Research on Railway Frequency Shift Signal Detection Based on Transient Electromagnetic Radar

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Abstract. In response to the characteristics of railway frequency shift signals, transient electromagnetic radar is used to start from two aspects: carrier frequency and low frequency. The carrier frequency uses the same frequency signal detection principle, while the low frequency uses a step sequence that can cover the entire low frequency band to detect unknown low frequencies. The detection principle and steps of carrier frequency and low frequency are given, and a simulation model is built and verified. Finally, accurate frequency shift signals are detected. Finally, the accurate detection of railway frequency shift signal is also realized under the condition of in band harmonic interference and white noise interference, and the bit error rate is analyzed under different signal to noise ratios. Compared with the traditional railway frequency shift signal measurement methods, the threshold of signal to noise ratio based on transient electromagnetic radar can be lower when detecting railway frequency shift signal.

Keywords: Electromagnetic Radar · Frequency Shift Signal · Signal Detection

1 Introduction

As an important infrastructure in transportation, railway is known as the main artery of national economy due to its outstanding advantages of huge transportation volume. It plays a very important role in promoting the exchange of materials between different regions and the prosperity of social economy. In recent years, with the continuous acceleration of railway, especially the emergence and continuous development of high-speed railway, railway is playing an irreplaceable role in passenger transport, so it is of great practical significance to vigorously develop railway industry and improve railway transport capacity [1, 2]. However, in order to improve the railway transportation capacity, it is necessary to improve the train running speed, increase the traffic density, shorten the train running interval. But at the same time, the railway running safety will face great challenges, in order to ensure the running safety, we must vigorously develop the railway signal automation, to provide a strong safety guarantee for the railway system.

Railway frequency shift signal is a general term for signal, interlocking, blocking and other equipment used in railway systems. In the railway frequency shift signal system,

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track circuit is a circuit composed of rail lines and rail insulation. It is an important basic equipment of railway frequency shift signal. Its function is to collect the real-time status of train operation, express the track occupancy, and transmit the frequency shift signal information to the signal display equipment through the way of electromagnetic radar [3–5]. With the continuous improvement of modern digital signal processing theory and the continuous improvement of digital signal processor performance, as well as the rapid development of digital demodulation technology, there are more implementation methods for the detection of railway frequency shift signal parameters, thus gradually solving various problems in the measurement of railway frequency shift signal parameters. For example, in reference [6], a parameter estimation and signal detection algorithm based on adaptive capture is proposed. First, the correlation between the signal and the leading sequence is used as the basis for frequency capture. Secondly, the frequency is estimated accurately based on interpolation algorithm. Finally, according to the characteristics of gradual frequency change, the phase-locked loop structure is used to track the frequency, and the frequency offset of the signal is eliminated in the digital down conversion stage, and the signal detection is realized. This algorithm consumes less resources and has low complexity. However, in the case of low signal-to-noise ratio, the detection accuracy will decrease and the bit error rate will be high.

Therefore, in order to solve the problem of low detection accuracy and high bit error rate under the condition of low SNR, a railway frequency-shift signal detection method based on transient electromagnetic radar is proposed, which can effectively reduce the detection SNR threshold and achieve accurate detection under the condition of low SNR. Firstly, the ResNet network model and LSTM network model are combined, and a dual-parallel RLA (ResNet LSTM Attention) network structure is proposed by taking advantage of the complementary advantages of the two models. Secondly, the structure is introduced in layers, and the function of each layer is defined. Then, the network structure is used for acquisition, feature extraction and fusion, and the modulation mode of radar signal is classified and recognized by RLA network. Finally, the amplitude and phase of the original signal data are extracted directly, the hidden information contained in the signal is distinguished from the time domain, and the storage detection is carried out to realize the detection research of railway frequency shift signal based on transient electromagnetic radar.

