a magnetic field; electrical currents are developed in the coil and mechanical reaction force, known as the electromotive force (EMF), is generated in the process. When the coil is attached to a passive diaphragm, EMF alters the system mechanical impedance. In this study, a moving-coil loudspeaker driver unit is chosen as the EMF mechanism without any external analogue input. To avoid possible confusion with a loudspeaker used as a sound radiator, this specially designed absorber will be called a Shunted Electro-Magnetic Diaphragm (SEMD) henceforth.

While the fundamental principle of EMF modification of mechanical impedance is known [4, 5], it remains to be seen if such EMF mechanism is practically useful in terms of adjusting the absorption performance of SEMD. To answer this question is the main motivation of the present paper. In what follows, Sec. 2 describes the design of the shunt circuit, and Sec. 3 reports three kinds of noise filter effects: (1) total sound absorption at a designated frequency, (2) broadband noise absorption at different levels, and (3) effective sound absorption in a specified frequency band. Conclusions are drawn in Sec. 4.

2. THEORECTICAL MODEL AND SHUNT CIRCUIT DESIGN

As shown in Fig. 2, a moving-coil loudspeaker is installed in a sealed rectangular box, and it forms the sample terminal of a standard impedance tube (not shown). A shunt circuit is attached to the device without external analogue signal input. The diaphragm is simply used as a sound absorber and is called a shunted electro-magnetic diaphragm (SEMD). The cone with the moving-coil is seen as a single degree-of-freedom, mass-spring system below the frequency of high-order mode cut-on for the diaphragm under linear hypothesis [6]. The mechanical impedance of SEMD in a sealed cavity with depth D is given as follows,

$$Z_0 = \delta + i\left[m\omega - \kappa/\omega - Z_{air}\cot\left(\omega D/c_0\right)\right] + \underbrace{\left(Bl\right)^2 \mathbb{Z}^{-1}}_{\Delta Z} \tag{1}$$

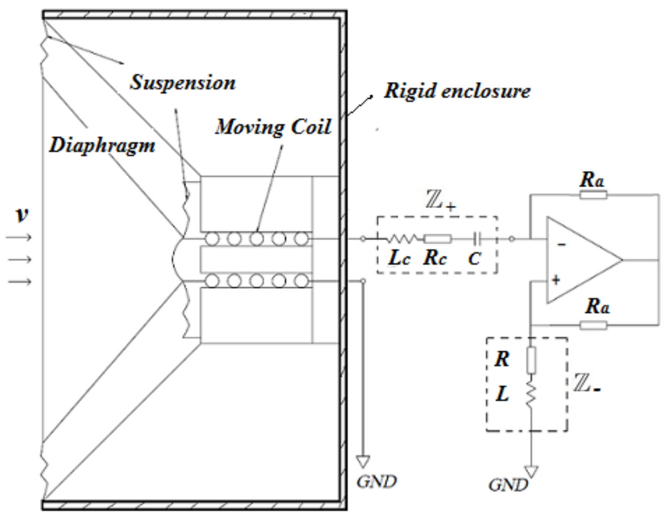

Figure 2. A shunted electro-magnetic diaphragm (SEMD) consisting of a moving-coil loudspeaker, with coil resistance R_c and inductance L_c, and a shunt circuit.

where ω is the angular frequency, c_0 is the speed of sound in air, m,δ,κ are the dynamic mass, damping and stiffness of the moving-coil loudspeaker, respectively, and $Z_{air} = \rho_0 c_0 A$ is the acoustic impedance of air over the cross section area, A, of the impedance tube. The terms in the square brackets in Eq. (1) are collectively called the acoustic reactance. As shown in the right-hand side of Fig. 2, a negative impedance converter (NIC) [7] is employed in the current test rig which can provide negative electrical impedance, Z_{-}. This is used to decrease the inherent resistance (R_c) and inductance (L_c) of the moving coil in the loudspeaker. Note that the use of NIC is for prototyping convenience based on loudspeakers purchased from the market, and it may be eliminated when a new moving-coil design is available with a suitable resistance and inductance. The last term in Eq. (1) is mechanical impedance induced by the entire electric shunt circuit, where Bl is the force factor of the moving-coil, and Z is the total electrical impedance. As can be seen from Fig. 2, $\mathrm{Z} = \Delta R + i\omega\Delta L + \left(i\omega C\right)^{-1}$ and $\Delta R = R_c - R,\ \Delta L = L_c - L$. The electrically induced extra impedance, $\left(Bl\right)^2 \mathrm{Z}^{-1}$, is defined as ΔZ and separated into real and imaginary parts as follows:

