Mechanical Systems and Signal Processing 95 (2017) 286–309

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Modeling and analysis of secondary sources coupling for active sound field reduction in confined spaces

Allahyar Montazeri *, C. James Taylor

Engineering Department, Lancaster University, Lancaster LA1 4YW, UK

A R T I C L E I N F O

Article history:
Received 20 December 2015
Received in revised form 7 November 2016
Accepted 17 March 2017

Keywords:
Active sound control system
Coupling of sources
Enclosure
Loudspeaker and microphone array
Modal analysis

A B S T R A C T

This article addresses the coupling of acoustic secondary sources in a confined space in a sound field reduction framework. By considering the coupling of sources in a rectangular enclosure, the set of coupled equations governing its acoustical behavior are solved. The model obtained in this way is used to analyze the behavior of multi-input multi-output (MIMO) active sound field control (ASC) systems, where the coupling of sources cannot be neglected. In particular, the article develops the analytical results to analyze the effect of coupling of an array of secondary sources on the sound pressure levels inside an enclosure, when an array of microphones is used to capture the acoustic characteristics of the enclosure. The results are supported by extensive numerical simulations showing how coupling of loudspeakers through acoustic modes of the enclosure will change the strength and hence the driving voltage signal applied to the secondary loudspeakers. The practical significance of this model is to provide a better insight on the performance of the sound reproduction/reduction systems in confined spaces when an array of loudspeakers and microphones are placed in a fraction of wavelength of the excitation signal to reduce/reproduce the sound field. This is of particular importance because the interaction of different sources affects their radiation impedance depending on the electromechanical properties of the loudspeakers.

1. Introduction

The problem of active sound field reduction/reproduction in enclosed spaces has been widely studied because of its practical significance. In case that the incident sound is annoying this problem is studied mostly under the title of active sound control in the literature. Nevertheless, when the sound field conveys some useful information it is desirable to control it actively while retaining some specific characteristics. Examples in which reduction of the target sound field in confined spaces is desired, include active control of tonal noise inside the cabin of aircraft and helicopters, i.e. noise resulting from blade passing frequency of the propeller driven aircraft and helicopters [1,2]; and in cars at specific engine orders [18,19,22]. Fundamental theoretical and experimental investigations on proof of concept of active control techniques in the global reduction of harmonically excited enclosed sound fields are provided in Refs. [5,7,17]. From the perspective of sound field reproduction active methods have shown promising results in applications such as immersive audio [25] and immersive communication systems [24].

* Corresponding author.
E-mail address: a.montazeri@lancaster.ac.uk (A. Montazeri).

http://dx.doi.org/10.1016/j.ymssp.2017.03.025

Theoretical approaches of sound field reproduction systems in free field are referred to as Wave Field Synthesis and Ambisonics [3]. However, inaccuracies in the reproduction due to the listener's movement and room reverberations led to the development of another technique known as multichannel inversion [4]. The underlying principles of this method share significant analogies with the theories of active control of sound fields [6]. The corresponding term associated with these two strategies in enclosed space are referred to as global and local control [8]. In global control, reduction of the acoustic pressure level at all points in the confined space is important (see e.g. [10] and the references therein) whilst local control aims to generate a quiet zone inside the enclosure (see e.g. [20,23] and the references therein). Two quantities used for global control of the sound field inside the enclosure are energy density and potential energy, whereas a norm of sound pressure at some discrete points in space is attempted most of the time to address local active noise control problems. Having a proper control strategy, the next important step in the design of an active control system is to find the optimal position for any secondary loudspeakers and error microphones according to the characteristics of the primary noise [13,15]. Most of the literature (e.g. [11,17]) suggests placement of secondary loudspeakers and error microphones at the corners of the enclosure to attenuate the low-frequency sound field in a global active control setting. However, analysis in reference [14] shows that when the dimensions of the enclosure are multiple integers of each other, placement of secondary loudspeakers at the corner of the cavity will not necessarily result in the maximum achievable global noise reduction.

Coupling of sources refers to the situation in which two coherent sources are placed within a fraction of the wavelength and affect each other's radiation impedance. This problem is studied in free space in reference [9]. In an enclosed space, the coupling happens through acoustic modes which in turn will change the radiation impedance of sources. However, relatively few articles to date have studied coupling of acoustic sources within a working environment [12,21] and in the context of an active control system. A preliminary investigation by the present first author on modeling coupling of a loudspeaker with the acoustic modes in an enclosed space is reported in [16] where the results for two loudspeakers when no microphone is available are presented. In this article, we extend these results to an array of L loudspeakers and M microphones, and investigate the effect of coupling of secondary sources on the overall performance of an active sound control system in a confined space. The modeling and analysis performed in this paper explains some of the behaviors of active control systems that occur in practice as a result of coupling of the secondary loudspeakers.

To be able to find a closed form solution for the problem, the enclosure is considered to have rigid boundary conditions. The proposed analytical model can be used to find an upper bound on the level of reduction of sound pressure and the required source strength when coupling exists among the sources in a multichannel active control system. The results are supported by extensive numerical simulations for both resonant and non-resonant frequencies of the enclosure. Preliminary results and notation are presented in Section 2. A closed form solution and the associated theorems derived from modeling and analysis of the coupling of secondary sources in an ASC system with L loudspeakers and M microphones is given in Section 3. These analytical results are obtained by generalization of the results from Section 2 and are supported by further analysis in Section 4 and extensive numerical simulations in Section 5. Finally, the conclusions are presented in Section 6.

2. Problem formulation and statement

2.1. Notations and hypothesis

In this section we present important definitions and notation used later in the article to formulate the problem. For all these definitions and assumptions refer to Fig. 1, where it is assumed that an array of N loudspeakers is distributed inside

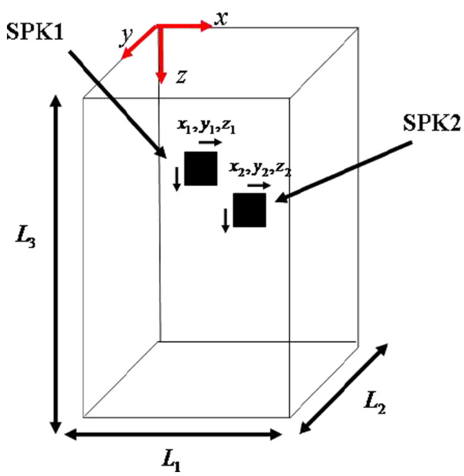

Fig. 1. A typical rectangular enclosure with coupled secondary loudspeakers.