2 Railway Frequency Shift Signal Detection

The network structure of railway frequency shift signal transient electromagnetic radar is introduced. Detection of railway frequency shift signal by network structure. In order to improve the effectiveness of the network model and achieve a higher recognition rate of transient electromagnetic radar signal modulation methods, this chapter combines the ResNet network model and the LSTM network model, and proposes a dual-parallel RLA (ResNet LSTM Attention) network structure. Among them, ResNet is a deep convolutional neural network designed to solve the problem of gradient disappearance in deep network training. It builds the network structure by introducing residual connections. Residual connections allow information to skip directly several layers in the network, making it easier for deeper networks to learn the identity map. This design avoids the problem of gradients fading away, making the network deeper and easier to train. The model can better capture the frequency domain and time domain characteristics of the frequency shift signal. LSTM is a type of recurrent neural network (RNN) specifically designed to process time series data. It comprises an input door, an oblivion door and an output door. These gating mechanisms control the flow of information and help LSTM networks capture and remember long-term dependencies. The LSTM network consists of a number of LSTM units, each of which has its own internal cell state, and determines how to update and pass the state and information through a gating mechanism to better model these relationships and improve the accuracy of detection. Therefore, the combination of ResNet and LSTM network model can improve the generalization ability of the model, with features with stronger expression ability, so that the model can process complex data more accurately, and accurately extract the features of the data, improve the modeling and detection ability of the timing characteristics of the frequency shift signal, and thus improve the accuracy and stability of detection. Achieve accurate railway frequency shift signal detection. The RLA network structure mainly consists of four parts: input layer, parallel layer, feature fusion layer, and output layer. The model structure is shown in Fig. 1.

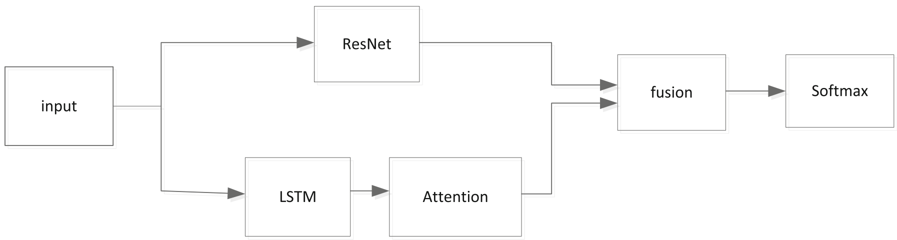


Fig. 1. RLA Network Model Diagram

The first part is the input part. The main function of the network input layer is to collect data. The data format of each input sample is a 2 × 2048 matrix. The upper half branch is a residual network, which takes advantage of its network advantages to complete the extraction of spatial features of radar modulated signal samples. ResNet adopts a residual unit composed of two convolution layers. Since the dimension of the data matrix input in this paper is not a traditional square, the convolution kernel size is set as [3 × 1], [5 × 1], which can effectively reduce model parameters. To improve the convergence speed, ResNet is formed by four residual units; the residual block is set as [2] by referring to ResNet18 network proposed by He Keming; the Pooling method is selected as Max Pooling; the learning rate is set as 0.001[7].The lower branch is a long-term and short-term memory network, mainly used to extract temporal features of radar signals. In order to balance algorithm accuracy, runtime, and convergence speed, through literature review and experimental comparison, it was found that blindly increasing the number of LSTM layers is not conducive to model performance. Therefore, a double-layer LSTM network with a Batch size of 1024 and a learning rate of 0.001 was adopted, and an Attention mechanism was added to allocate attention weights to the features extracted from the network, Summarize the features that are more prominent in the network extraction process.

