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A novel feedback active noise control for broadband chaotic noise and random noise

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ABSTRACT

The feedback active noise control (ANC) can be seen as a predictor, the conventional method based on filtered-x least mean square (FXLMS) algorithm can only be useful for linear and tonal noise, but for nonlinear and broadband noise, it is useless. The feedback ANC using functional link artificial neural networks (FLANN) based on filtered-s least mean square (FSLMS) algorithm can reduce some nonlinear noise such as chaotic noise, but the noise cancellation performance is not very well, at the same time, it is not useful to random noise. To solve the problem above, a new feedback ANC using wavelet packet FXLMS (WPFXLMS) algorithm is proposed in this paper. By decomposing the broadband noise into several band-limited parts which are predictable and each part is controlled independently, the proposed algorithm can not only suppress the chaotic noise, but also mitigate the random noise. Compared with FXLMS and FSLMS algorithms, proposed WPFXLMS algorithm also holds the best performance on noise cancellation. Numerous simulations are conducted to demonstrate the effectiveness of the proposed WPFXLMS algorithm.

1. Introduction

In recent years, with the development of industry, excessive noises are produced and seriously impact on people's life and work. Traditional methods to reduce these noise are passive noise control (PNC) using insulation and absorption techniques. However, they can't mitigate the low frequency noise, but most sounds in our life are low frequency signals which are usually less than 1 kHz [1], besides, PNC is also costly and bulky. Compared with PNC, the active noise control (ANC) put forward in the 1970s is an alternative, which can suppress acoustic noise at low frequency with much smaller size and lower cost [2,3]. The ANC system is an electro-acoustic device based on the principle of destructive interference by generating an anti-noise with same amplitude and opposite phase of the undesired noise. Because ANC is an adaptive control system depending on the properties of the noise, it can reduce different noise with the change of environmental conditions, so it is more meaningful in practical applications.

According to the structure of ANC system, it can be classified feedforward ANC and feedback ANC [4]. Comparing with feedforward ANC, the feedback ANC is not involved of reference microphone and only error microphone is required, it reduces the number of system components and cuts back the cost greatly [5–9]. Because there is no reference microphone, so the problem caused by secondary source (loudspeaker) output getting back to the reference microphone and affecting the performance of ANC system can be avoided. Another advantage of feedback ANC is that it is unaffected to multiple noise sources. The principle of feedback ANC is adaptive prediction technology [9–11]. According to the primary noise, the feedback ANC can be subdivided to narrowband feedback ANC and wideband feedback ANC. In this paper, wideband feedback ANC is focused on.

Feedback ANC system has been studied in many paper, most of them are used to cancel linear and tonal noise, which are predictable [5–11]. But for wideband noise like random noise and chaotic noise, less of them are involved. Wideband noise is very common in our life, for example the noise presented by a fan, which shows a combination of tonal noise and chaotic noise [12–15]. Conventional way used in feedback ANC is filtered-x least mean square (FXLMS) algorithm with finite impulse response (FIR) filter or infinite impulse response (IIR) filter, this method can only process linear noise and narrowband noise and can't work at all in nonlinear and wideband noise filed. The paper [15] firstly uses functional link artificial neural networks (FLANN) based on filtered-s least mean square (FSLMS) algorithm to reduce chaotic noise in feedback ANC system. To a large extent, it suppresses the chaotic noise, but the performance is not very well. Additionally, it is not involved the random noise. Therefore, for further improving the result of wideband noise cancellation, a better alterative using wavelet

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packet (WP) is proposed in this paper. Because the secondary path (the acoustic path from speaker to error microphone) shows non-minimum phase response in this paper, it means that the process of this feedback ANC for broadband noise is the process to predict primary noise.

Wavelet transformation has shown promising application in various areas [16,17], it is a main tool to analyze signal in time-frequency domain. By decomposition, the original signal is simplified and presents its local characteristic. Paper [18,19] proposed a wavelet transform domain LMS Algorithm, which has a faster convergence rate than the time domain LMS algorithm. Based on these methods, in paper [20], a multi-resolution FXLMS algorithm using discrete wavelet transform (DWT) is first used in ANC, which present an excellent performance on noise cancellation. But for broadband signal, the DWT can't work well, because it can only make a subdivision for the low frequency part and doesn't have the ability to decompose high frequency part [21,22]. While WP method can provide a more careful resolution ratios analysis, since it not only makes a decomposition for the low frequency part of signal, but also makes a decompositions for the high frequency part of signal, this advantage makes WP express an obvious superiority in broadband noise. By analysis above, the feedback ANC using WP for broadband noise would be effective. Through decomposing the broadband noise firstly and reducing each part of the noise independently, the original noise can be cancelled well. After WP decomposition, each part is band-limited, the decomposing level is more, the frequency band is narrower, and each part is more similar to narrow-band signal and easier to predict. Because the each part of broadband noise after WP decomposition is controlled by FXLMS algorithm, the proposed algorithm is called WPFXLMS algorithm.