$$\begin{gathered}\Delta Z = \left(Bl\right)^2 \mathrm{Z}^{-1} = \Delta Z_r + i\Delta Z_i \\ \Delta Z_r \equiv \mathrm{Re}\left(\Delta Z\right) = \frac{\left(Bl\right)^2 \Delta R}{\Delta R^2 + \omega^2 q^2}, \quad \Delta Z_i \equiv \mathrm{Im}\left(\Delta Z\right) = \frac{\left(Bl\right)^2 \omega q}{\Delta R^2 + \omega^2 q^2}\end{gathered} \tag{2}$$

where $q = \left(C\omega^2\right)^{-1} - \Delta L$. It is noted that q controls the sign of ΔZ_i. When frequency becomes low enough, q is positive, which means that the shunt circuit brings positive reactance at low frequencies. On contrast, mechanical reactance is always negative at low-frequency. Therefore, the shunt circuit can be used to cancel mechanical reactance.

A selected loudspeaker, Visaton BG-17, is used in the design and experiment. The prediction of reactance cancellation is shown in Fig. 3. Fig. 3(a) shows the real part (resistance) of the electrically induced mechanical impedance (dotted line), normalized the impedance of air. A typical mechanical resistance of the diaphragm is shown as the solid line. Ideally, the sum should be unity, and it is obvious that this is not the case. No effort is made to improve the resistance matching in the current study since the emphasis is on the reactance cancellation.

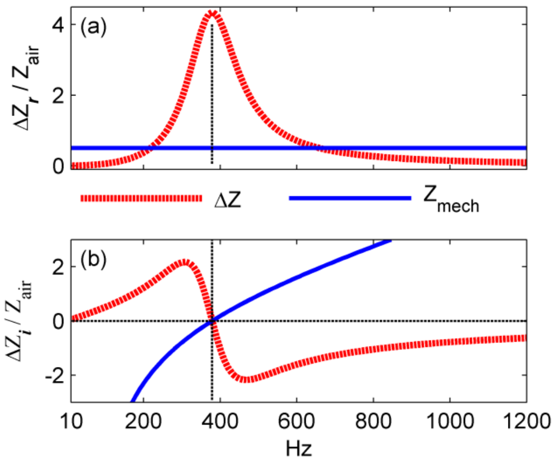

Figure 3. Typical spectra of (a) real and (b) imaginary parts of the electrically induced impedance ΔZ (dashed lines) compared with a mechanical impedance Z_{mech} (solid lines). The parameters for ΔZ are $\Delta R = 1\Omega$, $\Delta L = 1000\ \mu H$, $C = 176\ \mu F$, $f_c = 378 Hz$, while those for Z_{mech} are mass 3 g, spring stiffness 17 kN/m and damping 2.14 Ns/m.

Fig. 3(b) shows that the mechanical reactance of the loudspeaker (solid line) and electrically induced reactance (dotted line). Ideally, the sum should be zero. Here, the two reactance parts have different signs at all frequencies when the two have the same resonance frequency. It is precisely this special contrast of signs that is utilized for SEMD.

The absorption coefficient of SEMD is

$$\alpha(\omega) = \frac{4Z_{air}\left[\Delta Z_r + \delta\right]}{\left[\Delta Z_r + \delta + Z_{air}\right]^2 + \left[\Delta Z_i + m\omega - \kappa/\omega - \cot\left(\omega D/c_0\right)\right]^2} \quad (3)$$

Different patterns of noise absorption can be achieved by manipulating the electrical impedance Z. In the following section, three designs are described for typical applications in room acoustics.