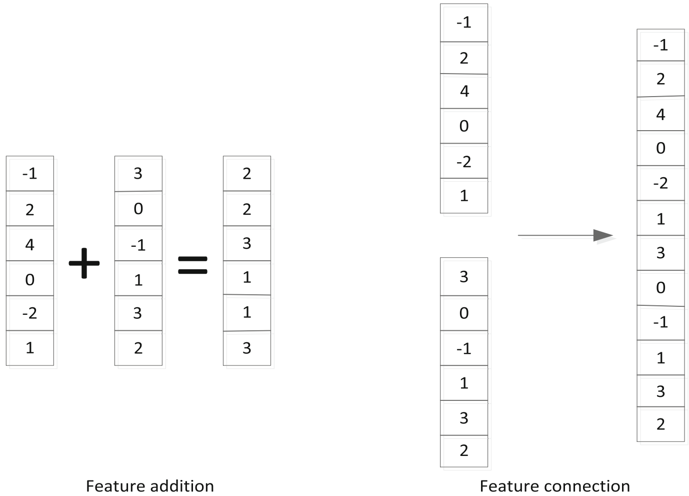


Fig. 2. Schematic diagram of feature fusion mode for the proposed method

The second layer is the feature fusion layer, whose main function is to integrate the features extracted from the double-channel parallel network that can identify and collect railway frequency shift signals. As shown in Fig. 2, there are generally two choices in the way of feature fusion. Due to the problem that two feature vectors cannot be added due to their different dimensions in the way of feature addition, or feature cancellation occurs after addition, the feature fusion mode in this section is selected as the feature connection mode, and features of the upper and lower branches are merged. That is to say, based on the spatial feature information mainly extracted by ResNet network and the temporal feature information mainly extracted by LSTM, new features are synthesized by the two features and sent to the next part [8]. Finally, the Softmax classifier classifies and outputs according to the features transmitted from the above part. This layer is an ordinary fully connected layer, including six nodes, which are used to output signals representing six different modulation modes respectively.

Using transient electromagnetic to identify and collect radar signal modulation methods often results in different feature extraction methods. At the same time, each modulated signal will have different time-frequency images and different feature attributes. When using time-frequency images as input, it is necessary to first convert the intercepted radar signal into a two-dimensional image before using a network model for recognition. Moreover, generating time-frequency images takes a long time, with a large number of sampling points for a single image and complex image processing, which is not conducive to the real-time requirements in radar processing [9]. Therefore, this chapter takes the time-domain amplitude and phase (AP) data features of the signal converted from the raw data of the transient electromagnetic radar signal as input, and uses the RLA network as the framework to classify and identify the modulation methods of the radar signal.

Generally speaking, modulated signals are represented as:

$$s(t) = A\exp\left[j(2\pi f_0 t + \varphi_0)\right] \tag{1}$$

In order to make the signal $s(t)$ collected by the transient electromagnetic radar receiver have better adaptability and simplicity in calculation, research and equipment processing, the amplitude and phase of the original signal data are extracted directly, and the hidden information contained in the signal is distinguished from the perspective of time domain.

In order to prevent overfitting of the model from being too complex, $L2$ norm naturalization was carried out on the extracted AP data, and $L2$ norm was defined as:

$$norm(x) = \sqrt{x_1^2 + x_2^2 + \ldots + x_n^2} \tag{2}$$

Among them, x_i represents the elements of the extracted amplitude data and phase data, and after normalization, each element is:

$$x_i = \frac{x_i}{norm(x)} \tag{3}$$

The processed data AP is stored in the matrix form of 2×2048 as the input form of the data set. Meanwhile, different modulation modes and corresponding signal-to-noise ratio information are also stored in the data set [10, 11].

Due to the frequent traffic of railway transmission vehicles, the site environment and transmitted information are becoming more and more complex, which affects the reception of railway frequency shift signals. Therefore, through the frequency shift signals collected in the data set, the transient electromagnetic radar can accurately detect railway frequency shift signals and ensure the normal transmission.

3 Experimental Analysis

The traditional railway frequency shift signal detection method has a good filtering effect on harmonic interference of traction current outside the frequency band of the railway frequency shift signal, but it cannot effectively filter out harmonic interference within the frequency band of 40 Hz. The following is an analysis of different proposed methods for carrier frequency detection and low-frequency detection, and the use of transient electromagnetic radar to analyze the harmonic interference in the traction current band, analyze the error rate, and verify the effectiveness of the proposed method in low-frequency band detection. And under white noise interference, the proposed method was used for ZPW-2000 railway frequency shift signal detection simulation and bit error rate analysis to verify the applicability of the proposed method. Finally, to further verify the superiority of the proposed method, under the same settings as the proposed method, the change in bit error rate between the proposed method and the traditional method was measured by changing the noise intensity. The dataset used for this test is the ‘Railway Track Maintenance Data Set’ dataset from the UCI Machine Learning Repository.

During the experiment, the amplitudes of railway frequency shift signals were added to be 0.01 V, 0.1 V, and 1 V, respectively. Then, traction current harmonics equivalent to noise were added, while other system parameters remained unchanged. In the process of judging the results, the detection statistics were calculated, and the phase diagram and domain output diagram were observed. The results obtained were consistent. In order to demonstrate more intuitive results, this article provides detection results for phase and domain diagrams in the following sections.

