Application of adaptive line enhancer based on NLMS algorithm in shaft-rate electric field signal detection

Wenshi Zeng*, Qiang Bian, Yude Tong

College of Electric Engineering, Naval University of Engineering, Wuhan Hubei 430000, China

*Corresponding author’s e-mail: zengwenshi@nue.edu.cn

Abstract. There is lots of useful signal feature in ship's shaft-rate electric field. Extracting the signal feature is vital in underwater target recognition. In order to extract the feature of the shaft-rate electric field, the shaft-rate electric field is processed by ALE based on NLMS. The improved NLMS algorithm is proposed to construct an adaptive line-spectrum enhancer, and then the measured data of shaft-rate electric field is processed by ALE. The results show that the algorithm can effectively separate the weak shaft frequency electric field signal from the broadband background noise at low SNR. Compared with the ordinary ALE, the algorithm has more significant effect in improving SNR, faster convergence speed and smaller steady-state error, which greatly improves the detection ability of ship shaft frequency electric field.

1. Introduction

Different metal structures of ship will have electrochemical reaction in seawater, which will produce corrosion current. Severe corrosion may lead to different degrees of damage to the hull structure, and is not easy to maintain. Therefore, to reduce the corrosion, the ICCP will be artificially installed on the ship, and the cathodic protection system will also produce the corresponding anti-corrosion current. The corrosion current and anti-corrosion current will flow from the hull to the propeller through seawater, and then return from the propeller to the hull through various bearings and mechanical circuits to form a loop. The resistance of the loop will change periodically with the rotation of the propeller, so that the loop current will be modulated, resulting in a time-varying electric field with the rotation frequency of the propeller as the fundamental wave, that is, the shaft frequency electric field[1]. In the research of ship electric field, after getting the actual electric field measurement signal, it is vital to minimize the environmental noise. In practice, the electric field sensor is usually extremely far away from the ship to be measured, which leads to the detection signal mixed with other noise signals. And because the shaft frequency electric field signal is weak, the SNR of the detected signal is low, and it is often submerged in the background noise. The frequency range of shaft-rate electric field is generally below 10Hz, which belongs to ultra-low frequency. However, it is very difficult to separate useful shaft-rate narrow-band signals from wideband noise signals. In recent years, domestic scholars have also put forward some corresponding detection methods. At present, some popular improved methods have been used to detect the shaft-frequency electric field signal of ships from the aspects of empirical mode decomposition [2], high-order spectrum analysis [3] and MUSIC spectrum estimation [4]. However, they all have shortcomings such as large calculation amount and complex processing process, and are difficult to be put into practical application. There are also many scholars using adaptive line spectrum enhancement technology [5-7] to deal with the ship shaft frequency electric field signal.
field, but the robustness is not high and require high SNR conditions. Because the line-spectrum of shaft frequency signal and background noise are mixed, the conventional digital filter like band-pass filter can't extract the line spectrum of the shaft frequency electric field effectively, while the ordinary adaptive filter needs the reference noise, which can't be realized in practice.

Therefore, this paper studies the ALE based on the normalized LMS (NLMS) algorithm. Through the analysis of the measured data, it shows that the algorithm can tremendously improve the SNR. The performance of ALE based on NLMS is better than the traditional LMS algorithm, which greatly improves the remote detection ability of ship shaft frequency electric field.

2. Filtering principle

2.1. adaptive noise cancellation

When a narrowband periodic signal is submerged in the broadband background noise, the signal and the noise spectrum are mixed together, the traditional band-pass filter cannot effectively separate it, and the adaptive filter can solve this problem well. Adaptive filter can effectively track the time-varying statistics in unknown environment by using the statistical characteristics of the signal, which is not available in conventional non-adaptive methods. The basic principle of adaptive filtering is to use the input vector and the expected response to calculate the estimation error, and use the error to control the weight coefficient of the filter. The adaptive filter can be generally divided into four application types: system identification, adaptive equalization, adaptive prediction and interference cancellation. The model of interference cancellation is applied in this paper. Assuming that the signal $s(n)$ is contaminated by additive noise $u(n)$, the response $d(n)=s(n)+u(n)$ of the filter is made of the signal superimposed by the two, and then a reference noise signal related to $u(n)$ is used as the input $u(n)$ of the filter, and the correlation between the two is used to produce a very approximate approximation to $u(n)$, that is, $y(n)$, to offset the noise in the mixed signal.