3. THREE ACOUSTIC FILTERS

3.1 Narrow-band filters

Narrow band filters function like ordinary resonators but with easy, passive electrical adjustment. As an electronic device, it may also be compared with a radio receiver. A radio receives wireless signal at a typical transmission frequency while SEMD absorbs sound at a designated frequency. Thus, such SEMD may also be called a negative acoustic radio. As Fig. 3(b) shows, electrically induced reactance has the opposite sign from the mechanical reactance. By adjusting component values of the shunt circuit, total absorption ($\alpha = 1$) at any designated frequency may be achieved. In this study, the first three peak frequencies shown in the ventilation noise spectrum, Fig. 1, are selected. These are 80Hz, 161Hz and 238Hz, respectively. The original mechanical impedance of the loudspeaker is derived from the specification of the Visaton loudspeaker BG-17, which is given at (http://www.visaton.com/en/ela/breitband/bg17_8.html). The loudspeaker is sealed in a rigid cavity with 100 mm depth. The predicted results of sound absorption are shown in Fig. 4.

Figure 4 has three rows and 9 sub-figures. The legends for all the curves are shown below the middle sub-figure and explained in the caption. The first row of Fig. 4 shows that 100% absorption is achieved at the three frequencies. Curves in the second row show that the acoustic resistance of the shunt loudspeaker is close to that of air. The third row shows that the mechanical reactance at selected frequencies are cancelled by circuit-induced reactance.

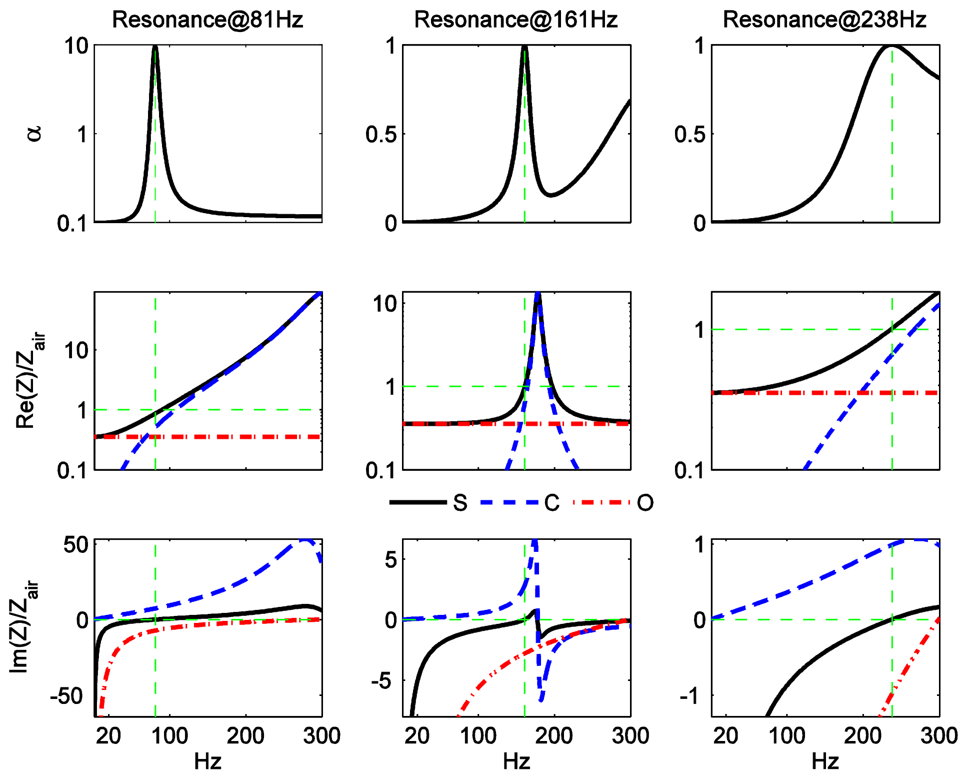

Figure 4. Realization of total noise absorption at designated frequencies. Legends: *S*, C and O stand for SEMD, circuit and original loudspeaker, respectively. The corresponding circuit parameters for the three designs are listed in Table 1.

Table 1. Circuit parameters to realize resonance at 80Hz, 161Hz and 238Hz

Resonant frequency	R(Ω)	L(μH)	C(μF)
80 Hz	0.05	2525	101
161 Hz	0.4	101	788
238Hz	2.5	101	1919

3.2 Broadband with adjustable sound absorption level

Broadband noise absorption is always desirable in room acoustics. By attaching a circuit to a loudspeaker driver unit, broadband absorption can be achieved. Visaton BG-17 is again selected and it is sealed in a rigid cavity with 60 mm depth. The sound absorption coefficient of SEMD is tested in a standard impedance tube. This is denoted as normal-incidence absorption coefficient, α_{norm} . The experimental data is shown in Fig 5 as the solid curve. The circuit parameters are $\Delta R = 1.6\Omega, \Delta L = 572\mu\text{H}, C = 779\mu\text{F}$. For room acoustics, it's always better to use random-incidence absorption coefficient (α_{rand}) as the evaluation of performance of noise absorbers or panels. This is found by integrating the oblique-incidence absorption coefficient as follows:

$$\alpha_{rand} = \int_0^{\pi/2} \alpha(\theta)\sin(2\theta)d\theta, \quad \alpha(\theta) = 1 - \left|\frac{Z\cos\theta - 1}{Z\cos\theta + 1}\right|^2 \qquad (4)$$

The random-incidence absorption coefficient can be predicted and is expected to match well with the real performance provided that the experimentally measured impedance Z is adopted in calculation. The result of such experiment-based prediction is shown as the dashed line in Fig. 5. It is found that the random-incidence in general has higher absorption coefficient than the normal incidence. This is so because the impedance match for the normal incidence for this particular design is such that there is excess impedance in the sample. The matching actually improves for the obliquely incident sound. The normal-incidence absorption coefficient of the loudspeaker without the shunt circuit is shown as the dash-dot line in Fig. 5.

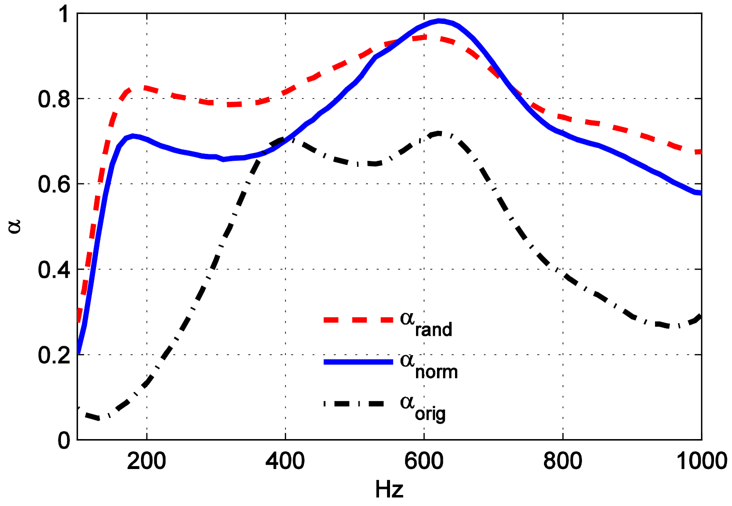

Figure 5. Absorption coefficient of random-incidence sound (dashed line) compared with the normal-incidence sound with (solid line) and without (dash-dot line) shunt circuit.

In controlling sound effects in a room, variable absorption coefficient is needed to achieve different purposes. This is a potential technical advantage for SEMD since the shunt circuit is easily tuned by varying the components in the R-L-C circuit. Such tuning is demonstrated by optimizing the bandwidth for which the random incidence sound absorption coefficient falls within a rather narrow band of $\alpha_{rand} \in [\alpha - 0.025, \alpha + 0.025]$ where α is the pre-set desired level of sound absorption coefficient, e.g. 0.5, 0.6, etc. Examples of optimized absorption spectra are shown in Fig. 6 with the circuit parameters given in Table 2.