3.1 Carrier Frequency Detection

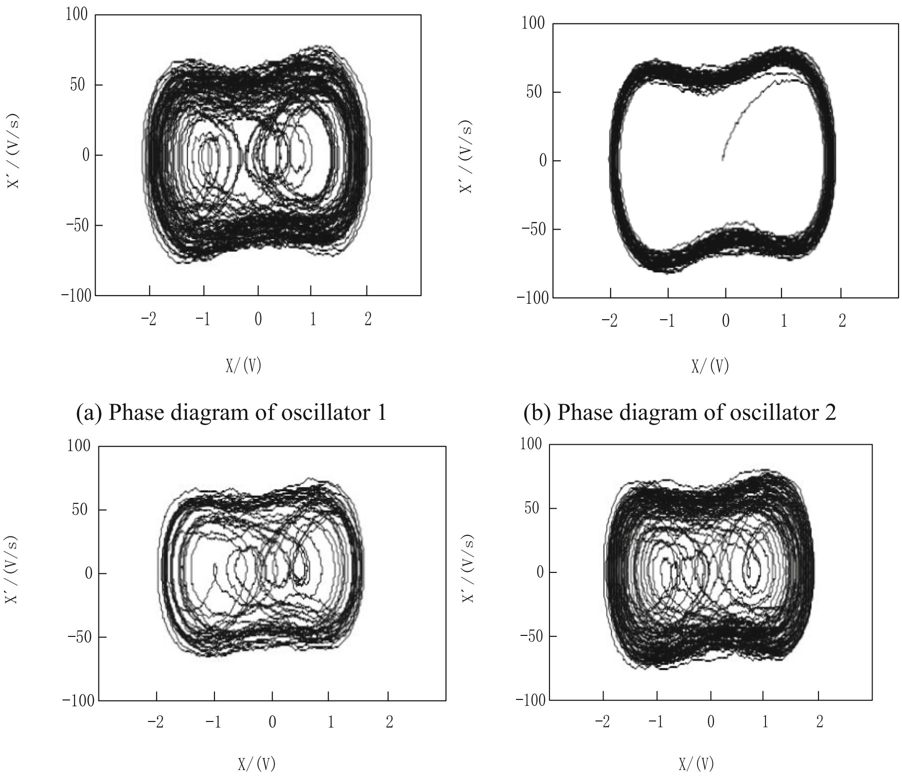
Firstly, analyze the railway frequency shift signal with an amplitude of 0.01 V and a carrier frequency of 2000–1 Hz. As the intensity of harmonic interference in the traction current in the band increases, calculate the signal-to-noise ratio and obtain that the desired frequency shift signal can still be detected through changes in the phase diagram when the signal-to-noise ratio is −24 dB. The results are shown in Fig. 3. The detection results of Fig. 3(a), Fig. 3(c), and Fig. 3(d) are in a chaotic state, that is, no co frequency signal with a carrier frequency of 2000–1 Hz was detected, while the oscillator with an internal driving force term set to 2000–1 Hz in Fig. 3(b) undergoes a phase transition, indicating that the co frequency signal was detected. When the amplitude of harmonic interference current is further increased to achieve a signal-to-noise ratio of −25 dB, the transient electromagnetic radar system cannot detect the same frequency signal.

Similarly, it can be concluded that with the increase of the amplitude of the in-band harmonic interference current, the frequency shift signal with a amplitude of 0.1 V can finally reach the detection SNR threshold of −19 dB; while with the increase of the amplitude of the in-band harmonic interference current, the frequency shift signal with a amplitude of 1 V can finally reach the detection SNR threshold of −17 dB. Therefore, it is found that with the increase of the amplitude of the signal to be measured, the higher the detection signal-to-noise ratio can be achieved, that is, compared with the noise, the weaker the signal of the detection system of the transient electromagnetic radar oscillator, the higher the detection sensitivity.

3.2 Low Frequency Detection

The most important aspect of detecting railway frequency shift signals is to obtain accurate low-frequency information. Similarly, when the amplitude of railway frequency shift signals is 0.01 V, 0.1 V, and 1 V, the minimum signal-to-noise ratio threshold that can be achieved by using transient electromagnetic radar is studied, that is, its anti-interference performance under the interference of harmonic interference of in band traction current.

