Detection of Ship Shaft-rate Electromagnetic Field Signal Based on NLMS Algorithm

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Abstract. Ship shaft-rate electromagnetic field signal contains a lot of valuable target feature information, and effectively extracting its line spectrum components plays an extremely important role in underwater target recognition. In order to effectively separate the characteristic line spectrum of ship shaft-rate electromagnetic field from broadband background noise, this paper studies and analyzes the shaft-rate electric field by using the line spectrum enhancement algorithm based on adaptive filtering. Firstly, the application principle of adaptive line spectrum enhancement and NLMS algorithm in ship shaft-rate signal detection is briefly described. Then, an adaptive line spectrum enhancer is constructed according to the improved NLMS algorithm, and the obtained shaft-rate electric field data are processed and analyzed by this method. Finally, it is verified by simulation data and experimental data. The results show that the algorithm can effectively suppress the background noise, significantly improve the signal-to-noise ratio, and enhance the detection ability of ship electromagnetic field signals in practical applications.

1. Introduction

In order to protect the hull from corrosion, modern ships are generally installed with cathodic protection system[1]. The corrosion current generated between different metal materials and the anticorrosion current generated by cathodic protection system will generate shaft-rate electric field[2] after being modulated by the rotating shaft. In recent years, with the rapid development of signal detection technology, the improvement of sensor performance and the continuous improvement of underwater acquisition technology of electromagnetic field signals, the research and utilization of shaft-rate electric field as an important target characteristic signal of ships has been paid more and more attention[3]. When acquiring ship electromagnetic field signals in the actual marine environment, it is easy to mix other noise signals into the detected shaft-rate signals because the sensor is far away from the measured ship, and because the shaft-rate electric field signals are very weak and belong to ultra low frequency (ULF), the signal-to-noise ratio of the detected signals is low, and they are often submerged in noise. Therefore, it is an essential step to eliminate the environmental noise of the acquired electromagnetic field signals. However, because the frequencies of shaft-rate signal and background noise are mixed together, the traditional band-pass filter can not effectively separate the line spectrum features of shaft-rate electric field, and the conventional LMS adaptive filtering algorithm needs to input reference environmental noise, which is difficult to meet in actual conditions. Therefore, it is necessary to study methods to adapt to the actual needs and further improve the detection ability of ship shaft-rate signal. In this paper, the application principle of adaptive line spectrum enhancement and variable step size NLMS algorithm in ship shaft-rate signal detection is
briefly described firstly, and then the adaptive line spectrum enhancer is constructed according to the improved NLMS algorithm. The obtained shaft-rate electric field data are processed and analyzed by this method, and finally it is verified by simulation test and actual measurement test. The analysis results show that this method can effectively improve the signal-to-noise ratio and greatly improve the remote detection capability of ship shaft-rate electromagnetic field.

2. Filtering principle of ship shaft-rate electromagnetic field signal

2.1. Principle of adaptive line spectrum enhancement

Adaptive line enhancer (ALE) is an adaptive spectrum estimation technique for estimating parameters of line spectrum in additive noise, which can be used to detect narrowband signals submerged in broadband noise environment[4]. In the case of narrowband signal plus wideband signal, the mixed signal is delayed without independent reference signal. The function of delay is to make wideband signal decorrelated, while narrowband signal is not decorrelated. LMS adaptive filter is used to adaptively match the related narrowband signal, thus separating the signal[5]. Different from the conventional adaptive denoising, the former uses the correlation of input reference noise to estimate the background noise in the desired signal, while ALE uses the delayed desired signal as the input signal, and directly estimates the required axial frequency signal by using the correlation. The principle is shown in Figure 1. Input \( x(n) \) is the original signal with noise, and the reference signal \( x(n-\Delta) \) is obtained after delay. Output signal \( y(n) \) is obtained from delayed signal through adaptive filter, and \( e(n) \) is the error signal between \( x(n) \) and \( y(n) \). The error signal at each moment is fed back to the adaptive filter to drive the filter to adjust its own parameters. ALE decorrelates the broadband components (signals with weak periodicity) and keeps the correlation of the narrowband components (signals with strong periodicity) by selecting appropriate time delay \( \Delta \), and finally achieves the purpose of filtering and enhancing the signals after superposition.

