LOW-FREQUENCY NOISE ABSORPTION BY A SHUNTED LOUDSPEAKER

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Low-frequency noise is annoying and hard to deal with. By connecting certain shunt circuit to a moving-coil loudspeaker, we demonstrate improved low-frequency absorption of normal incident sound. The loudspeaker is installed in a cavity of 5cm in depth. Negative impedance converter is used to construct a hybrid RLC-parallel and RLC-series shunt circuit. The low-frequency reactance of the shunted loudspeaker system is reduced in magnitude together with a modified system damping. The proposed device is measured in a well calibrated impedance tube, and good noise absorption performance is achieved in the frequency range of 100Hz to 400Hz as predicted.

1. Introduction

Low-frequency noise are very annoying [1] and difficult to control using readily available passive devices. New passive approaches such as metamaterials have been developed [2, 3]. A single-layer metamaterial can handle low-frequency noise in a narrow band effectively. Recently, broadband absorption in the low-frequency region by lining metematerials layers was also reported [4]. However, constrained by back cavity stiffness, the effective frequency band is not located in the sufficient low range. Another approach of passive method is to introduce external load to tune the impedance of devices to match that of air [5, 6]. The use of an electro-magnetic-mechanical absorber, which is a moving-coil loudspeaker in this case, belongs to the latter category.

Loudspeaker is used as a sample absorber in this work, and its reactance is reduced by a shunt circuit connected to the system. Such an approach is able to improve broadband impedance matching between the loudspeaker in cavity enclosure and air at low frequencies, thus improving sound absorption in that region. Both simulation and experimental results are presented.

Shunt circuits were first introduced into electromechanical vibrator by Hagood and von Flotow [7] who applied it in vibration control of piezoelectric ceramic. After that, researchers employed various types of circuits aiming to control the impedance of different electromechanical devices. Shunt circuit was hence introduced to tune the acoustic characteristics of piezoelectric panels in 2002 [8]; and afterward [9, 10, 11]. Recently, studies are concentrated on exploring the possibility of adding shunt circuit to loudspeakers. A moving-coil loudspeaker was used by Fleming et al. [12] to suppress the duct acoustic modes by constructing a side-branch Helmholtz resonator. Pietrzko's series of work on the use of negative impedance converter (NIC) is also reported with both simulation and experiments [13, 14]. Meynial *et al.* [15] first adopted shunted loudspeaker in room acoustics, followed by

Lissek *et al.* [16, 17, 18] with good performance in the low-frequency region. Lissek *et al.* [5, 18] focused on applying shunted loudspeaker to duct acoustics, controlling low-frequency noise, resonance, among other things. They analyzed the analogy between the shunt strategies and active impedance control in simulation. They found that the velocity feedback strategy performs better in noise reduction and such a system was validated experimentally. Zhang [6] made a comprehensive discussion on the effect of different electrical components in the shunt circuit of a loudspeaker and proposed a strategy to suppress the system dynamic mass for improved high frequency performance.

The effort paid on low-frequency noise absorption is well noted but convenient devices are still not readily available. Resonator devices are limited in its effective bandwidth and traditional porous materials requires large space [19]. We here propose a shunt-circuit-based low-frequency absorber. The circuit modifies the impedance of loudspeaker such as to match the characteristic impedance of air. A major benefit is that low-frequency absorption performance is improved a lot between 100Hz and 400Hz using a shallow cavity of 5cm in depth. Both theoretical and experimental discussions are conducted.

2. Loudspeaker with shunt circuits

2.1 General dynamic model of loudspeaker with shunt circuits

Under Linear hypothesis, a moving-coil loudspeaker can be seen as a single degree-of-freedom, mass-spring system below the cut-off frequency of the loudspeaker diaphragm. The impedance of a loudspeaker with open electrical terminals can be denoted by Z_{mo},

$$Z_{mo}(s) = ms + \delta + \kappa s^{-1} \tag{1}$$

where s is the Laplace variable, m, δ and κ are the dynamic mass, damping and stiffness of the moving-coil loudspeaker, respectively. The sum of the terms of mass and stiffness is called mechanical reactance. When such a loudspeaker is installed at the end of an impedance tube, the normal-incidence sound absorption coefficient is

