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Particle swarm optimization based nonlinear active noise control under saturation nonlinearity

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ABSTRACT

In this paper, a method is proposed to overcome the saturation non-linearity linked to the microphones and loudspeakers of active noise control (ANC) system. The reference microphone gets saturated when the acoustic noise at the source increases beyond the dynamic limits of the microphone. When the controller tries to drive the loudspeaker system beyond its dynamic limits, the saturation nonlinearity is also introduced into the system. The secondary path which is generally estimated with a low level auxiliary noise by a linear transfer function does not model such saturation nonlinearity. Therefore, the filtered-x least mean square (FXLMS) algorithm fails to perform when the noise level is increased. For alleviating the saturation nonlinearity effect a nonlinear functional expansion based ANC algorithm is proposed where the particle swarm optimization (PSO) algorithm is suitably applied to tune the parameters of a filter bank based functional link artificial neural network (FLANN) structure, named as PSO based nonlinear structure (PSO-NLS) algorithm. The proposed algorithm does not require any computation of secondary path estimate filtering unlike other conventional gradient based algorithms and hence has got computational advantage. The computer simulation experiments show its superior performance compared to the FXLMS, filtered-s LMS and genetic algorithms under saturation present at both at secondary and reference paths. The paper also includes a sensitivity analysis to study the effect of different parameters on ANC performance.

1. Introduction

The feedforward active noise control (ANC) system employs a reference microphone to sense the undesired noise, a secondary loudspeaker to produce anti-noise and an error microphone to sense the residual noise. The residual noise is used as the error signal for updating the weights of the adaptive controller [1–6]. The schematic diagram of a widely used single channel feedforward ANC system is shown in Fig. 1.

The convergence performance of linear ANC techniques is severely affected when it is applied to nonlinear noise process [7–17]. The nonlinearity introduced in ANC may be due to nonlinearity in primary and secondary paths as well as due to chaotic noise and nonminimum phase secondary path. Novel nonlinear ANCs using radial basis function based neural network [7], artificial neural network (ANN) [8,9], Volterra series based algorithms [10–12] and functional link neural network (FLANN) [13] with filtered-s LMS (FSLMS) [14–17] training scheme offer superior performance over the FXLMS based ANCs.

The FSLMS algorithm is well accepted due to its low computational burden and better performance over the Volterra filtered-x LMS (VFXLMS) algorithm. In recent past, improved nonlinear ANC algorithms using the VFXLMS and FSLMS algorithm [18–20] have been reported. In all these papers except [18], the authors have evaluated the performance of their algorithms in presence of nonlinearity due to primary path and chaotic noise.

The nonlinearity introduced due to the saturation effect of the microphones and loudspeakers are also important while designing the ANC. The saturation nonlinearity effect of the microphones and loudspeakers is observed when the amplitude of inputs is relatively high. This high amplitude of the undesired primary noise

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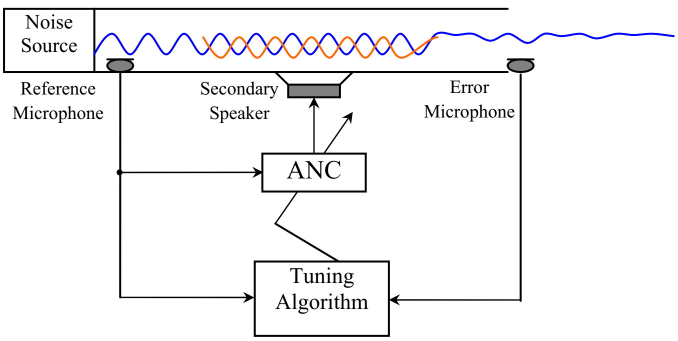

Fig. 1. Block diagram of single channel feedforward ANC.

drives these microphones and loudspeakers beyond their dynamic range because of their low power characteristics. Therefore, the saturation nonlinearity of the microphones and loudspeakers is considered as the primary source of nonlinearity in the ANC application. The standard FXLMS algorithm does not consider the saturation effect of these microphones and loudspeakers, and hence does not perform satisfactorily and offers poor convergence performance. In last two decades, many researchers have addressed the saturation nonlinearity problem and have proposed various techniques to tackle them.