The principle is shown in Fig. 1. The delay represented by $\triangle$ in the figure is usually called the prediction depth of ALE, which is measured by the sampling period. The input $x(n)$ is the original signal with noise, and the reference signal $x(n-\triangle)$ is obtained after $\triangle$ delay. The output signal $y(n)$ is obtained from the reference signal through adaptive filtering algorithm, and $e(n)=x(n)-y(n)$ is the error signal. The error signals at each moment are fed back to the adaptive filter to adjust the M tap weights of the filter. It is assumed that the environmental noise is a broadband signal with weak periodicity, and the axial frequency signal is a narrowband signal with strong periodicity. By selecting the appropriate delay $\triangle$, ALE can decorrelate the environmental noise in the original signal, and the useful electric field signal remains relevant. After the noise is filtered, the signal is finally enhanced.

![Figure 1. The principle of ALE.](image)

The adaptive filter is composed of a linear combiner, that is, the output signal is a linear combination from the array signal. Assuming that the input signal $\{x(n-i),d(n)\}$ $(i = 0, 1,\ldots, M - 1)$, there is:
\[ y(n) = \sum_{i=1}^{N} \omega_i(n)x_i(n) \]  
\[ e(n) = d(n) - \sum_{i=0}^{M-1} \omega_i(n)x_i(n) \]  

where \( x_i(n) \) and \( \omega_i(n) \) respectively represent the input signal and filter tap weights, and \( M \) represents the number of filter tap weights. According to the traditional form of LMS algorithm, the estimation error can be written as:

According to the principle of Wiener filter, in order to make the output \( y(n) \) of the filter the optimal estimation of the expected response \( d(n) \), it is necessary to adjust the weight coefficient \( \omega_i(n) \) of the filter to minimize the cost function \( J(n) = \left[ e(n) \right]^2 \). The core idea of LMS algorithm is to use square error instead of mean square error, that is to use the gradient of a single square error sequence \( J^*(n) = e^2(n) \) to estimate the gradient of multiple square error sequences:

\[ \omega_i(n+1) = \omega_i(n) - \frac{1}{2} \frac{\partial e^2(n)}{\partial \omega_i(n)} \]

\[ = \omega_i(n) + \theta e(n)x_i(n) \]  

Here, the scalar factor \( 1/2 \) is introduced for the convenience of mathematical processing, where \( \theta \) is the fixed step size.

2.2. NLMS algorithm

LMS algorithm is based on Wiener filter. To make the LMS algorithm converge, the step factor needs to be satisfied:

\[ 0 < \mu < \frac{2}{\lambda_{max}} \]  

Where \( \lambda_{max} \) is the maximum eigenvalue of the input correlation matrix \( R = X(n)X^H(n) \).

The step convergence condition of equation (4) requires the eigenvalue of the input signal autocorrelation matrix, which is not easy to obtain in practice. Moreover, LMS with fixed step factor can not meet the requirements of convergence speed and accuracy of LMS algorithm at the same time, so LMS algorithm with variable step size is needed to solve this problem.