$$\alpha(s) = 1 - \left|\frac{Z_{air} - Z_{mo}(s)}{Z_{air} + Z_{mo}(s)}\right|^2 \tag{2}$$

where $Z_{air} = \rho_0 c_0 A$ is the impedance of air and A is the cross section area of the impedance tube. From Eq. (1) we see that the loudspeaker reactance becomes larger when frequency goes to low which will decrease the absorption coefficient to zero at the DC frequency. When the back enclosure of the loudspeaker is small, the stiffness term is very large hence the low-frequency absorption is low. This is the problem that most resonator-type absorbers encounter and this is the issue we set out to address. The proposed device is shown in Figure 1. When the loudspeaker is connected to an electrical loading, Z_e, at the terminals of the loudspeaker, an additional mechanical impedance will be introduced.

The system impedance becomes,

$$Z_{ms}(s) = ms + \delta + \kappa s^{-1} + (Bl)^2 Z_e^{-1} \tag{3}$$

where Bl is the force factor derived from the magnetic field in the loudspeaker. Moving-coil resistance and inductance are contained in Z_e. If negative impedance converter (NIC) [20] is employed, Z_e could be any designed value, beyond the constrain of coil resistance and inductance. The full implementation of the system is shown in Figure 1. When a sound hits the loudspeaker diaphragm, electromotive force (EMF) is induced in the moving coil, which is proportional to $(Bl)^2$ times the mechanical excitation. Therefore, a current will flow and is inversely proportional to electrical loading Z_e and the additional acoustic impedance is $(Bl)^2 Z_e^{-1}$. By manipulating Z_e we can obtain a desirable acoustic impedance at low frequencies.

