Applied Acoustics 116 (2017) 170–176

Contents lists available at ScienceDirect

Applied Acoustics

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

Binaural active noise control using parametric array loudspeakers

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ARTICLE INFO

Article history:
Received 2 April 2016
Received in revised form 26 July 2016
Accepted 19 September 2016

Keywords:
Feedforward active noise control
Factory noise
Parametric array loudspeaker
Crosstalk

ABSTRACT

This paper reports the binaural active noise control (ANC) system developed to deal with factory noise. The control points are located in the vicinity of the left and right ears of a worker sitting along the production line. Due to the complicated safety requirements in the factory, secondary sources and error microphones are not allowed to be placed near the worker. Therefore, the proposed ANC system employs the feedforward structure and adopts the parametric array loudspeakers (PALs) as the secondary sources. The PAL is a type of directional loudspeaker that generates a much narrower sound field as compared to the conventional loudspeaker. Once the proposed ANC system has been trained offline, the error microphones can be removed. The performance of the binaural ANC system is successfully demonstrated based on a digital signal processor (DSP) implementation.

1. Introduction

In factories, workers suffer from noise induced hearing loss. They sit along the production line and are exposed to the noise generated by manufacturing equipment for prolonged hours. Protective measures are urgently needed to solve this problem. Since verbal communication may be hindered by passive noise control, ANC seems to be the most feasible solution [1]. In an ANC system, the noise source is called the primary source. The secondary source, *a.k.a.* the control source, transmits an anti-noise wave with the equaling amplitude and opposite phase of the noise wave. Based on the superposition principle of sound waves, cancellation of the noise wave can be achieved at the control point, where the error microphone is set up to make the ANC system a closed loop control [2].

There are two basic structures of an ANC system [3]. They are the feedforward and feedback ANC systems. The feedforward ANC system requires an additional reference microphone or sensor to obtain an early observation of the noise wave, while the feedback ANC system computes an estimation of the noise wave internally. If the secondary source and error microphone are placed far from the control point, the feedback ANC system can fail to function. In contrast, the feedforward ANC system can be trained offline to carry out the fixed coefficient implementation [4]. In the fixed coefficient ANC system, the error microphone is removed while the reference microphone continues to track the noise wave.

Usually, the single-channel ANC system uses one secondary source and targets only one control point. When the secondary source is omni-directional, noise reduction is achieved at the control point, but spillover of the anti-noise wave leads to increased noise levels in other areas [5]. For the same reason, when the single-channel ANC system is applied to target more than one control point, the overall noise reduction performance is often unstable. Alternatively, the dual-channel ANC system uses two secondary sources. Each of the secondary source is principally in charge of one control point. When the secondary sources are omni-directional, crosstalk becomes an unavoidable problem and brings extra computational cost in the implementation, on top of the spillover problem [6]. Therefore, there are advantages of using directional loudspeakers as the secondary sources in ANC systems.

The PAL is a type of directional loudspeaker that makes use of the nonlinear acoustic effect to generate an audio beam from an ultrasonic beam [7]. In literatures, Hansen et al. were the first to investigate the feasibility of using the PAL as the secondary source [8,9]. The preliminary results were negative at very low frequencies, where the conventional ANC system was recognized to be the most efficient. Nevertheless, there have been an increasing number of successful attempts on using the PAL as the secondary source [10]. They have been applied to the midrange and upper midrange bands, such as from 0.5 to 2.5 kHz [11–13].

Among those successful attempts, Tanaka and his colleagues explored many unique features of the PAL that may improve the conventional ANC system [14]. For example, they used the reflected audio beam of the PAL to transmit the anti-noise wave in order for the control point to be invisible from the secondary

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http://dx.doi.org/10.1016/j.apacoust.2016.09.021
0003-682X/

source [15]. A steerable PAL that was implemented based on the phased array of ultrasonic transducers was applied in the ANC system targeting a moving control point [16]. Moreover, a curved-type PAL was built up to achieve global noise reduction by manipulating the focal point of the curved-type PAL to be located at the exact location of a monopole noise source [17].

This paper reports the binaural ANC system developed to create quiet zones in the vicinity of the left and right ears of a worker in the factory. According to the complicated safety requirements in the factory, secondary sources and error microphones are not allowed to be placed near the worker. Hence, it is reasonable for the binaural ANC system to employ the feedforward structure and adopt the parametric array loudspeakers (PALs) as the secondary sources. The PAL used in this paper is shown in Fig. 1, of which the dimension is 20 cm in width and 11 cm in height. It is made up of four units of Tristate K-02617. The audio bandwidth ranges from 0.4 to 5 kHz. Furthermore, the fixed coefficient implementation is also essential for the binaural ANC system to get rid of the error microphones, under the consideration that the worker is able to adjust his or her position to rest in the quiet zones.

Therefore, this paper is organized as follows. In the next section, the performance of the single-channel ANC system that targets two control points is demonstrated using one PAL. In Section 3, the dual-channel ANC system is examined with and without the cross-talk secondary path models when two PALs are used as the secondary sources. Furthermore, the performance of the fixed coefficient ANC system is presented to prove the feasibility of the binaural ANC system when there are no secondary sources and error microphones placed near the control points.

