Applied Acoustics 132 (2018) 109–117

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Multi-degree-of-freedom low-frequency electroacoustic absorbers through coupled resonators

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ARTICLE INFO

Keywords:
Sound absorption
Acoustic impedance control
Electrodynamic loudspeaker
Performance optimisation
Electrical shunt

ABSTRACT

Electroacoustic absorbers represent an interesting solution for low-frequency sound absorption in rooms. These systems simply consist of closed-box electrodynamic loudspeakers, whose acoustic impedance at the diaphragm is judiciously adjusted by connecting a passive or active electrical control circuit. This paper presents a method for designing different electroacoustic absorber systems constituted of simple electrical and mechanical components that are coupled to a primary loudspeaker, resulting in multi-degree-of-freedom resonators. Each system is optimised to maximise the sound absorption performance with respect to different metrics. Experimental evaluations in an impedance tube confirm the model accuracy and method efficiency for achieving low-frequency sound absorption.

1. Introduction

Room modes cause uneven distributions in space and frequency of the sound field, thus altering the sound quality [1]. Conventional passive techniques based on foam-based absorbers and diffusers are often used to control the reverberation time and early reflections [2]. Since their size is dictated by the wavelengths in the targeted frequency range, they are not well suited to the low frequencies. Resonant absorbers and Helmholtz resonators are available for low-frequency sound absorption [3–5]. Nevertheless, even if the design of Helmholtz resonators can be optimised for a given room, their high quality factor causes a narrow frequency band of efficient sound absorption [6]. Thus, Helmholtz resonators with two and three degrees of freedom (DOF), which consist of pairs of cylindrical necks and cavities stacked in series, were designed to improve the sound absorption capabilities [7–9]. The effect of resonator arrays on the sound field in cavities were evaluated in Refs. [10,11]. These resonators can also be combined with micro-perforated panels constituted of very thin perforations backed by a cavity, which were firstly introduced in Ref. [12], so as to improve the sound absorption performance at higher frequencies [13,14]. Recently, an original design constituted of panels arranged with parallel extended tubes, was proposed in Ref. [15], resulting in four peaks of absorption from 150 Hz to 440 Hz.

Another approach is the active sound absorption with electroacoustic absorbers. These active absorbers are closed-box electrodynamic loudspeaker systems, whose acoustic impedance at the diaphragms is judiciously adjusted with [16] or without sensor [17], so as to maximize their sound absorption performance in rooms [18]. When an appropriate electrical resistance is connected to the transducer terminals, an optimal acoustic resistance can be achieved at the diaphragm, but limited to the resonance frequency of the system [19]. With parallel resistance - capacitance (RC) or resistance - inductance (RL) electrical networks, the peak of sound absorption can be tuned below or above the transducer resonance frequency respectively, thanks to the reactive electronic components [20,21]. Connecting a series resistance - inductance - capacitance (RLC) electrical network to the transducer terminals becomes a two-DOF resonator, resulting in two peaks of sound absorption [21].

Such Helmholtz resonators and shunted transducers can even be combined together. A multi-DOF electromechanical Helmholtz resonator, consisting of a Helmholtz resonator coupled to a shunted piezoelectric at the bottom of the cavity, was developed in Ref. [22]. This way, both resonance frequencies were tuned thanks to the shunted electrical load. The low-frequency sound absorption was also efficiently improved using a thin micro-perforated plate coated with a shunted piezoelectric transducer [23]. These different approaches introduce the idea of using mechanical or mixed electrical/mechanical resonators coupled to the primary closed-box loudspeaker interacting with the sound field, so as to imitate or improve the sound absorption capabilities relative to those obtained with electrical shunts.

The objective of this paper is to design innovative systems of multi-DOF electroacoustic absorber, which are only constituted of conventional electrical and mechanical components. First, the model of the closed-box electrodynamic loudspeaker is introduced, before presenting

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http://dx.doi.org/10.1016/j.apacoust.2017.10.019
Received 30 March 2017; Received in revised form 3 October 2017; Accepted 10 October 2017

the sound absorption performance through the definitions of the specific acoustic impedance, as well as the corresponding sound reflection coefficient and sound absorption coefficient. Then, different systems of electrical and mechanical resonators coupled to the primary closed-box loudspeaker are studied, and the sound absorption performance of each system is optimised with respect to specific objective functions. Finally, an experimental evaluation of these systems and a discussion on the measured sound absorption performance are given.

2. Acoustic impedance of multi-degree-of-freedom electroacoustic absorbers

2.1. Passive loudspeaker

In the low-frequency approximation, an electrodynamic loudspeaker can be modeled as a one-DOF oscillator mechanically driven by a voice coil within a magnetic field. All forces acting on the transducer, especially those resulting from the sound pressures P_f and P_r at the front and rear faces of the diaphragm, are assumed small enough so that the governing equations should remain linear. The mechanical part is modeled as a simple mass - spring - damper system in the low-frequency range, that is the mass M_{ms}, the mechanical compliance C_{ms} accounting for the surround suspension and spider, and the mechanical resistance R_{ms}, respectively. The electrical part is modeled with a DC resistance R_e and a self inductance L_e. We denote the effective piston area by S_d, the force factor by Bl, the incoming diaphragm velocity by V, the electrical current flowing through the voice coil by I, and the input voltage between the electrical terminals by U. Fig. 1 shows the schematic diagram of the electrodynamic loudspeaker.

