# *Functional Link Based Adaptive Filter for underwater acoustic detection signal*

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***Abstract*—The communication and detection signal become hard to recognize after they go through the underwater channel. To enhance the underwater signal, the functional link theory is introduced. According to the characteristic of the underwater signals, some improvements are made based on the split functional link adaptive filter. Experiment shows that the split functional link adaptive filter is fit for the lake channel through signal.**

***Keywords—functional links; collaborative adaptive filters; underwater acoustic signals; compressed sensing***

## I. INTRODUCTION

The underwater communication and signal detection are significant topics in the ocean resource development and the naval construction. However, many difficulties linger on satisfying the underwater signal processing accuracy requirement, including the detection accuracy, the location accuracy, etc. The underwater environment is an extremely complex circumstance. The nonlinearities including the marine background noise and the reverberation will be added into the underwater signal during transmission [1]. Meanwhile the multipath effect and the Doppler Effect will also cause nonlinearities [2][3]. Besides, the ratio between the two kinds of nonlinearity effect or the percentage of the linear and nonlinear signal power are unknown the priori. Moreover, it is the time varying for nonstationary signals. Thereby, it is not possible a priori to know the effect extent of the nonlinearities.

In recent years, different kinds of solutions are investigated to tackle the problems above. A high order spectrum is proposed in [4] to filter the underwater acoustic data. An improved harmonic wavelet is demonstrated in [5] to analyze the underwater acoustic signal time-frequency. The technique on the real-time feature extraction of continuous and line spectrums based on the power spectrum of radiated noise is studied in [6]. However all of these methods are ineffective in the complex cases, because of the ignorance of the nonlinearities and the variability in the ocean.

In the field of speech signal processing, the acoustic echo canceller has been widely studied in recent years, and some excellent methods were proposed to tackle the nonlinearities. A two-parameter sigmoid function is proposed in [7], the coefficient of the function can be updated in the algorithm that the slope and the amplitude of the function could improve along with the learning process. The adaptive Volterra filters derives from the Talor series, and it can model a large amount of nonlinearities [8]. However, the calculation amount will greatly increase as the Volterra order is lager than three [9].It is proved in [10] that the functional link theory shows more improvements and needs less computation compared to the Volterra Filter for the speech and the colored noise case.

In [11], The Volterra series theory has been used in analyzing the nonlinearities of the underwater acoustic signal. However the way is preliminary and it is not fit for the extremely complex circumstances because of the order problem. The functional link theory has been proposed in [12] for function approximation and pattern recognition to develop a class of single-layer feed forward neural networks with faster convergence rate and lesser computational load than the multi-layer one.

In this paper, the functional link theory is introduced and used in the underwater signal. Experiment shows that the split functional link adaptive filter is fit for the lake channel through signal. Some changes are made based on the performance of the functional link adaptive filter (FLAF) in [10]. The **proposed FLAF adds sparseness before functional expansion in accordance with the features of underwater acoustic signal.** Moreover, **the adaptive filter is spitted in the proposed structure.**

## II. FUNCTIONAL LINK ADAPTIVE FILTER

In [12] the Functional Link Network is a single layer artificial neural network. It receives an input signal formed by one or more samples and processes it by the functional expansion block. The functions in the block are linear independent. The functional expansion projects the input in a higher dimension space based on the machine learning theory, that the nonlinearities are weaken to obtain a higher signal to noise ratio (SNR).

The main idea which underpins the FLAF is enhancing the original input signal right from the start and weakens the background noise. The FLAF is carried out in two stages: the nonlinear functional expansion and the subsequent linear filtering. As depicted in Fig.1, where $g_i[\mathrm{n}]$ is the expanded

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signal, $d[\mathrm{n}]$ is the expected output, $y[\mathrm{n}]$ is the actual output and $e[\mathrm{n}] = \mathrm{d}[\mathrm{n}] - \mathrm{y}[\mathrm{n}]$, same represent as follows.

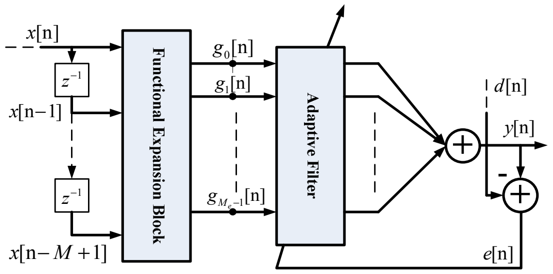


Fig 1 The functional link adaptive filter

FLAF receives an input $\mathbf{x}_n \in \mathbb{R}^M = [x[n]\ x[n-1] \ldots x[n-M+1]]^T$, where M is the input buffer length. The input is processed by the functional expansion block which consists of a series of orthonormal basis functions, satisfying universal approximation constraints [13]. According to [14], the functions can be described as:

