Control Engineering Practice 80 (2018) 1–16

Contents lists available at ScienceDirect

Control Engineering Practice

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

Shaping zones of quiet in a large enclosure generated by an active noise control system

Stanislaw Wrona [a,*], Maria de Diego [b], Marek Pawelczyk [a]

[a] *Institute of Automatic Control, Silesian University of Technology, ul. Akademicka 16, 44-100 Gliwice, Poland*

[b] *Institute of Telecommunications and Multimedia Applications, Universitat Politecnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain*

ARTICLE INFO

Keywords:
Acoustic control
Adaptive filters
Optimization process
Sensors and actuators arrangement
Noise reduction in enclosure

ABSTRACT

Performance of an Active Noise Control (ANC) system strongly depends on sensors and actuators spatial arrangement. It determines both achieved Noise Reduction (NR) levels and spatial distribution of obtained *zones of quiet*, making it an essential problem. However, if the acoustic field in the enclosure can be appropriately modelled, then optimization algorithms can be employed to find efficient configuration of the ANC system, enhancing its performance according to a formulated cost function and constraints. This paper proposes a complete method for enhancing NR levels and shaping *zones of quiet* generated with an ANC system by optimization of sensors and actuators arrangement. A Memetic Algorithm (MA) is utilized. The MA itself and its proposed operators are described. The optimization problem formulation is derived and discussed. As a control algorithm, Distributed Multiple Error Filtered-x Least Mean Square (DMEFxLMS) is used. Extensive simulation results are presented for an exemplary real enclosure. The model of the acoustic environment has been obtained by real-world experiments, resulting in identification of 36864 acoustic responses in total. Practically feasible cost function and constraints are evaluated. Advantages and limits of the method are pointed out and discussed.

1. Introduction

An excessive acoustic noise is an important problem in the modern society and it stimulates the development of a variety of noise reduction techniques. A common solution is to apply passive methods, such as the use of sound-absorbing/sound-insulating materials. They constitute a satisfactory solution to many noise problems. However, they are ineffective for noise at low frequencies. Moreover, they often are inapplicable due to unacceptable increase in mass and volume, and introduction of an additional heat insulation. An alternative approach is to use active control methods, by applying a set of sensors and actuators, and running a control algorithm (Antoñanzas, Ferrer, de Diego, & Gonzalez, 2016; de Diego, Gonzalez, Ferrer, & Piñero, 2004; Tuma, Suranek, Mahdal, & Wagnerova, 2016; Wyrwal, Zawiski, Pawelczyk, & Klamka, 2017). Active methods are better suited for reduction of low frequency noise (Preumont, 2012), and do not introduce heat transfer problems.

One of the active control approaches is the Active Noise Control (ANC). The ANC methods can be explained by the principle of superposition, where in contrast to passive methods, additional energy is introduced to the system through a set of control inputs (secondary sources) to obtain a secondary response that adds to the primary disturbance field. In result, the total response of the system can be reduced (destructive interference) or altered in the desired manner. Typically, ANC systems consist of (i) an electronic controller and (ii) a set of sensors and actuators, usually microphones and loudspeakers. The controller drives actuators basing on sensors signals. It often runs in an adaptive way to follow changes in the primary disturbance field or secondary transfer path.

Performance of an ANC system strongly depends on sensors and actuators spatial arrangement in an acoustic environment. It determines both achieved Noise Reduction (NR) levels and spatial distribution of obtained *zones of quiet*, making it an essential problem. Moreover, there are often multiple constraints imposed on admissible sensors and actuators configuration, making the problem even more complex and difficult to solve. However, if the acoustic environment can be modelled (by theoretical calculations or experimental measurements), then optimization algorithms can be employed to find efficient configuration of the ANC system, enhancing its performance according to a formulated cost function.

Optimization techniques have been used over the years to enhance performance of ANC systems. The use of a genetic algorithm to optimize loudspeakers locations of an ANC system in a telephone kiosk is reported

* Corresponding author.
E-mail addresses: stanislaw.wrona@polsl.pl (S. Wrona), mdediego@dcom.upv.es (M. de Diego), marek.pawelczyk@polsl.pl (M. Pawelczyk).

https://doi.org/10.1016/j.conengprac.2018.08.004
Received 24 March 2018; Received in revised form 26 June 2018; Accepted 11 August 2018

in Montazeri and Poshtan (2009). The authors utilized the average of acoustical potential energy reduction as a performance index. The optimization of arrangement of ANC system secondary sources around a single monopole primary source is shown in Duke, Sommerfeldt, Gee, and Duke (2009). The authors considered minimization of radiated sound power in the free field. The optimization of microphones and speakers arrangement of an ANC system in an aircraft is presented in Diamantis, Tsahalis, and Borchers (2002). In the employed genetic algorithm, the average noise reduction obtained by the ANC was used as a fitness function. Secondary sources and error sensors locations are optimized in Huideng and Arui (2011), considering the summation of the squared pressure at all evaluated points and the total control energy in the cost function. Other reports of ANC system configuration optimization are given e.g. in Baek and Elliott (1995), Li and Hodgson (2005) and Manolas, Borchers, and Tsahalis (2000). The most of the cited reports consider optimization with indices describing the ANC system global performance (in the whole room, enclosure or space). However, in many applications such global reduction is unfeasible and unnecessary. Hence, it is practically sensible to define the *target zones* where the noise reduction is truly required (where people are often present) and neglect the control results elsewhere (where people are rarely or only for short periods of time). In general, such approach results in the lesser necessary number of sensors and actuators, thus reducing control unit computational burden and energy effort. But in order to satisfy the application-related requirements of noise reduction, the generated *zones of quiet* should be appropriately shaped to fit the *target zones*. If necessary, the zones can follow people moving in the enclosure, based on different kind of sensors localizing them and application of virtual microphone technique.

