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Adaptive nonlinear active noise control algorithm for active headrest with moving error microphones

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ABSTRACT

Nonlinear active noise control (ANC) algorithms are used to control nonlinear noise processes. In this paper, a generalized filter bank based nonlinear ANC algorithm is proposed for active headrest application. The algorithm is used to control the noise at both ears by using two moving error microphones which are mounted on the head. Mounting of microphones can be made using a wearing item such as a hat or band. Due to this, these microphones move along with the head. The adaptive ANC algorithm is shown to be very effective for head-movement. Real-time implementation of nonlinear ANC algorithm is made using a dSpace 1104 system for both ears. The robust performance of adaptive nonlinear ANC algorithm is shown for controlling nonlinear noise process at both ears even during head movement using a pair of moving error microphones without re-estimating the secondary paths for the new position.

1. Introduction

Active headrest is a system where the occupant gets a quite zone to avoid surrounding noise. This uses the principle of active noise control (ANC) where antinoise is created using one or multiple loudspeakers near the head region. The concept of active headrest was first given by Olson and May [1]. Latter in 90's many researchers worked towards its implementation [2–4]. However, all these algorithms were meant to control linear noise processes. Nonlinear noise processes are seen in many practical situations. Some of them are as follows [5].

(1) When the primary path behaves nonlinearly due to turbulence. In other words, the reference signal of ANC and the noise at the point of cancellation bear a nonlinear relationship.
(2) If the noise is chaotic and the secondary path is nonminimum phase.
(3) If the loudspeaker system and the noise sensing system have nonlinear response such as saturation nonlinearity.

Out of these three types of nonlinear noise processes, the primary path nonlinearity due to turbulence is considered in this paper.

The trigonometric functional link artificial neural network (FLANN) based ANC for active control of noise under primary path nonlinearity and chaotic noise cases has been proposed in [5]. The same concept for multichannel ANC system is presented in [6]. Computational efficient nonlinear ANC algorithms are proposed in [7]. A generalized FLANN structure using both trigonometric and Volterra series has been proposed in [8]. Other popular nonlinear ANC algorithms use recursive FLANN filter [9], radial basis function network and Volterra series [10,11], reduced feedback functional link neural network [12], adjoint nonlinear filter [13], cascaded FLANN [14], spline adaptive filters [15] and exponential functional link network [16]. A survey of various nonlinear ANC algorithms can be found in [17]. In most of these papers, authors have evaluated their algorithms through simulation studies using single channel cases. However, one of the important applications of active noise control is active headrest. The application of active headrest are seen for crew-rest compartment mock-up [18], control of helicopter gearbox noise [19], etc. To reduce the computational complexity of active headrest algorithm, both side loudspeakers were driven by one controller and signals of both the error microphones were combined in [20]. Active headrest with head tracking system [21] and an ear mounted microphone system using simultaneous perturbation (SP) methods [22] were

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proposed to accommodate head movement. ANC algorithms with moving error microphone for single channel controller are shown in [23,24]. Active headrest with moving error microphones were presented for linear noise processes [25]. One of the important issue in active headrest is the performance degradation due to head movement. Virtual microphone techniques were proposed to cancel the noise at a remote location where it is difficult to mount microphones [26–29]. Such virtual sensing techniques were applied for active headrest application [30–39]. All these algorithms cater to linear noise processes. Most of them are also not suitably tested for any random head movement condition. Nonlinear ANC algorithm is applied for active headrest application in [40] where it is shown that nonlinear noise can be controlled at a remote location using virtual sensing technique. However, no results were shown for head movement conditions.

In this paper, a nonlinear noise process was considered in active headrest application. In addition to this, the head movement towards left, right, forward and backward are considered to evaluate the efficiency of the nonlinear ANC algorithm. Different types of the nonlinear ANC algorithms with different types of nonlinear functional expansions are considered for performance comparison.

Organization of the paper is as follows. Section 2 presents the proposed adaptive nonlinear ANC algorithm for active headrest considering movable error microphones. Section 3 is dedicated for exhaustive experiments using practical setup. Conclusion is presented in Section 4.

2. Proposed adaptive nonlinear ANC algorithm for headrest

Active headrest typically consists of two loudspeakers and two error microphones at either side of the head (Left and Right). The two loudspeakers are excited by two controllers which generate anti-noise. The two error microphones are used to sense the noise at both sides of the head. The error microphone signals are used to tune both the ANC controller in such a way that the square of the error signals at both sides are minimized. Both the controllers are fed by a reference signal which is usually by a reference microphone. For multiple noise sources, multiple reference microphones can be used, however, in this proposed computationally efficient algorithm only one reference microphone is used. It is assumed that the reference microphone can receive composite noise which can be fed to controllers of both sides. The objective of the controller is to minimize the noise at both sides of the head. The error microphones are placed very close to the ear so that the noise received by these two microphones is equivalent to the noise entering into the respective ears. In this case, it is proposed to have a head mounting device such as a cap having two microphones placed near both ears. Since these error microphones are now movable, and also changes with time, the received signals are a function of time and position. Accordingly, the cost function of the control algorithm is

$$J(n,k) = \frac{1}{2}[e_L^2(n,k) + e_R^2(n,k)] \tag{1}$$

where $e_L(n,k)$ and $e_R(n,k)$ represent the signals received by the left and right error microphones at sample time n and position k.