Firstly, analyze the railway frequency shift signal with an amplitude of 0.01 V and a carrier frequency of 2000–1 Hz. After extensive simulation research, it can still detect low-frequency information using transient electromagnetic radar when the signal-to-noise ratio is −28 dB. The results are shown in Fig. 4, and Fig. 4(a) shows the waveform of the ZPW-2000 railway frequency shift signal under in band harmonic interference. At two consecutive steps, intermittent chaotic phenomena occurred, as shown in Fig. 4(b) and Fig. 4(c). When the signal-to-noise ratio is −29 dB, low-frequency information



(a) Phase diagram of oscillator 1 (b) Phase diagram of oscillator 2

(c) Phase diagram of oscillator 3 (d) Phase diagram of oscillator 4

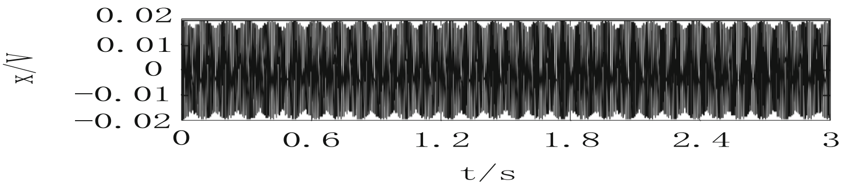
Fig. 3. Output Phase Diagram of Transient Electromagnetic Radar Detection System under 2600 Hz Intraband Harmonic Interference

cannot be detected. At the step size where intermittent chaos occurs, the zero crossing distance method is used to obtain a low frequency of 11.4254 Hz, which meets the requirement that the detection error should not exceed 0.03 Hz.

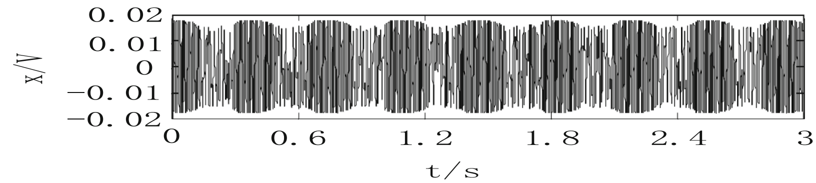
Change the amplitude of railway frequency shift signal. When the amplitude is 0.1 V, the threshold value of detected signal-to-noise ratio is −25 dB. When the amplitude is 1 V, the detection SNR threshold is −21 dB. After a large number of simulation experiments, the conclusion is that the use of transient electromagnetic radar detection system can accurately detect the low-frequency information under the condition of in-band harmonic interference, and the signal is weaker and can achieve a lower signal-to-noise ratio.

3.3 Bit Error Rate

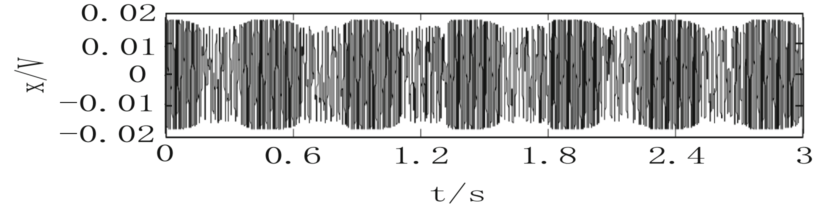
In the analysis of bit error rate, two aspects can be approached: on the one hand, when the carrier frequency is the same but the low-frequency is not the same, and on the other hand, when the low-frequency is the same but the carrier frequency is not the same. Firstly, we study the bit error rate situation when the carrier frequency is not the



(a) Waveform diagram of ZPW-2000 frequency shift signal under harmonic interference in the 2000-1Hz band



(b) Time domain diagram of transient electromagnetic radar oscillator 2 output under harmonic interference in the 2000-1Hz band with step size a_{143}



(c) Time domain diagram of transient electromagnetic radar oscillator 2 output under harmonic interference in the 2000-1Hz band with step size a_{144}

Fig. 4. Low frequency detection results under harmonic interference in the 2000–1 Hz band

same, and select the low-frequency as 10.3 Hz and 29 Hz, respectively. The results are shown in Fig. 5. In Fig. 5(a), for a certain carrier frequency, the error rate increases as the signal-to-noise ratio decreases. When the carrier frequency is 1700 Hz and the signal-to-noise ratio is greater than or equal to −14 dB, the error rate is approximately considered 0. When the signal-to-noise ratio is around −20 dB, the error rate increases to around 0.5. And for different carrier frequencies, at the same signal-to-noise ratio, the bit error rate decreases as the carrier frequency decreases. For the highest carrier frequency of 2600 Hz, when the signal-to-noise ratio is greater than −9 dB, the bit error rate is basically considered to be 0.