This paper proposes a complete, ready to apply, method for enhancing NR levels and shaping spatial distribution of *zones of quiet* in large enclosures generated with an ANC system by optimization of sensors and actuators arrangement. The method is based on an optimization approach utilizing a Memetic Algorithm (MA). The MA itself and its proposed operators are described in details. The proposed method employs a model of the acoustic environment and evaluates the ANC system in various configurations, according to the optimization procedure. As a result, an efficient arrangement is found that optimizes the specified cost function. The major differences of this work comparing with the previous ones are: (i) the precisely designed spatial distribution of *target zones* is embedded in the cost function (leading to shaped *zones of quiet*), instead of employing a scalar global performance index; (ii) the computationally-efficient Memetic Algorithm is used to find optimal solution, which operators are proposed and discussed in details. The optimization problem formulation is derived and discussed.

To facilitate presentation of the proposed method, an exemplary scenario is introduced. The scenario considers a room with a device generating excessive noise. In the room a user of the device is present and the goal is to generate a *zone of quiet* around listener's location (reducing the noise that he is exposed to). The scenario is used to investigate the proposed shaping method performance by simulation studies. A model of the acoustic environment is obtained by experimental measurements (a real room located at the Audio Processing Laboratory of the Polytechnic University of Valencia has been utilized for this purpose, which was equipped with 96 loudspeakers generating acoustic excitation and 384 microphones locations acquiring the responses, what resulted in identification of 36864 acoustic responses in total, available at www.gtac.upv.es/room.php). Multiple scenario variants, parameters and imposed constraints are tested. As a control algorithm, Distributed Multiple Error Filtered-x Least Mean Square (DMEFxLMS) is employed (Elliott, Stothers, & Nelson, 1987; Ferrer, de Diego, Piñero, & Gonzalez, 2015).

This paper is organized as follows. Section 2.1 introduces the exemplary scenario, which constitutes a basis for explanation of the proposed method. Section 2.2 is devoted to the ANC system that is utilized in the presented research. Then, Section 2.3 formulates the problem of sensors and actuators arrangement optimization. Section 3 is devoted to the shaping method itself. Firstly, an overview of the proposed method is given. Subsequently, the modelling of the acoustic environment is discussed. Then, several feasible cost functions are proposed. Afterwards, the employed memetic algorithm is described, along with its proposed operators. Then, Section 4 presents assumptions adopted for simulations presented in this paper. The parameters of the ANC system and the shaping method are given. Then, in Section 5 the obtained simulation results are presented. Temporal, spatial and frequency characteristics are shown. An impact of three important parameters on the obtained noise reduction results is studied. Finally, advantages and limits of the proposed approach are pointed out and discussed, and conclusions for future research are drawn.

2. Problem description

2.1. The exemplary scenario

For the sake of clarity, the proposed method is presented in this paper on the basis of an exemplary scenario, although, the presented considerations preserve generality. In the example, a large room with a disturbance source—a device generating an excessive broadband noise, is considered. It is a situation commonly encountered in real life. The aim is to reduce the noise for which the user of the device is exposed to (they have to be present in the room with the device). It is assumed that passive methods are insufficient in this case (low frequencies are dominating in the noise spectrum, and the users cannot be separated from the noisy device by a barrier), therefore the ANC system is introduced. Its goal is to generate a *zone of quiet* around a known location (potential user location) with a limited number of sensors, actuators, and their admissible locations. The objective of the optimization process is to find efficient arrangement of sensors and actuators, enabling the control algorithm to achieve the highest possible NR levels within the *target zone*, while outside the zone noise enhancement is allowed. It is a practically feasible approach, as the global noise reduction with ANC system in real applications represents very high energy demand and is very difficult (or even impossible) to obtain due to physics and technological limitations (Preumont, 2012). On the other hand, global noise reduction is often not needed. Hence, a distribution of *target zones* should be defined, where the noise should be reduced, neglecting the effects obtained in other areas (where the presence of people is unlikely). The proposed shaping method is employed to achieve the goal.

An alternative active control approach worth mentioning, is the employment of an active casing, which relies on actively controlling vibration of the device casing with bonded actuators so that the emitted noise to the environment is reduced. Under certain conditions, it can provide global noise reduction with low energy demand. However, this approach is out of the scope of this paper and the reader is referred to other publications dedicated to it (Mazur, Wrona, & Pawelczyk, 2018; Wiora, Wrona, & Pawelczyk, 2017; Wrona & Pawelczyk, 2014, 2016a).

2.2. The ANC system

2.2.1. Control algorithm

The control algorithm implemented in the ANC system controller is the Distributed Multiple Error Filtered-x Least Mean Square (DMEFxLMS) (Ferrer et al., 2015). It is based on the Multiple Error Filtered-x Least Mean Square (MEFxLMS) that has been proven to perform very well for ANC systems with multiple sensors and actuators (Elliott et al., 1987). The DMEFxLMS has been implemented with a collaborative incremental strategy in the network. The ANC system consists of N_n separate nodes communicating and collaborating with each other to achieve a common goal. Each node consists of a controller and its own sensors and actuators. However, no communication constraints have been imposed in the network in this research, hence, the control system exhibits the same performance as the centralized implementation. In this