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

The calculation formula is as follows:

\[
y(k) = \sum_{i=1}^{M} w(k)x(k-\Delta-i) \tag{1}
\]

\[
e(k) = x(k) - y(k) \tag{2}
\]

\[
w(k+1) = w(k) + 2\mu e(k) x(k-1), \quad w(0) = 0 \tag{3}
\]

Where \( M \) is the filter order; \( \mu \) is the adaptive learning step. The performance of ALE is closely related to such parameters as delay time \( \Delta \), order \( M \) and step factor \( \mu \), which should be carefully selected in practical application[6]. Delay time \( \Delta \) is called prediction depth or decorrelation delay of ALE, which is measured by sampling period \( T_s \). The selection of delay time \( \Delta \) should be large enough to eliminate the autocorrelation between signals with weak periodicity in mixed signals[7]. Most importantly, because ALE uses the periodic autocorrelation of signals to eliminate broadband noise, the delay time \( \Delta \) should be a multiple of the sampling period \( T_s \). In order to make the system stable, the step factor \( \mu \)
should satisfy a certain range. The smaller $\mu$ is, the higher the convergence accuracy of the algorithm, but the slower the convergence speed and tracking speed[8]. Therefore, using a fixed step size factor can not meet the convergence speed and convergence accuracy requirements of LMS algorithm at the same time. This paper adopts a variable step size method to solve this contradiction. The order $M$ should be properly selected to reduce the bandwidth of the filter, but $M$ should not be too large, otherwise the LMS algorithm will generate iterative noise, which will lead to the decline of filtering effect and increase the computational complexity of the algorithm[9].

2.2. Variable step size LMS algorithm

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, and its weight coefficient update formula is:

$$w(k+1)=w(k)+\frac{\mu'}{\|x(k)\|^2}x(k)e(k) \quad (4)$$

$$\mu' = \frac{\mu}{\|x(n)\|^2} \quad (5)$$

$$\|x(k)\|^2 = \sum_{k=0}^{M-1} |x(n-k)|^2 \quad (6)$$

Where is equivalent to taking the time-varying step size of $\mu$, which makes the step size update the iterative step size of the algorithm in real time with the increase of input signal, and greatly improves the convergence speed and accuracy compared with LMS algorithm.

Next, the convergence of NLMS is discussed. It is not difficult to verify that, in order to make NLMS algorithm converge, the improved step size should meet $0<\mu'<2$, so the step size $\mu'$ range of NLMS algorithm can be determined in advance. In addition, in order to avoid that $\mu(k)$ is too large when two-norm square of signal vector is small, and further restrict and improve NLMS algorithm, a correction amount $\alpha$ larger than zero can be added in the iterative formula, which can ensure that the algorithm cannot converge when there is less input signal data at the initial time. The improved NLMS algorithm is as follows:

$$w(k+1)=w(k)+\frac{\mu'}{\alpha + \|x(k)\|^2}x(k)e(k) \quad (7)$$

Where $\alpha$ is the correction amount greater than 0.

3. Simulation verification

The NLMS adaptive line spectrum enhancer has a step size $\mu'=0.1$, a correction amount $\alpha=1$, and a filter order $N=7$. In the simulation experiment, the shaft-rate electric field signal is simplified as the superposition of several sinusoidal frequency signals, which is set as follows:

$$y_0=6\sin(2\pi f_0t)+5\sin(2\pi f_1t)+3\sin(8\pi f_2t)+\sin(12\pi f_3t)$$

The fundamental frequency $f_0=3$Hz, the sampling frequency $F_s=50$Hz, and 2500 sampling points. Background noise is equivalent to white Gaussian noise, and note the noisy signal as $y_1$, and the filtered signal as $y_2$. And then MATLAB is used to simulate the adaptive spectral line enhancer under different signal-to-noise ratios, and comparative analysis is made.

Also, in order to test the performance of the proposed algorithm under different signal-to-noise ratios, the corresponding data are generated by mixing the specified signal-to-noise ratios. Signal-to-noise ratio is defined by energy. Let $E_s$ and $E_n$ be the energy values of signal and noise respectively, and the calculation formula is as follows:

$$SNR=10\log\frac{E_s}{E_n} \quad (9)$$
Firstly, the SNR of noisy signal y1 is high. When the SNR is set at 1.46dB, which is improved to 7.16dB after filtering. Figure 2 shows the time domain diagram of y1 before and after filtering, and Figure 3 shows the normalized spectrum of y2 extracted after filtering as follows.

![Figure 2. Time domain diagram with SNR of 1.46dB.](image)

![Figure 3. Normalized spectrum after noise reduction with SNR of 1.46dB.](image)

When the SNR of noisy signal y1 is low, which is increased to 3.11dB after filtering when it is set to -4.43dB. Respectively, Figure 4 shows the time domain diagram of y1 before and after filtering, and Figure 5 shows the normalized spectrum of y2 extracted after filtering.