Then analyze the bit error rate when the carrier frequency is fixed but the low frequency is changed. The low frequencies of 10.3 Hz and 29 Hz at 1700 Hz and 2600 Hz are analyzed respectively, and the results obtained are shown in Fig. 6. It can be seen that in Fig. 6(a), when the carrier frequency is fixed at 1700 Hz and the low frequency is 10.3 Hz, the bit error rate will increase as the signal-to-noise ratio decreases. When the signal-to-noise ratio is greater than or equal to −14 dB, the bit error rate will be approximately 0, and when the signal-to-noise ratio is about −20 dB, the bit error rate

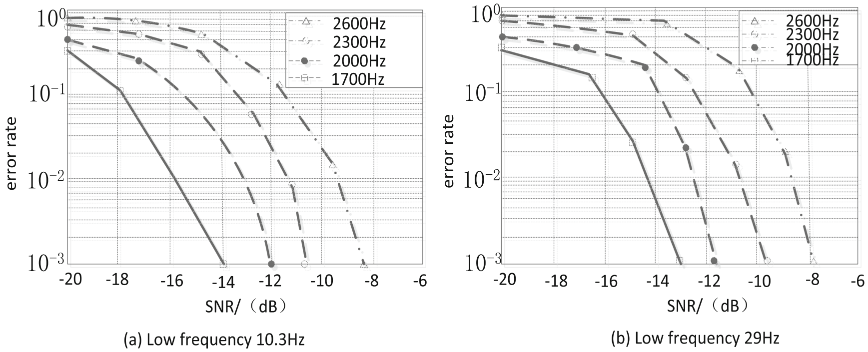


Fig. 5. Error rate of carrier frequency detection at different low frequencies

will be about 0.6. And with the increase of different low frequency value, the bit error rate is larger. When the carrier frequency is fixed at 2600 Hz, the variation curve of bit error rate is consistent with the trend of 1700 Hz, as shown in Fig. 6(b). For the most unfavorable 29 Hz, the bit error rate is basically 0 when the signal-to-noise ratio is greater than or equal to −9 dB.

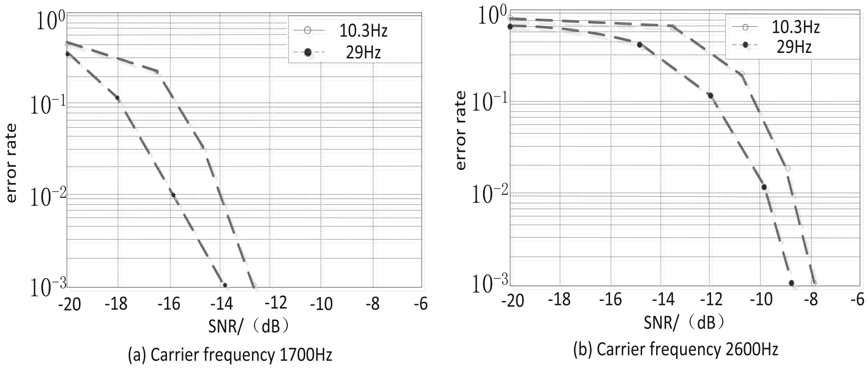


Fig. 6. Low frequency detection error rate under different carrier frequencies

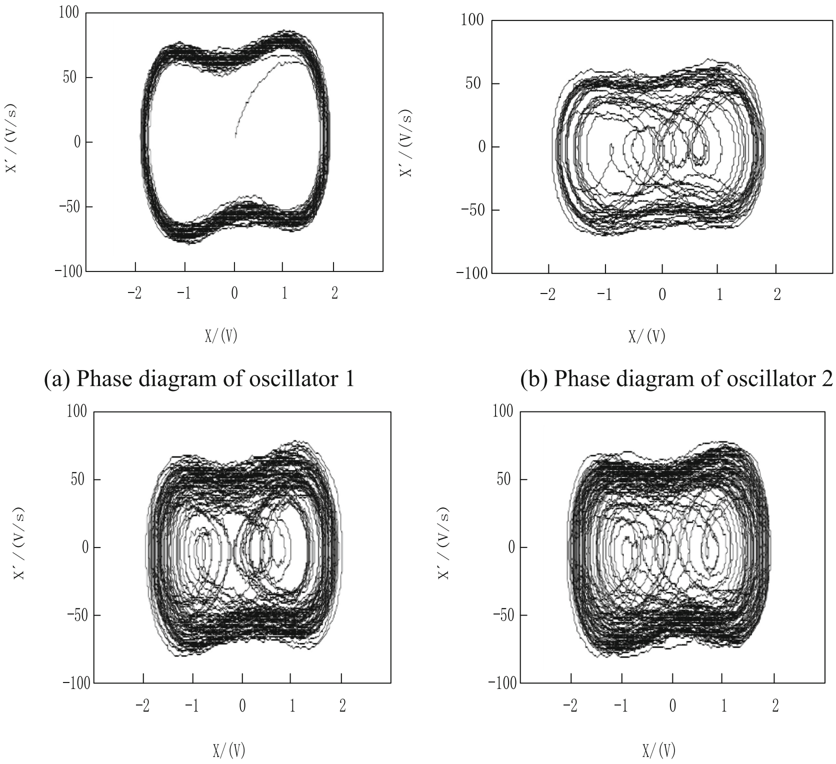
The following conclusions can be drawn from the above detection of railway frequency shift signals under the interference of in-band traction current harmonics: The railway frequency shift signals under the interference of in-band harmonics can be detected by using the transient electromagnetic radar detection system.