Using the Fourier transform where ω is the angular frequency, the governing equations of the loudspeaker are expressed as

$$S_d P_f(\omega) = \left(Z_{ms}(\omega) + \frac{S_d{}^2}{j\omega C_{ab}}\right)V(\omega) + BlI(\omega) \quad (1)$$

$$U(\omega) = Z_e(\omega)I(\omega) - BlV(\omega) \quad (2)$$

where $Z_e(\omega) = j\omega L_e + R_e$ is the blocked electrical impedance of the voice coil, $Z_{ms}(\omega) = j\omega M_{ms} + R_{ms} + 1/(j\omega C_{ms})$ is the mechanical impedance of the loudspeaker, $C_{ab} = V_b/(\rho c^2)$ is the acoustic compliance of the enclosure, ρ is the density of the medium and c is the speed of sound.

The specific acoustic impedance is defined as the complex ratio of the sound pressure $P_f(\omega)$ at the front face of the diaphragm to the diaphragm velocity $V(\omega)$. When the loudspeaker is left open circuit, namely the case where no electrical current $I(\omega)$ circulates through the voice coil, this quantity is directly derived from Eqs. (1) and (2) as

$$Z_s(\omega) = \frac{Z_{ms}(\omega)}{S_d} + \frac{S_d}{j\omega C_{ab}} \quad (3)$$

The corresponding resonance frequency is equal to

$$f_0 = \frac{1}{2\pi\sqrt{M_{ms}\frac{C_{ms}C_{ab}}{S_d{}^2C_{ms} + C_{ab}}}} \quad (4)$$

Under normal incidence, the sound reflection coefficient $r(\omega)$ and

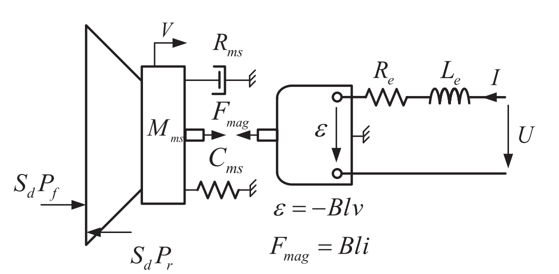

Fig. 1. Schematic diagram of the electrodynamic loudspeaker.

sound absorption coefficient $\alpha(\omega)$ are defined as

$$r(\omega) = \frac{Z_s(\omega) - \rho c}{Z_s(\omega) + \rho c} \text{ and } \alpha(\omega) = 1 - |r(\omega)|^2 \quad (5)$$

In the following, three different systems of electroacoustic absorber are investigated:

- System A: the loudspeaker is coupled to an electrical resonator.
- System B: the primary loudspeaker is coupled to a secondary loudspeaker, where an electrical resistance is connected at its terminals, which is denoted the "mechanical resonator".
- System C: the primary loudspeaker is coupled to a secondary loudspeaker, where an electrical resonator is connected at its terminals, which is denoted the "electromechanical resonator".

2.2. Loudspeaker connected to an electrical resonator

When an appropriate electrical load is connected at the loudspeaker terminals, the active sound power at the diaphragm can efficiently be dissipated through mechanical and electrical losses, thus modifying its sound absorption capability. The electrical load, represented by the complex impedance $Z_l(\omega)$, is added in series to the blocked electrical impedance $Z_e(\omega)$. When the voice coil moves with the velocity $V(\omega)$, the electromotive force generates the current $I(\omega)$ circulating through the closed electrical circuit, which is expressed as

$$I(\omega) = \frac{Bl}{Z_e(\omega) + Z_l(\omega)}V(\omega) \quad (6)$$

The study focuses on the electrical resonator constituted of the series RLC network, as highlighted in Fig. 2 (in shaded area). The electrical impedance of this shunt network is written as

$$Z_l(\omega) = j\omega L_l + R_l + \frac{1}{j\omega C_l} \quad (7)$$

The equivalent acoustic circuit of the closed-box loudspeaker connected to this electrical resonator (system A) is illustrated in Fig. 3, where $Q(\omega) = S_d V(\omega)$ is the volume flow. Combining Eq. (6) with Eqs. (1) and (2) gives the expression of the specific acoustic impedance of system B as

$$Z_{s_A}(\omega) = \frac{Z_{ms}(\omega)}{S_d} + \frac{S_d}{j\omega C_{ab}} + \frac{Z_{me_A}(\omega)}{S_d} \quad (8)$$

where

$$Z_{me_A}(\omega) = \frac{(Bl)^2}{j\omega(L_e + L_l) + R_e + R_l + \frac{1}{j\omega C_l}} \quad (9)$$

corresponds to the equivalent mechanical impedance of the electrical resonator in series with the electrical impedance of the loudspeaker. The corresponding resonance frequency of the electrical resonator is

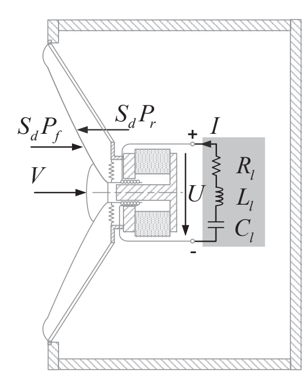

Fig. 2. System A: the loudspeaker connected to an electrical resonator (series resistance – inductance – capacitance network).