$$\Phi = \{\varphi_0(\bullet), \varphi_1(\bullet), \cdots, \varphi_{Q-1}(\bullet)\} \tag{2.1}$$

where $Q$ is the number of the functions. These functions process each input Variable $\mathbf{x}_n$ by passing them as argument for the chosen functions. The subvector is depicted as:

$$\overline{\mathbf{g}}_{i,n} = \begin{bmatrix} \varphi_0(x[n-i]) \\ \varphi_1(x[n-i]) \\ \vdots \\ \varphi_{Q-1}(x[n-i]) \end{bmatrix} \tag{2.2}$$

The described process, for $i = 0, \ldots, M-1$, is depicted as:

$$\begin{aligned} \mathbf{g}_n &= [\overline{\mathbf{g}}_{0,n}^T \ \ \overline{\mathbf{g}}_{1,n}^T \ \cdots \ \overline{\mathbf{g}}_{M-1,n}^T]^T \\ &= [g_0[n] \ \ g_1[n] \ \cdots \ g_{M_e-1}[n]]^T \end{aligned} \tag{2.3}$$

which is a concatenation of subvectors and whose individual entries are denoted as $g_m[n]$, with $m = 0, \ldots, M_e - 1$, where $M_e \geq M$ is the expanded buffer length.

A generic set of functional links using trigonometric basis expansion of the i-th sample of the input buffer can be written as:

$$\varphi_j(x[n-i]) = \begin{cases} x[n-i], & j = 0 \\ \sin(p\pi x[n-i]), & j = 2p-1 \\ \cos(p\pi x[n-i]), & j = 2p \end{cases} \tag{2.4}$$

where $p = 1, \ldots, P$ is the expansion index. P is the expansion order, and $j = 0, \ldots, Q-1$ is the functional link index.

The construction of the functional link block which provides a satisfying approximation of a continuous multivariate function is depicted as in Fig 2.

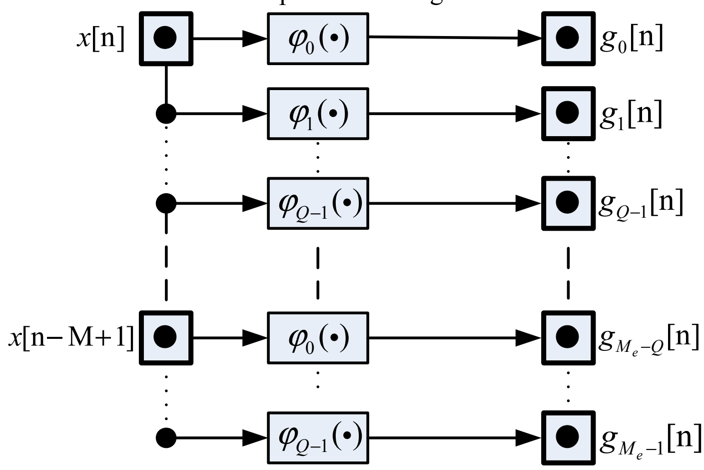


Fig 2 Functional Link Block

The second step is the design of the adaptive filter. The filter weight vector $\mathbf{w}_n \in \mathbb{R}^{M_e}$, is defined as:

$$\mathbf{w}_n = [w_0[n], w_1[n], \ldots, w_{M_e-1}[n]]^T \tag{2.5}$$

The error signal is:

$$\begin{aligned} e[n] &= d[n] - y[n] \\ &= d[n] - \mathbf{g}_n^T \mathbf{w}_{n-1} \end{aligned} \tag{2.6}$$

whose minimization depends on a proper estimate of the filter weights. Hence, the goal is to find out the weight vector, and the stochastic rule is used in the algorithm.

According to [10], the Split Functional Link Adaptive Filter is depicted in Fig. 3. The output depends on both the linear filter and the nonlinear filter:

$$y[n] = y_L[n] + y_{FL}[n] \tag{2.7}$$

where

$$\begin{aligned} y_L[n] &= \mathbf{x}_n^T \mathbf{w}_{L,n-1} \\ y_{FL}[n] &= \mathbf{g}_n^T \mathbf{w}_{FL,n-1} \end{aligned} \tag{2.8}$$

being $\mathbf{w}_{L,n} \in \mathbb{R}^M = [w_0[n], w_1[n], \ldots, w_{M-1}[n]]^T$ the coefficient vector of the linear filter, and $\mathbf{w}_{FL,n} \in \mathbb{R}^{M_e} = [w_0[n], w_1[n], \ldots, w_{M_e-1}[n]]^T$ the coefficient vector of the nonlinear filter. The filters are adapted using the overall error signal $e[n] = d[n] - y[n]$.