3.4 Detection Simulation and Bit Error Rate Analysis of ZPW-2000 Railway Frequency Shift Signal Under White Noise Interference

In this section, the amplitude of the railway frequency shift signal is also set to 0.01 V, 0.1 V, and 1 V, respectively, and white noise is added, while the other system parameters remain unchanged. The frequency shift signal and bit error rate analysis of the transient electromagnetic radar oscillator detection under white noise interference are carried out.

(1) Carrier frequency detection

First, analyze the railway frequency shift signal with amplitude of 0.01 V and carrier frequency of 1700–1 Hz. As the strength of white noise increases, when the signal-to-noise ratio is −23 dB, the results are shown in Fig. 7. The detection results in Fig. 7(b), Fig. 7(c), and Fig. 7(d) are in a chaotic state, while the oscillator shown in Fig. 7(a) with the internal driving force term set to 1700-Hz undergoes a phase transition. Increase the strength of white noise. When the signal-to-noise ratio is −24 dB, the transient electromagnetic radar system cannot detect the same frequency signal.



(a) Phase diagram of oscillator 1 (b) Phase diagram of oscillator 2

(c) Phase diagram of oscillator 3 (d) Phase diagram of oscillator 4

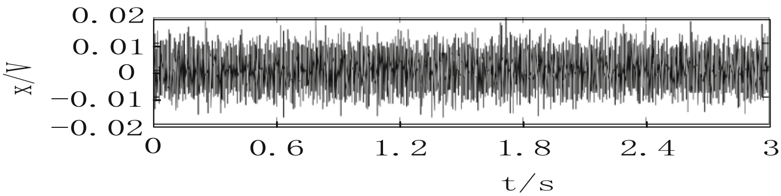
Fig. 7. Output × time domain waveform of transient electromagnetic radar detection system under white noise interference

Similarly, it can be obtained that the threshold value of signal to noise ratio for the frequency shift signal with a amplitude of 0.1 V is −18 dB, while the threshold value of signal to noise ratio for the frequency shift signal with a amplitude of 1 V is −16 dB.

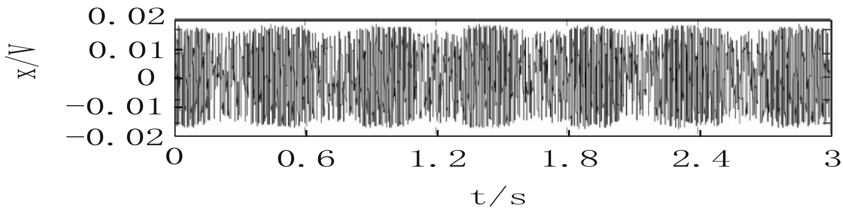
(2) Low frequency detection

In the low frequency detection, the lowest SNR threshold that can be reached by the transient electromagnetic radar oscillator is studied when the amplitude of the frequency shift signal is 0.01 V, 0.1 V and 1 V respectively, that is, its anti-interference performance in the case of white noise interference.