2. Single-channel ANC system using the PAL

The experimental setup of the single-channel ANC system is shown in Fig. 2. The factory noise sample shown in Fig. 3(a) is played back by an omni-directional loudspeaker to provide the noise source. There are periodical impulsive components generated by the packaging machine. The ambient noise in the factory is shown in Fig. 3(b), which is used to provide another noise source in the latter part of this paper. The reference microphone is placed close to the noise source. The PAL shown in Fig. 1 is used as the sec-

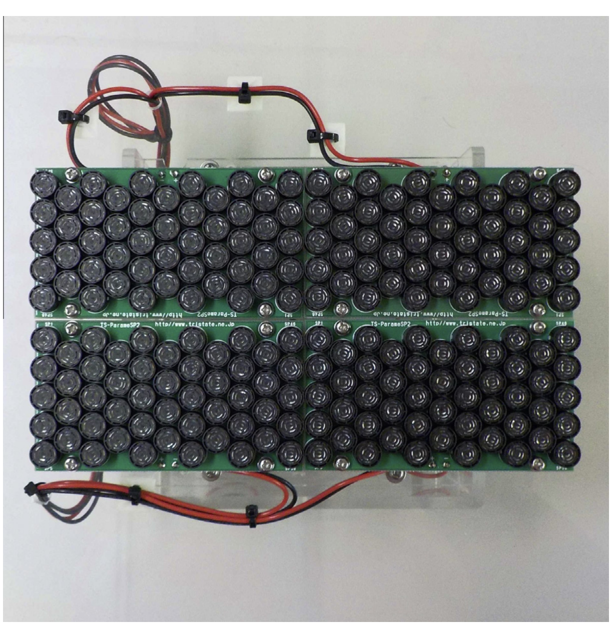

Fig. 1. A picture of the PAL.

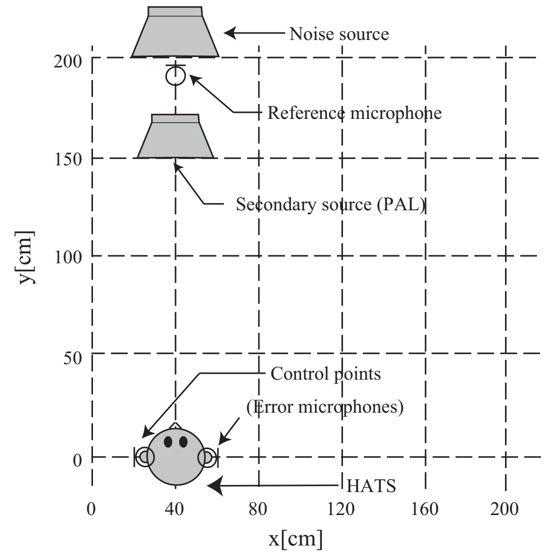

Fig. 2. Experimental setup of the single-channel ANC system.

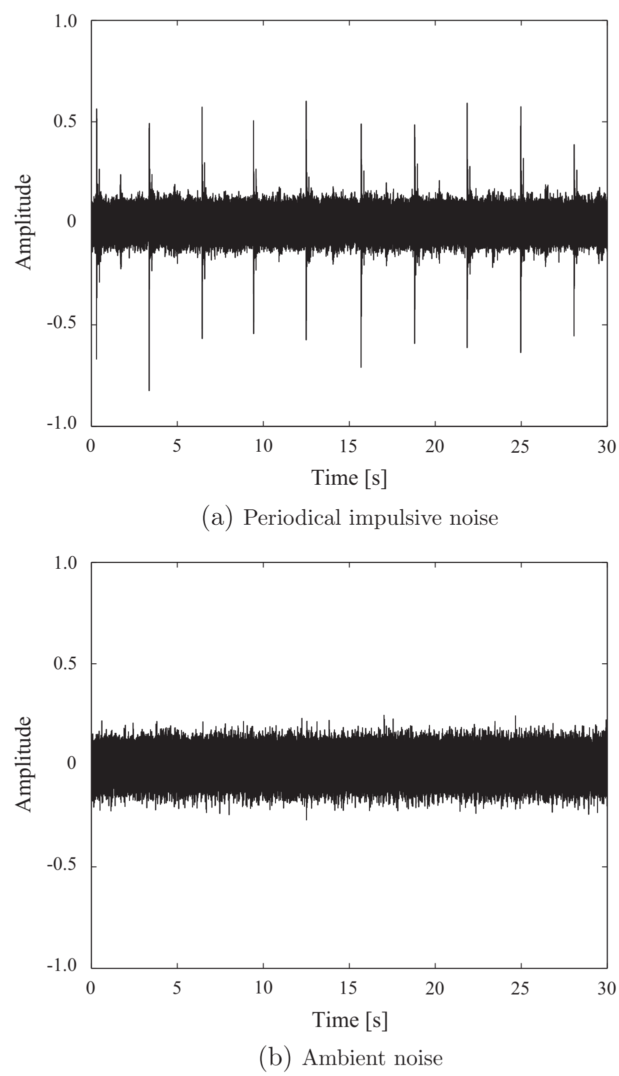

Fig. 3. Noise samples recorded in the factory.