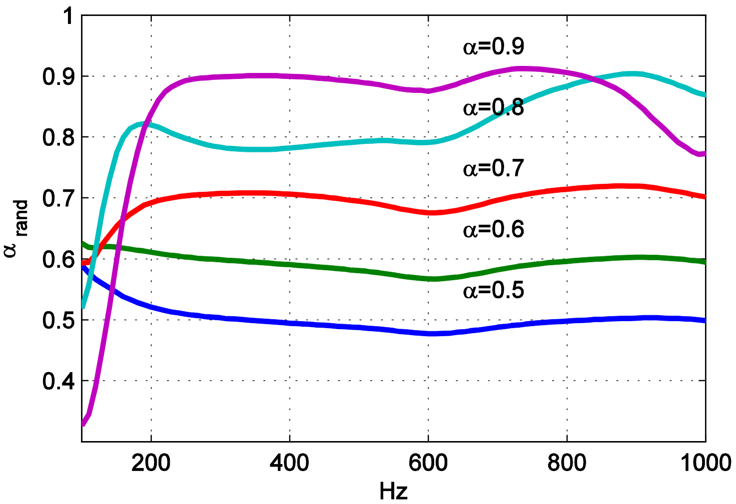

Figure 6. Optimized broadband spectra for a set of specified level of sound absorption. The circuit parameters are given in table 2.

Table 2. Shunt circuit design for specified random incident noise absorption coefficients

Pre-set coefficient	R(Ω)	L(μH)	C(μF)
$\alpha = 0.5$	0.8	42	2935
$\alpha = 0.6$	1.1	66	2345
$\alpha = 0.7$	1.6	113	2012
$\alpha = 0.8$	2.0	406	565
$\alpha = 0.9$	3.4	645	313

3.3 Acoustic band-stop filter

In audio recording rooms, there may be a need to absorb noise within a finite frequency band instead of over a broad band or at a single frequency. SEMD can also provide such capability. Fig. 7 shows that the effective absorption band can be adjusted by circuit parameters, in a manner like electronic filter design. The curves in this figure are predicted using different

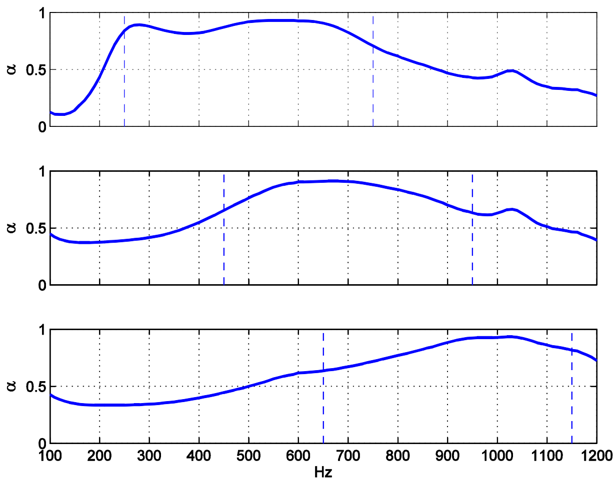

Figure 7. Noise absorption achieved in selected frequency bands by adjusting the shunt circuit parameters (Table 3).

Table 3. Circuit parameters to realize different absorption bands

Frequency bands	R(Ω)	L(μH)	C(μF)
[250Hz 750Hz]	2.3	2975	65
[450Hz 950Hz]	0.92	1046	2235
[550Hz 1150Hz]	0.56	483	2959

combinations for the circuit components (shown in Table 3) but the basic acoustic impedance is based on the experimentally measured values for Visaton BG-17. The designated band limits are shown as vertical dashed lines in Fig. 7.

4. CONCLUSIONS

In this paper, a shunt-circuit-based strategy to achieve different patterns of noise absorption is proposed. Three types of noise filter are designed and their performance is predicted in calculation based on experimentally measured acoustic impedance for the base loudspeaker. The three filters are narrow band absorber, broadband absorber and acoustic band-stop filter, respectively. The prediction for the second type, the broadband absorber, is validated experimentally. The proposed device can be compact in construction and its absorption pattern can be easily altered by manipulating component values of the shunt RLC circuit. This contrasts with pure mechanical absorbers which often require large space, complex design and lack adjustability.

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