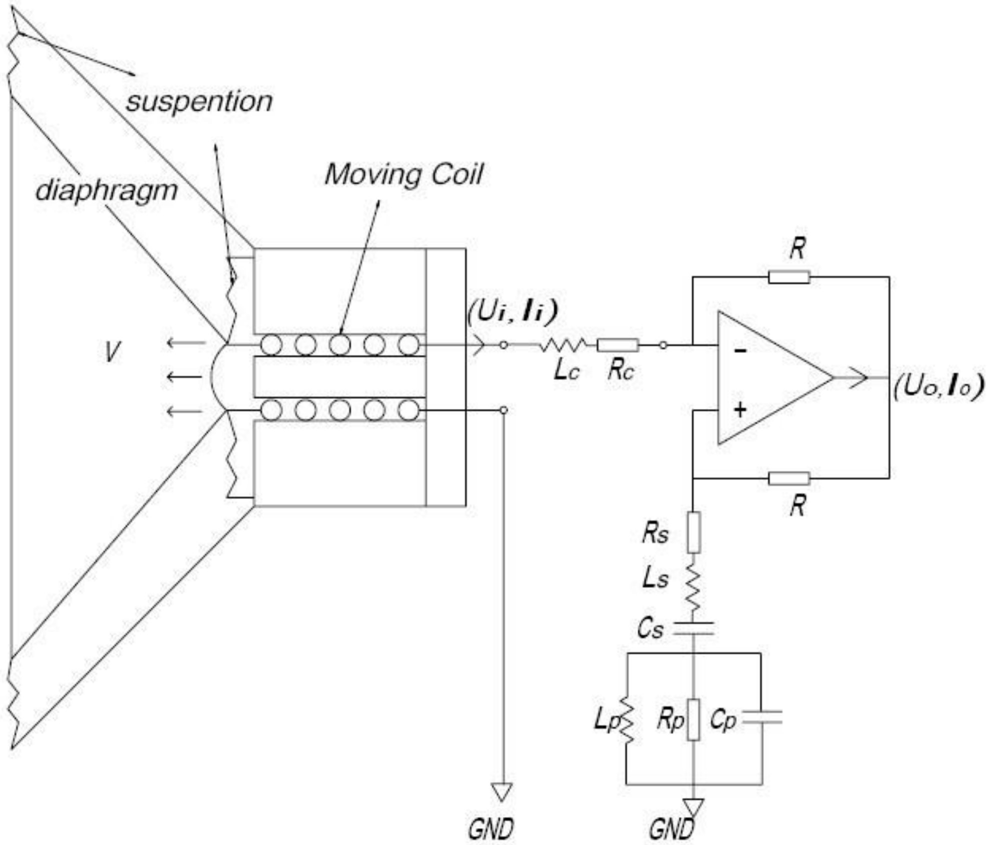

Figure 1. Moving coil loudspeaker with shunt circuit

2.2 Stability

While an active unit such as NIC is connected to the system, it's possible to cause the system to be unstable. Without loss of generality, we here only consider an R-L-C series shunt circuit. The transfer function is Eq. (4) and the stability characteristic equation is Eq. (5)

$$V = \frac{F}{ms + \delta + \kappa s^{-1} + (Bl)^2 Z_e^{-1}} \tag{4}$$

$$\begin{cases} a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0 = 0 \\ a_4 = mL_s \\ a_3 = mR_s + L_s\delta \\ a_2 = mC_s^{-1} + R_s\delta + \kappa L_s + (Bl)^2 \\ a_1 = \delta C_s^{-1} + \kappa R_s \\ a_0 = \kappa C_s^{-1} \end{cases} \tag{5}$$

Aware that coil resistance and inductance R_c and L_c is included in R_c and L_c for the convenience of reading in Eq. (5). It's a fourth order equation which is not easy to solve analytically. However, we can use Routh-Hurwitz stability criterion to derive the stability boundary, according to which the stability requires

$$\begin{cases} a_n > 0, n = 0,1,2,3,4 \\ a_3 a_2 - a_4 a_1 > 0 \\ a_3 a_2 a_1 - a_4 a_1^2 - a_2 a_0^2 > 0 \end{cases} \tag{6}$$

It follows that

$$R_s > 0,\ \ L_s > 0,\ \ C_s > 0 \tag{7}$$

will guarantee a stable system.

2.3 Impedance design

From Eq. (2) and Eq. (3), we get:

$$\alpha(s) = 1 - \left| \frac{Z_{air} - \left[ms + \delta + \kappa s^{-1} + (Bl)^2 Z_e^{-1} \right]}{Z_{air} + \left[ms + \delta + \kappa s^{-1} + (Bl)^2 Z_e^{-1} \right]} \right|^2 \tag{8}$$

To make good low-frequency absorption, it's key to design Z_e to decrease the system reactance at low frequency. Our design starts from a hybrid R-L-C circuit as shown in Figure 1. The acoustic impedance induced by the circuit is

$$Z_{me} = (Bl)^2 Z_e^{-1} = \frac{(Bl)^2}{R_s + L_s s + C_s^{-1} s^{-1} + (R_p^{-1} + L_p^{-1} s^{-1} + C_p s)^{-1}} \tag{9}$$

The imaginary part of Z_{me} should be positive for frequencies below the eigen frequency of the unshunted loudspeaker, $\omega < \omega_r$, and slightly negative after that in order to reduce the magnitude of the system reactance. In Eq. (9) we can see that C_p is not effective at both low frequency and high frequency. Therefore, for the sake of convenient analysis, we make it zero. Z_{me} is written as Eq. (10), separated into real and imaginary parts. The real part is the induced damping and the imaginary part reactance.

$$\begin{cases} Z_{me} = \dfrac{p}{p^2 + q^2\omega^2}(Bl)^2 - i\omega \dfrac{q}{p^2 + q^2\omega^2}(Bl)^2 \\ p = R_s + \dfrac{R_p L_p^2 \omega^2}{R_p^2 + L_p^2 \omega^2} \\ q = \dfrac{L_s C_s \omega^2 - 1}{\omega^2 C_s} + \dfrac{R_p^2 L_p}{R_p^2 + L_p^2 \omega^2} \end{cases} \tag{10}$$

where ω is the angular frequency. Making ω smaller and larger than the unshunted loudspeaker (henceforth 'open loudspeaker') resonance, we can get approximations of Z_{me}:

$$Z_{me}\Big|_{\omega \ll \omega_r} = \frac{(Bl)^2 R_s}{\omega^2 C_s^2 R_s^2 + 1} + i \frac{(Bl)^2 \omega C_s}{\omega^2 C_s^2 R_s^2 + 1} \tag{11}$$

$$Z_{me}\Big|_{\omega \gg \omega_r} = \frac{(Bl)^2 (R_s + R_p)}{(R_s + R_p)^2 + (L_s + \dfrac{R_p^2}{L_p \omega^2})^2 \omega^2} - i \frac{(Bl)^2 (L_s + \dfrac{R_p^2}{L_p \omega^2})\omega}{(R_s + R_p)^2 + (L_s + \dfrac{R_p^2}{L_p \omega^2})^2 \omega^2} \tag{12}$$