The variable step size LMS algorithm is also called normalized LMS algorithm (NLMS). Its filter output formula and estimation error formula are the same as those of the basic LMS algorithm:

\[ w(k+1) = w(k) + \frac{\tilde{\mu}}{\|x(k)\|^2} x(k) e(k) \]  

In addition, in order to avoid that \( \mu(k) \) is too large when two-norm square of signal vector is small, a correction amount \( \alpha \) larger than zero can be added in the iterative formula. The improved NLMS algorithm is as follows:

\[ w(k+1) = w(k) + \frac{\tilde{\mu}}{\alpha + \|x(k)\|^2} x(k) e(k) \]  

For the traditional LMS algorithm or RLS algorithm, the selection of learning step size directly affects the final performance of the learning system, so how to make the learning step size adaptively adjust with the change of input signal is particularly important. NLMS algorithm is a good solution to
this problem. It effectively uses the experience in the learning process to make the learning algorithm more adaptive. The experimental results also show that the performance of NLMS algorithm is better than that of LMS algorithm. Compared with LMS algorithm, it has faster convergence speed and smaller steady-state error.

3. Experimental verification

3.1. Experimental method

The target signal is measured by the 1:100 scale model of the ship in the laboratory, and the propeller speed is about 300r/min. In order to simulate the seawater conductivity as much as possible, the target signal is about $3.95 (\Omega \cdot m)^{-1}$. It is necessary to add industrial salt to the tank for modulation. The shaft frequency electric field measurement system is mainly composed of sensor, signal conditioning circuit and data acquisition system. The electric field sensor uses high sensitive three-axis Ag/AgCl electrode to measure the three-dimensional components of the ship electric field in X, y and Z respectively. The measured electric field data is transmitted to the measurement system by coaxial cable and stored in the computer.

3.2. Experimental result

The sampling frequency was set as 2500Hz in the experiment, and the electric field sensor was fixed about 250cm directly below the ship model. The signal data on the X-axis of the electric field were selected for processing. The measuring results are shown in Figure 2 and the spectrum is shown in Figure 3.

![Figure 2. Shaft-rate modulated electric field signal.](image)

![Figure 3. Normalized frequency spectrum of shaft-rate modulated.](image)

It can be seen from Fig. 4 and Fig. 5 that the SNR of the input data is very low, so it is difficult to separate the shaft-rate electric field signal from the ambient noise. The traditional LMS algorithm and NLMS algorithm are simulated by MATLAB. The results are as follows:

The step size of LMS adaptive line spectrum enhancer is set as $\mu = 0.1$, and its filter order is set as $N=7$. The spectrum of signal processed by LMS algorithm is shown in Figure 4, and the number of iterations is shown in Figure 5.
The step size of NLMS adaptive line spectrum enhancer is set as $\mu = 0.1$, and its filter order is set as $N=7$. The spectrum of signal processed by LMS is shown in Figure 6, and the iterations number is shown in Figure 7.

Comparing Fig. 4 and Fig. 6, it can be seen that the signal spectrum characteristics after adaptive line enhancer processing based on NLMS algorithm are more obvious than those based on LMS algorithm, which can better reflect the signal characteristics of shaft-rate electric field. And comparing Fig. 5 and Fig. 7, it is not difficult to see that under the same conditions, the number of iterations of adaptive line enhancer based on NLMS algorithm is less than that of LMS algorithm. And the output error of LMS adaptive line enhancer is much larger than that of NLMS adaptive line enhancer, which shows that the adaptive line enhancer based on NLMS algorithm can converge faster and better.

4. Conclusion
In this paper, an adaptive spectral line enhancer based on NLMS algorithm is proposed. Based on the idea of making the iteration step adaptive too, the signal processing ability of the algorithm is improved, and it has better performance than the traditional LMS algorithm. The experimental results show that the background noise is greatly suppressed and the narrowband shaft-rate signal can be separated effectively after the signal is processed by the ALE based on NLMS algorithm. It can be seen that the fundamental frequency of the shaft-rate line spectrum is about $5Hz$, which is consistent with the rotation rate of the actual ship model screw propeller. The adaptive line enhancer based on NLMS algorithm can effectively separate the weak shaft frequency electric field characteristic signal.
from the environmental background noise, and has fast convergence speed and small output error, which provides a more effective technical method for the signal detection of ship shaft frequency electric field.

Acknowledgments
This work was supported in part by the Basics Strengthening Program Technology Foundation (2019-JCJQ-JJ-050).

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