The error signals are the residual signals remaining due to the superimposition of both primary noise and the secondary noise generated by ANC controllers. The residual noise at both sides of the controllers are

$$e_L(n,k) = d_L(n,k) + \hat{d}_L(n,k) \tag{2}$$

and

$$e_R(n,k) = d_R(n,k) + \hat{d}_R(n,k) \tag{3}$$

where $d_L(n,k)$ and $d_R(n,k)$ represent primary noise at both ears (left and right) for head position k for sample time n. $\hat{d}_L(n,k)$ and $\hat{d}_R(n,k)$ represent the anti-noise generated at either side to control the noise which is generated by controllers of two sides. The controller outputs are passed through loudspeaker systems (conventionally known as secondary paths) to act as anti-noise at both sides. Since the output of left loudspeaker can affect the noise at right side and vice versa, the anti-noise of either side are defined as follows

$$\hat{d}_L(n,k) = y_L(n,k) * s_{LL}^k + y_R(n,k) * s_{LR}^k \tag{4}$$

and

$$\hat{d}_R(n,k) = y_R(n,k) * s_{RR}^k + y_L(n,k) * s_{RL}^k \tag{5}$$

where s_{LL}^k, s_{LR}^k, s_{RR}^k and s_{RL}^k represent the impulse response of the four secondary paths in this headrest system where the secondary path s_{pq}^k relates to the output of q side controller and p side error microphone. p and q can be either Left (L) or Right (R). $y_L(n,k)$ and $y_R(n,k)$ are the output of controllers of left and right sides respectively. '$*$' denotes convolution operations.The nonlinear controller proposed here has filter bank architectures as shown in Fig. 1. The reference signal $x(n)$ is used to generate the output of either side. The controller output of both sides are computed as

$$y_L(n,k) = x(n) * w_{0,L}(n,k) + g_1[x(n)] * w_{1,L}(n,k) + \dots g_M[x(n)] * w_{M,L}(n,k) = \sum_{m=0}^{M} g_m[x(n)] * w_{m,L}(n,k) \tag{6}$$

and

$$y_R(n,k) = \sum_{m=0}^{M} g_m[x(n)] * w_{m,R}(n,k) \tag{7}$$

where $w_{m,L}(n,k)$ and $w_{m,R}(n,k)$ are the adaptive filter coefficients and $g_m[x(n)]$ is a nonlinear function for $m = 1, 2, \dots M$ and $g_0[x(n)] = x(n)$. Referring to Fig. 1, it can be marked that the reference signal is directly passed to a linear adaptive filter $W_{0,L}$ for left side controller (and $w_{0,R}(n,k)$ for right side). It can also be marked that the same reference signal is nonlinearly modulated by a set of nonlinear functions $g_1(\cdot)$ to $g_M(\cdot)$ and then individually passed through linear adaptive filters represented by $W_{1,L}$ to $W_{M,L}$. The symbols of these filters are capitalized in Fig. 1 to represent them in transfer function notation which corresponds to their equivalent impulse responses, e.g. $W_{m,L}$ corresponds to $w_{m,L}(n,k)$. Let us consider, each of these adaptive filters to have N numbers of filter coefficients and is represented in its vector form as $\mathbf{w}_{m,L}(n,k)$. The input signal vectors for these filters which are generated from nonlinearly modulated reference signal except $m = 0$ are represented as $\mathbf{x}_{m,L}^g(n)$. Accordingly, (6) and (7) can be represented as

$$y_L(n,k) = \sum_{m=0}^{M} \mathbf{x}_m^g(n)[\mathbf{w}_{m,L}(n,k)]^T \tag{8}$$

and

$$y_R(n,k) = \sum_{m=0}^{M} \mathbf{x}_m^g(n)[\mathbf{w}_{m,R}(n,k)]^T \tag{9}$$

The weight vectors of either side of the ANC controllers are adapted by using a gradient decent method to minimize the cost function defined in (1) as follows

$$\mathbf{w}_{m,L}(n+1,k) = \mathbf{w}_{m,L}(n,k) - \mu \nabla_{\mathbf{w}_{m,L}(n,k)} J(n,k) \tag{10}$$

and

$$\mathbf{w}_{m,R}(n+1,k) = \mathbf{w}_{m,R}(n,k) - \mu \nabla_{\mathbf{w}_{m,R}(n,k)} J(n,k) \tag{11}$$