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Turning a loudspeaker into an active Helmholtz resonator: Underlying law, principle and design methodology

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ABSTRACT

This paper is concerned with how to turn a moving-coil loudspeaker into an active Helmholtz resonator (AHR): that is, an active noise control loudspeaker used in conjunction with a microphone and a feedback controller to actively realize the Helmholtz resonator. The natural law of control is studied to justify that the AHR is an effective means for resonant noise control. The principle of duality is then applied to reveal that the AHR can be designed and analyzed in an analogous way to its vibration dual, i.e., the active dynamic absorber. A systematic design methodology is finally established, in consideration of the inherent loudspeaker dynamics. It is theoretically shown that a low, band, and high pass filter of second order are desirable control filters to construct a low-, mid-, and high-band AHR that are, respectively, for uses in the volume displacement, velocity, and acceleration drive frequency range of the loudspeaker used. Experimental work is also presented, in which a high-band AHR was constructed to absorb the broadband resonant noise of a long duct between about 165 Hz and 1.3 kHz, to illustrate the efficacy and to investigate the absorption mechanism of the AHR.

1. Introduction

It is well known that moving-coil loudspeakers can be used for reducing resonant noise of an acoustic cavity [1–3]. A loudspeaker can act as a Helmholtz resonator (HR) as it is also a resonating device. Its noise reduction mechanism is analogous to the vibration reduction mechanism of a dynamic vibration absorber (DVA). They are in fact in dual relationship so that resonant noise can be reduced because of the small impedance of an HR (or a loudspeaker) placed on a cavity wall that is otherwise completely rigid, whereas resonant vibration can be reduced because of the large impedance of a DVA attached to a point of a structure that is otherwise completely free. The impedance applied by such a loudspeaker is resistance in a limited bandwidth around the natural frequency of the device. It can be tuned in both mechanical and electrical ways to meet some target resistance for yielding perfect noise neutralization or absorption. However, achieving any of these over a considerable bandwidth is difficult because of many limitations and tradeoffs among passive design parameters: For example, the damping has to be small for noise level reduction while being large for the control bandwidth. This is the reason for the introduction of various active loudspeaker systems [4–8] including those in this paper.

Among various active systems in the literature, the simplest may be the active noise control (ANC) loudspeaker used in conjunction with a microphone and a feedback controller connecting the two transducers that are further collocated. This is the system that Olson and May introduced in the 1950s to realize an active pressure-releasing zone in a free acoustic space [6].

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A miniature form of this, the ANC headphone, was also introduced in the 1980s to reduce the noise inside the small volume of a blocked human ear [7]. Clark and Cole in the 1990s expanded the application to a cavity having many acoustic modes [8]. A proportional gain was used as the control filter since their idea of control was based on Balas's direct velocity feedback for vibration control [9]. Second order filters were later attempted to improve the robustness [10].

In support of this line of cavity noise control research, a fundamental and comprehensive study is presented in this paper on how to turn a moving-coil loudspeaker into an ANC loudspeaker for reducing resonant noise of an acoustic cavity. More specifically, the aim is to design an active Helmholtz resonator (AHR) that actively realizes the pressure releasing mechanism of the HR. The natural law of noise (vibration) control is studied to justify that such a damping device acting as an HR (a DVA) is an effective means for resonant noise (vibration) control. The principle of duality is then applied to reveal, with presenting simple but exact analogous models, that the AHR is in principle the acoustical dual of the active dynamic absorber (ADA), known also as the active electrical dynamic absorber (EDA) [11–13]. This duality relationship greatly facilitates the design and analysis of the AHR since the ADA theory can also be applied here. However, a complexity is that a loudspeaker generally has its own dynamics: It acts as a volume displacement, velocity, and acceleration source in its low, mid, and high frequency region, respectively [1,13]. Thus, a low, band, and high pass filter of second order are respectively proposed as the control filters for the AHRs in the three different frequency regions above. These ANC loudspeakers are hereby called the *low-*, *mid-*, and *high-band AHR*, respectively. Since the mid-band AHR has already been published together with its mathematical model [14], the main foci of this paper are to combine the theories of the AHR and the ADA for a unified understanding of resonant noise and vibration control; and also to develop the design methods of low- and high-band AHRs for a full use of the entire working frequency range including the volume displacement and acceleration drive frequency ranges of the loudspeaker used.

Apart from their convenience of tuning [14], the AHRs have another advantage over the passive [2] and semi-active [15] HRs in that they can be designed to perform extremely well since their control filter parameters are relatively free to change without limits. There have been further semi-passive HRs such as shunted loudspeakers combined with synthetic electric circuits, which often contain negative electric components incurring instability [3]. An advantage of the AHRs over these is then that feedback control theory can be readily applied to ensure optimal and robust designs. Moreover, the control filters employed in this paper are simple second-order filters that can be easily designed by loop shaping [16].

The paper is structured as follows. Section 2 presents the two natural laws of vibration and noise control (i.e., the impedance and mobility sum laws) that are essentially the same but in dual relationship. It subsequently turns out that the principle of the AHR is also essentially the same as that of the ADA but in dual relationship. Section 3 reviews a mathematical model of an acoustic cavity driven by multiple loudspeakers. Section 4 establishes a systematic design methodology of the low-, mid- and high-band AHRs. Simulation and experimental works are then presented in Section 5, followed by some conclusions in Section 6.

2. Natural laws of control and principles

2.1. Vibration control law

Consider a structure subjected to a harmonic force f at a single point and let the vibration motion at the point be denoted by velocity v_0. If this motion is unacceptably large, a conventional passive control method is to attach at the point an appendage system of '*large*' impedance Z_A. This can be represented by the impedance diagram in Fig. 1(a), where Z_S means the internal impedance of the primary system. The total impedance of the complete system becomes $Z = Z_S + Z_A$: *Impedance sum law*. The velocity v after control can then be written in standard form as [17,18]

$$v = \frac{Y_S}{1 + Y_S Z_A} f, \tag{1}$$

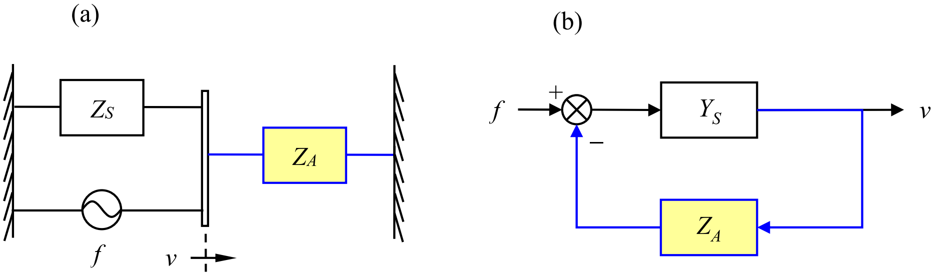

Fig. 1. Vibration control of a system Z_S by a parallel connection of an appending system Z_A. (a) Impedance diagram and (b) the equivalent control block diagram.