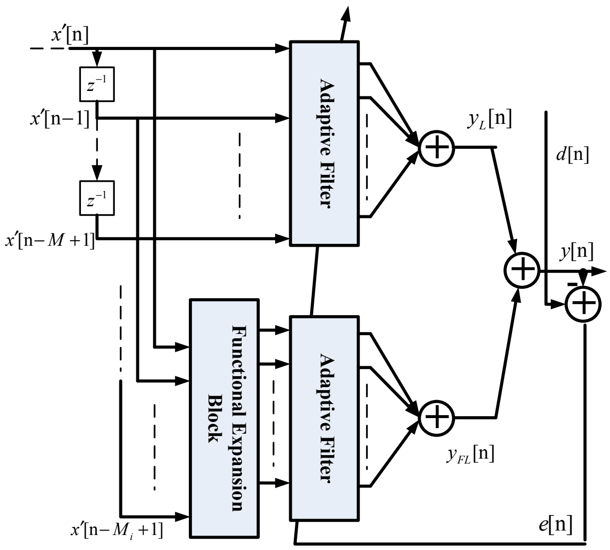


Fig 3 The Split Functional Link Adaptive Filter

## III. THE IMPROVED FUNCTIONAL LINK ADAPTIVE FILTER

As the communication or detection signals are transmitted in the ocean, the marine background noise and the reverberation affect the signals, meanwhile the multipath effect and Doppler Effect also occur. The marine background noise has a complicated composition. It is composed by thermal current, hydrodynamic force, marine transportation, earthquake, etc. The reverberation is emerged from the reflection and scattering, which can be expressed by:

$$\Psi(r_t, f) = \Psi_i(r_t, r_0, f) + \Psi_s(r_t, f) \tag{3.1}$$

where $\Psi_i(r_t, r_0, f)$ is the incidence sound field, and $\Psi_s(r_t, f)$ is the scattering sound field. The multipath effect results in the change of the phase and amplitude. A moving signal source results in the Doppler Effect:

$$f_d = f_r - f_0 = \frac{\Delta V}{c} f_0 = \frac{V_s \cos\theta}{c} f_0 \tag{3.2}$$

where， $\Delta V$ is relative velocity, $f_0$ is source frequency, $V_s$ is the speed of sound source to the sonar movement, $c$ is the sound velocity, $\theta$ is included angle between velocity and motor direction. The Doppler Effect causes the change of each frequency component in the frequency spectrum. Corresponded to each frequency multiply by a weighting factor:

$$\delta_v = \frac{\Delta V}{c} = \frac{V_s \cos\theta}{c} \tag{3.3}$$

$\delta_v$ is a variable, so the estimation of the Doppler Effect is difficult.

Combining the above analysis, the time-delayed input $\mathbf{x}_n \in \mathbb{R}^M = [x[n]\ x[n-1]\ \ldots x[n-M+1]]^T$ can weaken both multipath effect and Doppler Effect. The complexity of input signal, some transactions are made for the input. According to the compressed sensing theory, $\mathbf{x}_n$ can be made sparse by the Gaussian matrix:

$$x' = \Theta * x \tag{3.4}$$

where $\Theta$ is the Gaussian matrix. Then the functional expansion block is as depicted in Fig. 4, where some vectors in $\mathbf{x}'(\mathrm{n})$ are equal zero.

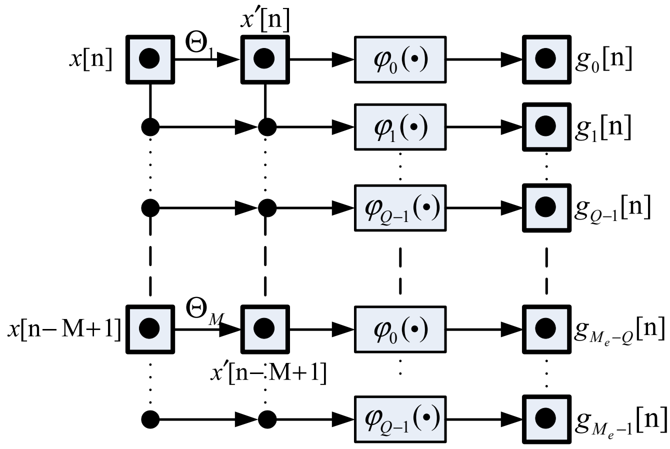


Fig 4 The improved functional expansion block

The Split FLAF depicted in [10] should also make some imprivements. We split the adaptive filter, to build a new structure, as depicted in Fig. 5. The filters are adapted using the linear and the nonlinear error signal separately.