Eq. (11) shows that the induced reactance is positive at low frequencies, and the series capacitance and resistance are important for this purpose. When the frequency is higher, the reactance becomes negative as we want. The by-product is an extraordinary damping spectrum introduced. The situation is complex in the mid frequency range, the ranges of ‘low’, ’high’ and ‘mid’ being relative to the design frequency.

3. Experimental validation

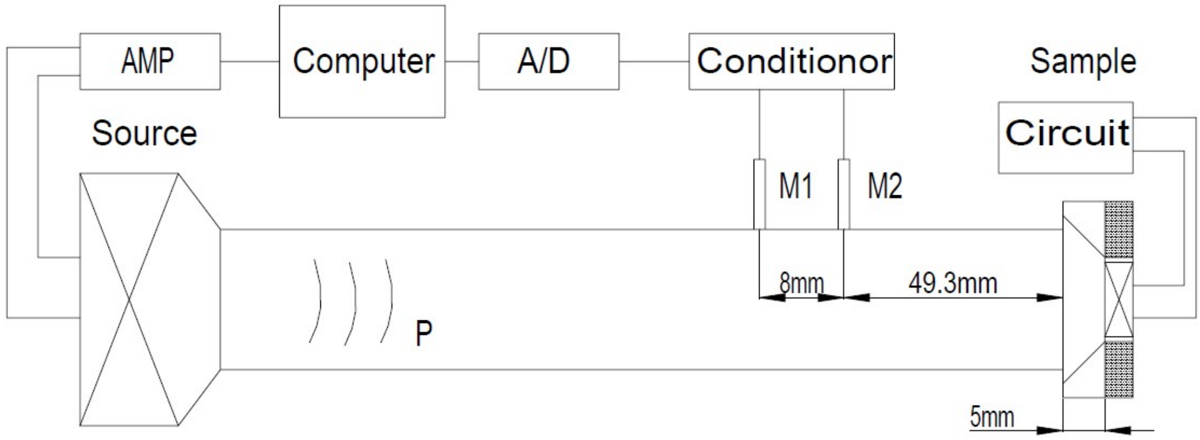

Figure 2. Measurement setup.

In what follows, we will conduct simple numerical calculations to predict the performance of the designed loudspeaker as absorber, which will be validated experimentally. First, the impedance of the open-circuit loudspeaker is measured, and the impedance data are extracted to predict the absorption coefficient of the shunted loudspeaker. The sample loudspeaker used is Visaton WS-17 whose technical data are shown in Table 1. The loudspeaker is sealed in a rigid box whose depth is adjustable, the value used in this study being 5cm. The shunted loudspeaker is installed at the end of a rectangular impedance tube, as illustrated in Fig. 2. Two microphones are mounted in the tube for standing-wave measurement and decomposition. A computer controls the driving excitation and data collection. The shunted circuit is connected to the loudspeaker terminals and the designed circuit parameters are shown in Table 2.

Table 1. Technical data of WS-17 according to
http://www.visaton.com/en/chassis_zubehoer/tiefton/ws17e_8.html

Dynamic moving mass	Nominal impedance	D.C. resistance	Voice-coil inductance
13 g	8 Ω	5.8 Ω	0.9 mH
Force factor Bl	Effective piston area	Resonance frequency	
3.9 Tm	143 cm^2	45 Hz	

The measured absorption coefficient of the open circuit loudspeaker is shown in Fig. 3 and the reactance and damping shown in the figure are all dimensionless. Fig. 3 shows that, because of the large reactance below 150 Hz, the absorption performance is poor. Meanwhile, its dimensionless damping is below 1 which is not sufficient. Therefore, a shunt circuit is designed to connect the loudspeaker to modify its mechanical impedance.