The organization of this paper is as follows. In Section 2, some preliminaries are presented, which include the introduction of chaotic noise, discrete wavelet transform and wavelet packet. In Section 3, the proposed WPFXLMS algorithm is introduced. Section 4 gives exhaustive simulation studies to confirm the effectiveness of proposed WPFXLMS algorithm. Section 5 concludes the work in this paper.

2. Preliminaries

2.1. Chaotic noise

The chaotic signals play an important role in signal processing field, we can see them in some deterministic nonlinear system like rotating machines, fans and airfoils etc. Different chaotic signals can be delimited differently, but in term of the natural characteristics of these chaotic signals, they are similar. For example, they are broadband, random-like and difficult to predict the behavior of the systems in long term because of the complexity and sensitive dependence on initial condition of chaotic system. For ANC system, the chaotic signals are seen as an undesired noise to reduce, the most common one is logistic chaotic noise, which can be expressed by

$$x(n) = \lambda x(n-1)[1 - x(n-1)] \tag{1}$$

where $\lambda = 0.4$ and $x(0) = 0.9$, and n is the time/sample index.

It is clearly shown from the Eq. (1) that the present state of this noise only depends on its last state. However, in practical cases, the logistic chaotic noise is not always expressed like Eq. (1), the present state of the noise may depend on its past states not the last state. So the logistic chaotic noise can be modified like follow

$$x(n) = \lambda x(n-Q)[1 - x(n-Q)], \quad \{Q \geqslant 1 | Q \in \mathbf{Z}_+\} \tag{2}$$

where $\lambda = 0.4$ and $\{x(i)\}_{i=0}^{Q-1} = 0.9$, $n = Q,\ Q+1,\ \ldots$. In this paper, the chaotic noise like Eq. (2) is called logistic chaotic noise Q.

Other than logistic chaotic noise, the Henon chaotic noise is also one common chaotic noise, which can be produced by

$$\left.\begin{array}{l} \frac{dy}{dt} = 1 - ax^2 + y \\ \frac{dy}{dt} = bx \end{array}\right\} \tag{3}$$

where x and y are the chaotic time series, the initial values of x and y are chosen as 0.1. The parameters are chosen as $a = 1.4$ and $b = 0.3$.

For comparison, uniform random noise is involved in this paper. The uniform random noise is generated between −1 and 1 by MATLAB function

$$x(n) = 2 \times rand - 1 \tag{4}$$

Referring to the paper [13,15], it can be known that the simplest way to establish the feature of chaotic noise is to plot the present sample with respect to its delayed samples, this plot is usually considered as phase plot. Taking 1000 samples of logistic chaotic noise 1 and random noise to plot their phase plots, which are shown in Fig. 1(a) and (b) respectively. It is seen that the logistic chaotic noise shows dense periodic orbits, which means the points on the orbit are approached randomly. But random signal doesn't display any such periodic orbits.

2.2. Discrete wavelet transform

In practical application, especially calculating in computer, the continuous wavelet transform (CWT) must be discretized. Usually, the scale factor a and shift factor b in CWT are replaced by $a = a_0^j$ and $b = ka_0^j b_0$ $(j, k \in \mathbf{Z}, a_0 > 1, b_0 > 0)$, so the discrete wavelet function (DWT) can be expressed by

$$\psi_{j,k}(t) = a_0^{-\frac{j}{2}} \psi(a_0^{-j} t - kb_0) \tag{5}$$

In Eq. (5), a_0 and b_0 are usually set as $a_0 = 2$, $b_0 = 1$. Then the discrete wavelet coefficient and reconstructed function are given by

$$C_{j,k} = 2^{-\frac{j}{2}} \int_{-\infty}^{\infty} f(t) \psi(2^{-j} t - k) dt \tag{6}$$

$$f(t) = \sum_j \sum_k C_{j,k} \psi(2^{-j} t - k) \tag{7}$$

In the DWT, a signal is represented by inner products with basis functions that are temporal shifts and dilatation of a prototype function (mother wavelet). The DWT can be considered a signal in a dyadic sub-band decomposition.

2.3. Wavelet packet

Multi-resolution analysis can decompose the signal effectively in time-domain and frequency-domain, but because the scale function it uses changes in binary, the resolution in high frequency part of signal is poor. In order to improve the decomposing performance of high frequency part, the scale subspace V_j and wavelet subspace W_j are replaced by a new subspace U_j^{2n}. Setting as $U_j^0 = V_j, U_j^1 = W_j, j \in \mathbf{Z}$, the orthogonal decomposition $V_{j+1} = V_j \oplus W_j$ can be replaced by

$$U_{j+1}^0 = U_j^0 \oplus U_j^1 \tag{8}$$

Supposing function $u_n(t) \in U_j^n$ and function $u_{2n}(t) \in U_j^{2n}$, and then

$$\left\{\begin{array}{l} u_{2n}(t) = \sqrt{2} \sum_{k \in \mathbf{Z}} h_k u_n(2t - k) \\ u_{2n+1}(t) = \sqrt{2} \sum_{k \in \mathbf{Z}} g_k u_n(2t - k) \end{array}\right. \tag{9}$$