The nonlinearity exhibited by the microphones and loudspeakers due to their saturation behavior is modeled by a scaled error function and a statistical analysis of these error functions in the secondary path by the FXLMS is presented in [21]. A stochastic analysis of the least mean square (LMS) algorithm under saturation nonlinearity is made in [22,23]. A modified cost function to avoid nonlinear saturation effect in FXLMS algorithm is presented in [24]. An indirect method for analyzing the saturation effects in steady state using Fourier analysis [25], bilinear FXLMS algorithm [26] and a nonlinear multiple channel FXLMS using Hammerstein structure to model the secondary path is proposed [27] to analyze and tackle this saturation nonlinearity issue. Nonlinear ANC controllers using neural networks [28] and a training algorithm based on back propagation algorithm for a multilayer perception neural network [29] are developed for nonlinearity due to saturation. Recently, a new method based on predistorter technique is proposed to alleviate the saturation nonlinearity problem of the loudspeaker present in the secondary path [30]. It is observed that all these algorithms use a gradient based adaptive algorithm to train the parameters of a nonlinear or linear control structure. In many situations these derivative based algorithms have a tendency to provide sub-optimal performance.

In recent past, a variety of soft and evolutionary computing algorithms has been reported in the literature for performing multivariable and multi-constrained optimization tasks. These population based optimization tools have been successfully employed for many engineering applications such as low-frequency oscillation damping control for energy storage [31], textile defects inspection system [32], optimal freeway local ramp meter [33], proportional-integral-derivative (PID) controller in automatic voltage regulator system [34], pulse width modulated based series compensator (PWMSC) damping controller [35], photovoltaic-fuel cell of hybrid electric vehicles [36], driving guidance of full electric vehicles [37], image processing [38], test array generator for fault detection [39] and damage detection using vibration data [40]. These optimization schemes can also be used as derivative free learning of the weights of adaptive systems with less probability of being trapped by local minima problem. Various popular evolutionary computing algorithms recently used in designing efficient ANC systems are genetic algorithms (GA) [41–43] and particle swarm optimization (PSO) [44,45].

After reviewing the literature in the area of ANC, it is observed that the implementation of an efficient adaptive ANC system depends on the proper operation of the microphones and loudspeakers systems. These two subsystems ideally should operate within their dynamic limits for achieving proper convergence of the weights of the controller during tuning of the ANC. However, in practice, it is not possible to meet these ideal conditions as the noise source and the environment are mostly dynamic in nature. Thus, there is a requirement to design an efficient ANC system which can update the control parameters properly in presence of saturation nonlinearity of the two subsystems used.

To achieve this objective, the paper proposes an evolutionary computing based adaptive training scheme using a nonlinear ANC structure. Out of varieties of evolutionary computing tools the PSO has been chosen because of its simplicity and potentiality of effective optimization of the cost function. The novelty of this paper is the use of nonlinear filter bank adapted with PSO based tuning algorithm for nonlinear ANC problems unlike the previously proposed PSO based ANC [44] where the FIR filter based ANC controller has been tuned with PSO algorithm. In addition to this, a number of simulation cases with varied degree of saturation nonlinearity both at input and output of the controller have been carried out in this paper for the performance evaluation of the proposed algorithm. Unlike the linear ANC algorithms, the nonlinear ANC algorithms need more computation for a number of filtering through secondary path estimate filters for parameter tuning. However, the use of PSO based tuning algorithm for nonlinear ANC algorithm does not require any filtering operation for secondary path estimate and hence is computationally efficient. The conventional linear and nonlinear ANC algorithms also have performance degradation when there is saturation effect as the secondary path is estimated using a low level auxiliary noise excitation and a linear adaptive filter. However, since the present PSO based nonlinear ANC algorithm does not require the secondary path estimate, the performance of the ANC algorithm is not affected due to this estimation error. This is another advantage of the proposed algorithm in addition to the computational advantage.

The paper is organized as follows. The ANC system using FXLMS algorithm with saturation nonlinearity is discussed in Section 2. Section 3 presents in detail, the proposed method of PSO based nonlinear structure (PSO-NLS) ANC. Section 4 deals with the computer simulation results of the FXLMS, FSLMS, GA and the proposed PSO-NLS ANC. The sensitivity analysis for parameter tuning is carried out in Section 5. The conclusion of the paper is presented in Section 6.

2. The ANC using FXLMS algorithm with saturation nonlinearity

The conventional FXLMS algorithm [1–6] assumes that the secondary path is linear in nature. Accordingly, a linear estimate of the secondary path, $\hat{S}(z)$ is pre-evaluated and is used to filter the reference signal, $x(n)$. The secondary path is an electro-acoustic path consisting of a digital to analog converter, reconstruction filter, power amplifier, loudspeaker, acoustic path from the canceling loudspeaker to the error microphone, preamplifier, anti-aliasing filter and analog to digital converter. As explained earlier, when there is a nonlinear response seen within the secondary path, due to the saturation effect of the loudspeaker and amplifiers, this algorithm fails to adapt its parameters and hence provide poor performance. The increase in the noise level may also drive the reference microphone to its saturation limit which again introduces further nonlinearity. Therefore, the block diagram shown in