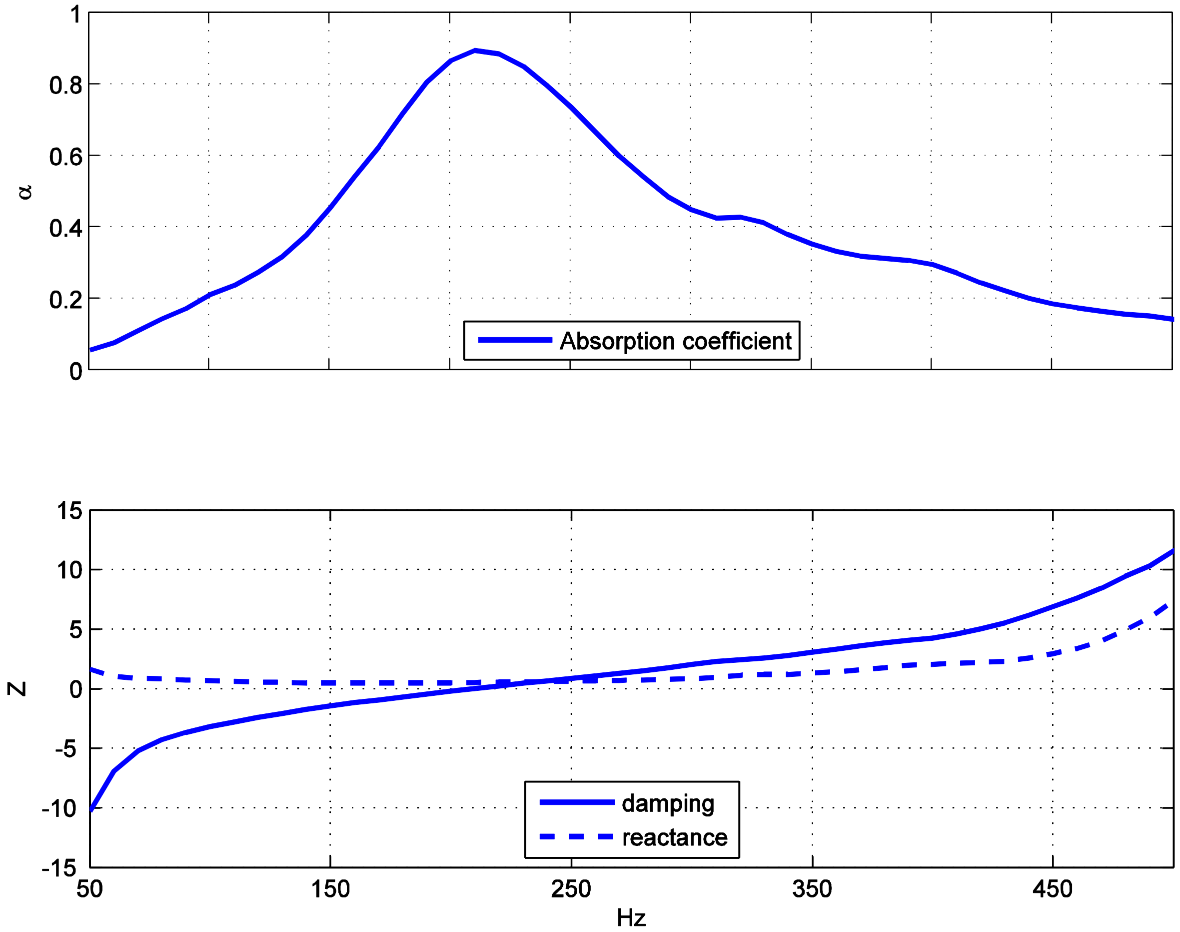

Figure 3. Absorption coefficient and impedance of open termination loudspeaker

The shunt circuit parameters are listed in Table 2. We use Eq. (8) to predicte the absorption coefficient and impedance, shown in Fig. 4. The experimental results of the shunted loudspeaker are shown in the same figure.

