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Fundamentals of active shielding based on implicit control

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Active noise control is a methodology to attenuate low frequency noise. The attenuation is usually achieved near the sensor which is used in the controller. In order to achieve the desired attenuation inside a desired zone without locating a sensor inside, a method called active shielding can be used. It works by controlling the pressure at boundaries of the desired zone. This article presents a novel method for implementing active shielding only using pressure sensors. It is based on a new concept called implicit control, which takes into account the locations of sensors. Some simulations validate the presented method for free fields.

1. Introduction

The active noise control is a methodology to attenuate the noise using the property of superposition. First approaches were published by Paul Leug and Coanda [1,2]. Specifically, the noise generated by a source is attenuated by adding another source which generates an "anti-noise" wave [3]. To produce an active attenuation, there are two schemes, feedback and feed-forward. They are differentiated because feed-forward scheme produces the control signal as a transformation of a reference signal of the emitted noise, while feedback scheme only uses information of acoustic pressure at the desired silent location through sensors. [4] is a review which depicts several issues in this field for both schemes.

In order to attenuate the pressure at a sensor location inside an enclosure, several algorithms have been created. Some of them are based on adaptive filters such as the filtered X Least Mean Squares (LMS) algorithm, Filtered U LMS algorithm, etc. [5]. Other algorithms are based on robust control theory, e.g. [6–9]. According to these references, these algorithms obtain an attenuation around 20 dB at the sensor location. A detailed description of these algorithms are found in [10], which is a review that includes nonlinear algorithms. However, the attenuation of the sound is only accomplished at or near the sensor location. Usually, the user, who is exposed to the noise, is not located at the sensor position. Inside enclosures with large volume, the mentioned ANC systems only control the noise at locations near the sensors. In order to increase the silent zone (locations where the noise is attenuated), multichannel control have been used [11,12].

Let's center the attention in the case that sensors cannot be located at the position of the users. Then, increasing the silent zone without using microphones at the user locations is a problem mentioned by several authors. A solution was proposed in [13], where an optimization problem is suggested. This mentions the possibility to optimize the sound pressure using the sensors and actuators (also called secondary sources) as optimization variables. A similar procedure is applied in

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[14], but it applies two consecutive optimization stages. The first stage takes into account only the sources positions, and the second the sensor locations. This can be applied using a simulation of the room. Thus, the sources and sensors are located optimally where the simulation results indicate.

Increasing the silent zone is possible by estimating the pressure at a desired location. It is known as virtual sensing. This method is carried out by first measuring the sound pressure at a different location. This signal is then transformed to obtain an approximation of the pressure at a desired location to be used as the error signal. The first algorithm was called virtual microphone arrangement [15]. It takes into account the sound pressure measured by a sensor. Its limitation is due to the assumption that the sound pressure generated by the noise sources is equal for the virtual and real sensor locations (desired and measured locations respectively). A modification called remote microphone [16] applies the same concept. However, it uses a transformation of the estimation of primary noise to avoid the assumption that the sound pressure components generated by the primary source are equal at both locations, and this transformation is not determined if it is not causal. [17] uses a Kalman filter as the estimator of the pressure, which also needs to establish a model of the system. Another proposal is based on the correlation of the pressure at different locations [18], but it is limited by the distance between real and virtual sensors. [19] introduces a nonlinear estimation to solve the problem of the non-causality relation between the measured and estimated pressure. The solution is a modification of the remote microphone algorithm. Other algorithms have been presented but only applied to one dimensional or not enclosed systems e.g. [20–22]. [23] deals with the problem that attenuating the noise using high number of virtual sensors requires high computational cost. Another issue is that the estimation is carried out using a sensor, but the real receiver is a human, which can produce a change on the estimation. To solve it, [24] proposes an approximation of a mathematical model of the identification system by using a head and torso simulator instead of human ears in the experiment.

Another important methodology for active control of sound field in a discrete region is active shielding. It works on the principle of boundary control with actuators on the boundary surface using information gathered from sensors on the boundary surface. The method developed by Jessel and Mangiante [25] and Canevet [26], known as the JMC method, uses Huygens' principle to formulate control of sound field in a zone with secondary sources on the boundary. Pressure and velocity detectors and monopole and dipole actuators are generally required to facilitate the sound field control [27]. Active shielding can also be derived from a formulation of Kirchhoff-Helmholtz integral equation [28]. In this case, only pressure sensors and monopole actuators are required, but the formulation suffers from the integral equation's inherent failure at the characteristic frequencies of the interior region [29]. Munjal and Erikson developed another approach based on electro-acoustic analogies, but it is limited by sensor position. It cannot be located at the same position as that of a node [30]. These active shielding approaches seek to minimize the total sound pressure (noise) in the region. In some cases, it may be possible to use directional measurements to separate the unwanted and wanted sound components in the region [31], but such application is limited since in most realistic cases the wanted component cannot be completely separated out by directional measurement alone. The method of using generalized Calderon's potentials and boundary projection operators [32], and the discrete formulation based on difference potentials [33–36], are a general class of active shielding methods that has the advantage of automatically preserving wanted sound in the region while attenuating unwanted sound coming into the region. However, similar to the JMC method, these approaches have the disadvantage of requiring both pressure and velocity sensors on the boundary surface to guarantee a universal solution. As demonstrated in [33,34], both monopole and dipole sources were also required to successfully realize the active shielding in practice. The method developed in this paper aims to avoid the additional cost and complexity of including velocity sensors and dipole control sources, and as a consequence it will sacrifice the generality of automatically preserving wanted sound in the shielded region.

Recently, an active shielding was applied also based on virtual sensing for a cylindrical shell [37], which is a method restricted to cylindrical shape and include the problems of virtual sensing. From these methods in active shielding, it is important to remark that they have a limitation. All of them produces a solution and not a control algorithm. In order to make the control system more robust, it is desired to obtain a feedback control [38].

This paper deals with the attenuation of noise of a zone inside a microphone array. The solution is a novel active shielding method which reduces the hardware complexity respect to virtual sensing methods because it avoids the estimation process. Furthermore, it only uses pressure sensors, instead of the particle velocity sensors. Regarding the limitation of other active shielding systems proposed in state of the art, this article shows that it can use any controller based on an optimization process to obtain the attenuation inside the silent zone (see the controller in Appendix B, which is the solution obtained for algorithms similar to the FxLMS). Moreover, this result is differentiated by an analysis that includes the time variable. It is based on the wave equation instead of Helmholtz equation.

This article is divided as follows: the next section defines the concept called implicit control. This concept is used to propose a novel method for active shielding in Section 3. In Section 4, several simulations validate the active shielding method. Furthermore, a comparison between virtual sensing and the proposed active shielding method is carried out in Section 5. Finally, some conclusions are given in Section 6.

2. Implicit control

Before understanding how the proposed active shielding system works, it is necessary to define a new concept: