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# Improved functional link artificial neural network filters for nonlinear active noise control

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ABSTRACT

The functional link artificial neural network (FLANN) structure using trigonometric function expansion is used successfully in nonlinear active noise control (NANC) system. However, there are still two potential shortcomings to deteriorate its performance. One is that the FLANN filter may perform poorly when the cross-terms exist in NANC system, and the other is that the FLANN filter cannot obtain its optimal solution in some complex nonlinear cases because its nonlinear parts have intrinsic coefficient dependences between each other. To surmount these shortcomings, improved FLANN (IFLANN) filter and simplified IFLANN (SIFLANN) filter are proposed in this paper. To reduce the computational complexity further, the filtered-error least mean square (FELMS) algorithm is considered in the NANC system using these two proposed filters. IFLANN and SIFLANN filters solve these problems by inserting a corrective filter before trigonometric function expansion to offer suitable cross-term delay samples and counterbalance the nonlinear coefficients calculation. Moreover, detailed computational complexity analysis and extensive simulations with different reference signal and acoustic path are provided to demonstrate the effectiveness of the proposed IFLANN and SIFLANN filters. Compared to FLANN filter and its other improved versions, the proposed IFLANN and SIFLANN filters have better performance on computational burdens and noise attenuation.

## 1. Introduction

Active noise control (ANC) system is an electro-acoustic device based on the principle of destructive interference by generating the signal which has the same amplitude and opposite phase with the undesired noise [1,2]. Because of the potential industrial applications and digital signal processing advantages, many different kinds of ANC algorithms are developed quickly in recent years [3–5]. More widely used of them is filtered-x least mean square (FXLMS) algorithm based on linear finite impulse response (FIR) filter [2], which works well in most cases. However, these superiorities are only applied in linear control problem. In other words, when the reference signal measured by the acoustic sensor or the transfer functions of the primary path and secondary path are nonlinear, the ANC system based on FXLMS algorithm performs poorly and even fails to work [6].

In order to solve the nonlinear distortions in ANC system, a variety of nonlinear structures and algorithms are proposed over past fifteen years [7–32]. Functional link artificial neural network (FLANN) filter using trigonometric function expansion is one more widely used of them. Recently, FLANN filter is used in many cases, such as feedforward ANC, feedback ANC, single channel ANC, multichannel ANC [28–31]. Though the FLANN filter is applied successfully, it still faces two shortages. One is that it does not include the cross-terms which usually exists in nonlinear primary noise [21–25]. The other one is that the controller coefficients of nonlinear parts have intrinsic dependence relationship so that it is difficult to find precise solutions.

The cross-terms are some products between different time delay samples of input signal like $[x(n-i)]^m[x(n-j)]^n...[x(n-k)]^l, i \neq j \neq k$. In FLANN filter, it is clear that the nonlinear mapping capability depends on the trigonometric function. Expanding the trigonometric function using Maclaurin formula, the sinusoidal component and cosine component are composed of some polynomials which are only the power function of current input samples. Therefore, the FLANN filter cannot effectively reduce those noise caused by cross-terms. To solve these problems, Sicuranza and Carini proposed generalized FLANN (GFLANN) filter, complete FLANN (CFLANN) filter and even mirror Fourier nonlinear filters (EMFN) in 2011, 2012 and 2014 [22–25], respectively. Since then the cross-terms problem of FLANN filter is considered a necessary issue in NANC system. Of course, there are other different nonlinear models (such as nonlinear autoregressive models with exogenous variables (NARX) models, Volterra models, bilinear models, etc.) where cross terms are naturally considered and accounted

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for [13–17]. However, these models also have their limitations. For example, they are all polynomial functional expansion which leads to the computational complexities of them are generally heavier than trigonometric function expansion. Furthermore, polynomial filters have a constrained structure, which can only model specific types of nonlinearities [21]. Therefore, completing the FLANN filter is one very necessary work.

Though the GFLANN, CFLANN and EMFN filters can be used to solve the cross-terms problem of FLANN filter, the coefficient dependences of nonlinear parts of FLANN filter have not been involved currently. These intrinsic coefficient dependences of nonlinear parts can be found by analyzing the principle of FLANN filter. The coefficient of each nonlinear part is not calculated independently so that these coefficients cannot reach their optimal solutions. To weaken these dependence relationships, an improved FLANN (IFLANN) filter by adding corrective filters before trigonometric expansion is introduced. By this way, the coefficients of nonlinear components are composed of two separate parts. Moreover, a simplified IFLANN (SIFLANN) filter which saves the computational loads greatly compared to IFLANN filter is also developed. To simplify the proposed filters further, the filtered-error least mean square (FELMS) algorithm is used to update the controller and corrective filter weights. Because the proposed IFLANN and SIFLANN filters are modified based on the CFLANN filter, they also have the ability to compensate the cross-terms. Therefore, the motivation of this paper can be concluded as follow: (1) providing a comprehensive expression for the cross-terms $[x(n-i)]^m[x(n-j)]^n\ldots[x(n-k)]^l, i\neq j\neq k$; (2) weakening the intrinsic dependences between nonlinear coefficients to improve the performances of FLANN and its other modified versions.

This paper is organized as follows. The performance and principle analysis of FLANN filter used in NANC system are introduced in Section 2. The IFLANN and SIFLANN filters using FELMS algorithm are proposed in Section 3, and the computational complexity is also presented in this section. Some simulation results are shown in Section 4. Concluding remarks follow in Section 5.