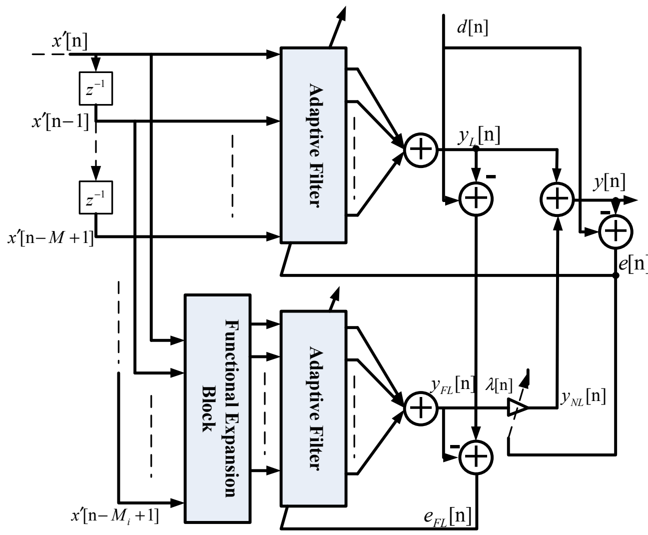


Fig 5 The improved functional link adaptive filter

## IV. EXPERIMENTAL RESULTS

A simulation and an experiment in lake are provided to illustrate the performance of the functional link adaptive filter applied in the underwater signal in two different channels. The first channel is Gaussian noise with zero mean and unitary variance. The other is the lake channel. The input signal is a simple frequency signal with the sampling frequency of 52000Hz.

The Split Functional Link Adaptive Filter is compared with the Volterra filter, which only have the main diagonal. The linear step size is $\mu_L = 0.2$ . The nonlinear and the kernel of Volterra filter step is both 0.1. Performance of the methods is evaluated in terms of signal to error ration (SER), which is defined as:

$$SER = 10\lg\left(\frac{E\{d^2[n]\}}{E\{e^2[n]\}}\right) \tag{4.1}$$

where E{} is the mathematical expectation.

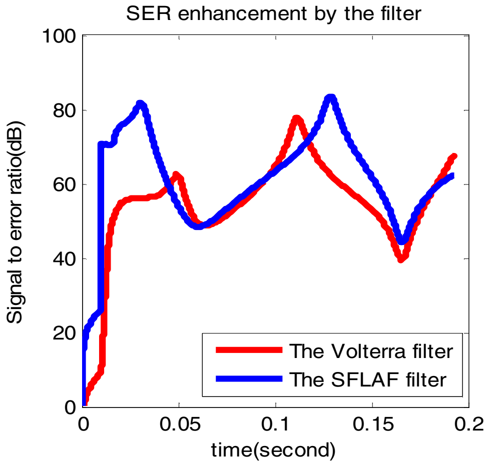


Fig 6 Gaussian noise channel SER

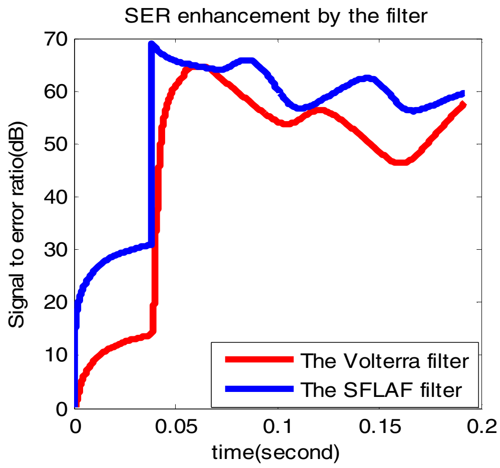


Fig 7 Lake channel SER

In Fig 6 we compare the SFLAF with the Volterra filter in a Gaussian noise channel. The behavior of the SFLAF is better than the Volterra filter as a whole, but not very stable.

In Fig 7 we compare the SFLAF with a Volterra filter in a lake channel. It is possible to notice the behavior of the SFLAF is better than Volterra filter. Hence, the SFLAF can be used in the underwater signal enhancement.

## V. CONCLUSION

This paper introduces a method to enhance the signal in the underwater channel. The functional link theory has been used in the speech signal processing, and obtained a good effect. Simulation shows that the functional link theory can also be used in the underwater environment, which is more complicated. We will make further improvement based on the characteristic of underwater signal, and design the sea trials in the future.

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