![Figure 4. Time domain diagram with SNR of -4.43dB.](image)

![Figure 5. Normalized spectrum after noise reduction with SNR of -4.43dB.](image)

Through the simulation experiment of different SNR signals, the results show that this algorithm not only has a good effect on mixed signals with high SNR, but also has a good effect on signals with low SNR. It can also be observed from the time domain diagram that this algorithm has a good suppression effect on background noise. Through frequency domain analysis, it is found that this method can effectively suppress narrowband noise line spectrum, and distinguish narrowband shaft-rate line spectrum with obvious harmonic frequency doubling relationship, which is helpful for further signal recognition.

4. Experimental verification
The target signal is measured by the ship model in the laboratory, and the propeller speed is about 300r/min, in order to simulate the conductivity of seawater as much as possible, it is necessary to add industrial salt to the tank for modulation. Shaft-rate electric field measurement system is mainly composed of sensors, signal conditioning circuit and data acquisition system. The three-axis Ag/AgCl
electrode with high sensitivity is used in the electric field sensor to measure the components of ship electric field in X, Y and Z three-dimensional space. In this paper, only the components on the X axis of the electric field are selected for processing, and whether the shaft-rate electric field can be extracted effectively is observed, thus verifying the feasibility of this method. During the experiment, the sampling frequency was set at 2500Hz, the electric field sensor was fixed about 200cm below the ship model, and 74200 sampling points were taken. Figure 6 and Figure 7 are time domain and frequency domain diagrams, respectively.

![Diagram](image1.png)

Figure 6. Time domain diagram of measured signal.

The measured raw data is filtered and denoised by this algorithm, and its power spectrum is shown in Figure 8. From the spectrograms before and after filtering, it can be seen that this method can effectively separate narrowband shaft-rate signals. The shaft-rate line spectrum extracted from the ship electric field power spectrum is a series of spectral lines, which has more obvious harmonic frequency doubling relationship than before filtering, and can clearly distinguish the fundamental frequency and the second and third harmonics. The fundamental frequency of the shaft-rate spectrum is about 5Hz, which is consistent with the actual propeller rotation frequency.

![Diagram](image2.png)

Figure 7. Normalized spectrum of measured signal.

![Diagram](image3.png)

Figure 8. Normalized spectrum of measured signal after noise reduction.

5. Conclusion
In this paper, the adaptive spectral line enhancer is improved by using the variable step size NLMS algorithm with good convergence, the shaft-rate electric field signal submerged in broadband background noise is processed, and the effective spectral line features of the ship shaft-rate detection
signal are extracted, which solves the problem that the conventional adaptive filtering needs reference noise input, and improves the traditional LMS adaptive filtering algorithm. Experimental results show that under different SNR conditions, the algorithm can effectively suppress the background broadband noise, which is helpful to further extract and process spectral line features, significantly improve the SNR, and enhance the detection ability of ship electromagnetic field signals in practical applications.

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References
[1] Lu, X.C., Gong, S.G., Sun, M. (2004) Experimental measurement and analysis of spatial distribution characteristics of shaft-rate electric field of ships. J. Journal of Wuhan University of Technology (Traffic Science and Engineering Edition), 04: 498-500.
[2] Fei, Z.G., Cai, X.D., Bao, Z.H. (2014) Adaptive enhancement of ship shaft-rate electric field signal based on higher-order cumulants. J. Ship Science and Technology, 36: 120-124.
[3] Yang, G.Y. (2011) Research status of underwater electromagnetic field of ships abroad. J. Ship Science and Technology, 33: 138-143.
[4] Liu, H.T., Cong, W.H., Pan, X. (2007) Line spectrum detection of narrowband weak signals- Coherent accumulation frequency domain batch adaptive line spectrum enhancement method. J. Journal of Zhejiang University (Engineering Edition), 12: 102-105.
[5] Ghogho, M., Ibnkahla, M. (1998) Analytic behavior of the LMS adaptive line enhancer for sinusoids corrupted by multiplicative and additive noise. J. IEEE Transactions on Signal Processing, 46: 2386-2393.
[6] Lee, S.K., White, P.R. (1998) The enhancement of impulsive noise and vibration signals for fault detection in rotating and reciprocating machinery. J. Journal of Sound and Vibration, 217: 485-505.
[7] Zhao, S.B., Sheng, W.J., Zhang, G.Y. (2009) Application of adaptive filtering based on ALE in bearing fault diagnosis. J. Bearings, 02: 40-43.
[8] Hou, P., Qin, S., Li, C. (2009) Adaptive equalization performance analysis of LMS algorithm. J. Communication Technology, 42: 61-62+83.
[9] Simon, H. (2006) Principle of Adaptive Filter. Electronic Industry Press, Beijing.