## 2. Conventional FLANN filter and its performance

### 2.1. FLANN filter

Artificial Neural Network (ANN) is applied widely to solve nonlinear problems because of its better performance on nonlinear mapping and self-learning. However, in ANC system which emphasizes on real-time control, conventional ANN is too complex to be used in practical application. Compared with conventional ANN, functional link ANN (FLANN) solves the nonlinear problems using nonlinear functional expansion to replace the hidden layers of ANN. So FLANN involves less computational complexity than ANN. Fig. 1 shows the block diagram of FLANN filter.

In FLANN filter, the input vector is given by

$$\mathbf{x}(n) = [x(n)\ x(n-1)\ \ldots\ x(n-N+1)]^T \tag{1}$$

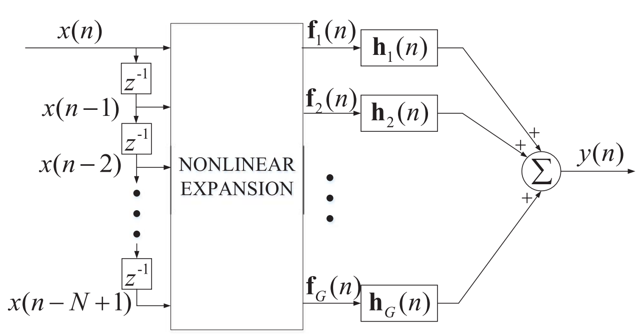


**Fig. 1.** The block diagram of FLANN filter.

where $N$ is the number of input neuron. The output vector after function expansion can be expressed by

$$\mathbf{F}(n) = [\mathbf{f}_1^T(n)\ \mathbf{f}_2^T(n)\ \ldots\ \mathbf{f}_G^T(n)]^T \tag{2}$$

where sub-vectors $\{\mathbf{f}_i(n)\}_{i=1}^G$ are expressed by

$$\mathbf{f}_i(n) = [FE_i(x(n))\ FE_i(x(n-1))\ \ldots\ FE_i(x(n-N_i+1))]^T \tag{3}$$

where $N_i \leqslant N$ and $FE_i(\bullet)$ is the expansion function.

As a consequence, the output of FLANN filter is

$$y(n) = [\mathbf{h}_1(n)]^T\mathbf{f}_1(n) + [\mathbf{h}_2(n)]^T\mathbf{f}_2(n) + \ldots + [\mathbf{h}_G(n)]^T\mathbf{f}_G(n) \tag{4}$$

where vectors $\{\mathbf{h}_i(n)\}_{i=1}^G$ are some linear filters such as FIR filter.

$$\mathbf{h}_i(n) = \left[h_{i,0}\left(n\right)h_{i,1}\left(n\right)\ldots h_{i,N_i-1}\left(n\right)\right]^T \tag{5}$$

Through the introduction above, it is clear that the nonlinear expansion functions used in FLANN filter are the key to solve nonlinear problems.

### 2.2. NANC system using FLANN filter

There are many nonlinear functions which can be used as expansion function, such as Legendre function, Chebyshev function, trigonometric function etc. In nonlinear ANC (NANC) system, the FLANN filter based on trigonometric function expansion is widely used. Therefore, the FLANN filter usually indicates the FLANN filter based on trigonometric function expansion. The structure of NANC system using FLANN filter is shown in Fig. 2.

Generally, in FLANN filter, $\{N_i\}_{i=1}^G$ are equal to $N$. So the output after trigonometric function expansion is given by

$$\begin{aligned}
&FE_1(x(n)) = x(n)\\
&FE_2(x(n)) = \sin[\pi x(n)]\\
&FE_3(x(n)) = \cos[\pi x(n)]\\
&FE_4(x(n)) = \sin[2\pi x(n)]\\
&FE_5(x(n)) = \cos[2\pi x(n)]\\
&\vdots\\
&FE_{2P}(x(n)) = \sin[P\pi x(n)]\\
&FE_{2P+1}(x(n)) = \cos[P\pi x(n)]
\end{aligned} \tag{6}$$

where $P$ is the expansion order and $G = 2P+1$. Therefore, $\{\mathbf{f}_i(n)\}_{i=1}^G$ are expressed as follows

$$\begin{aligned}
&\mathbf{f}_1(n) = [x(n)x(n-1)\ldots x(n-N+1)]^T\\
&\mathbf{f}_2(n) = [\sin(\pi x(n))\sin(\pi x(n-1))\ldots\sin(\pi x(n-N+1))]^T\\
&\mathbf{f}_3(n) = [\cos(\pi x(n))\cos(\pi x(n-1))\ldots\cos(\pi x(n-N+1))]^T\\
&\vdots\\
&\mathbf{f}_{G-1}(n) = [\sin(P\pi x(n))\sin(P\pi x(n-1))\ldots\sin(P\pi x(n-N+1))]^T\\
&\mathbf{f}_G(n) = [\cos(P\pi x(n))\cos(P\pi x(n-1))\ldots\cos(P\pi x(n-N+1))]^T
\end{aligned} \tag{7}$$

The total output of FLANN filter is given by

$$\begin{aligned}
y(n) &= \sum_{p=1}^{2P+1} y_p(n)\\
&= \sum_{p=1}^{2P+1} \mathbf{h}_p^T(n)\mathbf{f}_p(n)\\
&= \sum_{j=0}^{N-1} h_{1,j}x(n-j) + \sum_{p=1}^{P}\sum_{j=0}^{N-1}[h_{2p,j}\sin(p\pi x(n-j))\\
&\quad + h_{2p+1,j}\cos(p\pi x(n-j))]
\end{aligned} \tag{8}$$

By analyzing the Eq. (8), it can be known that the first part of right is linear control term and the second part of right is nonlinear control term. Knowing from the Maclaurin expansion of trigonometric function

$$\cos(x(n)) = 1-\frac{(x(n))^2}{2!} + \frac{(x(n))^4}{4!} - \frac{(x(n))^6}{6!} + \ldots \tag{9}$$