Table 2. Shunt circuit parameters

Op-amp	R_s	L_s	C_s
LM358	1 Ω	0.9 mH	0.7mF
R	R_p	L_p	C_p
0.32 Ω	0.5 Ω	0.18 mH	*absent*

When the output of the operational amplifier (op-amp), I_o and U_o , are too large to be supplied by the chosen op-amp, the op-amp goes into saturation. In our design, R should be kept small and R_s should avoid being too small [6]. L_p and R_p are not important in determining properties of shunt circuit . However, we still keep them in the analytical analysis and experiments for the sake of completeness in analysis.

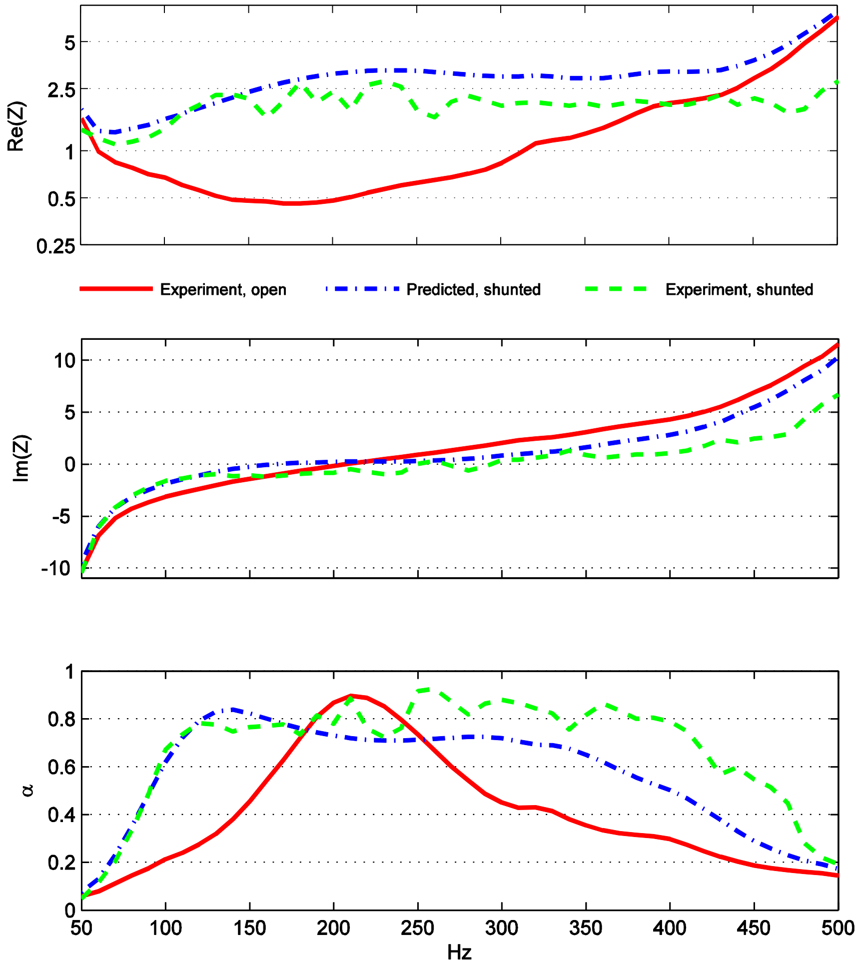

Figure 4. Impedance and sound absorption for the open-circuit and shunted loudspeakers. The legends shown between the first two sub-figures apply to all.

We find that the absorption coefficient is improved a lot and it is above 0.7 in the range of 100~420 Hz. The predicted coefficient agrees with the experimental result well while the effective band is found to be broader in experiments. In Fig. 4, it is clear that the low-frequency reactance is decreased as we anticipated, and the damping gets larger. A good absorption performance is achieved in the low frequency range considering the thin structural design.

4. Conclusion

In this paper, a shunt-circuit-based strategy to achieve broadband low-frequency absorption is proposed, and the numerical prediction is validated experimentally using an impedance tube. The proposed devices have thin structure and simple implementation which can effectively reduce system reactance and increase damping. Series capacitor and resistor are found to be key to overcome large reactance provide by the shallow enclosure, realizing low-frequency absorption.

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