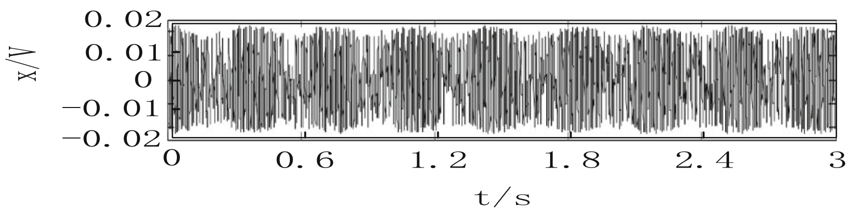
Firstly, the frequency shift signal with a amplitude of 0.01 V was analyzed. After a large number of simulation studies, array chaos was detected at two consecutive steps, and the low-frequency information could still be detected by using the transient electromagnetic radar oscillator when the signal-to-noise ratio was −27 dB, as shown in Fig. 8. At the step of array chaos, the low frequency of 11.3722 Hz is obtained by using the zero crossing distance method, which meets the requirement that the detection error should not be greater than 0.03 Hz.



(a) Waveform of ZPW-2000 frequency shift signal with white noise interference



(b) Output time domain diagram of transient electromagnetic radar oscillator 1 when step size is a_{143} under white noise interference



(c) Output time domain diagram of transient electromagnetic radar oscillator 1 when step size is a_{144} under white noise interference

Fig. 8. Low frequency signal detection results under white noise interference

Similarly, the amplitude of railway frequency shift signal is changed. When the amplitude is 0.1 V, the threshold value of signal to noise ratio detected is −24 dB. When the amplitude is 1 V, the detection SNR threshold obtained is −20 dB. After a large number of simulation experiments, the conclusion is that the use of transient electromagnetic radar oscillator measurement system can accurately detect the low-frequency information in the case of white noise interference, and the signal is weaker and can achieve a lower signal-to-noise ratio.

(3) Error rate analysis

Starting from fixing the carrier frequency and low frequency separately, consider the error rate situation. Firstly, fix the carrier frequency, and the error rate results obtained as the low frequency changes are shown in Fig. 9. In Fig. 9(a), for a certain carrier frequency, the bit error rate increases as the signal-to-noise ratio decreases. Taking the 2600 Hz carrier frequency as an example, when the signal-to-noise ratio is greater than or equal to −8 dB, the bit error rate is so small that it can be approximately considered 0. When the signal-to-noise ratio is around −20 dB, the bit error rate increases to around 0.9. And for different carrier frequencies, at the same signal-to-noise ratio, the bit error rate decreases as the carrier frequency decreases. Therefore, for the lowest carrier frequency of 1700 Hz, when the signal-to-noise ratio is greater than −14 dB, the bit error rate is basically considered to be 0.

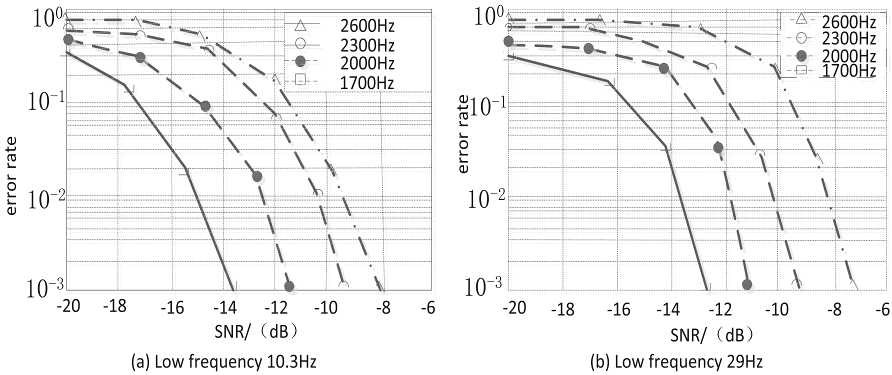


Fig. 9. Bit error rate of carrier frequency detection at different low frequencies under white noise interference

Next, analyze the error rate when the low-frequency is fixed but the carrier frequency changes. The results obtained by analyzing the low frequencies of 10.3 Hz and 29 Hz at 1700 Hz and 2600 Hz are shown in Fig. 10. In Fig. 10(a), when the carrier frequency is fixed at 1700 Hz and the low frequency is 10.3 Hz, the error rate increases as the signal-to-noise ratio decreases. When the signal-to-noise ratio is greater than or equal to −13 dB, the error rate is considered to be approximately 0, and when the signal-to-noise ratio is around −20 dB, the error rate is about 0.5. And as the values of different low-frequency frequencies increase, the error rate increases. The error rate variation curve when the carrier frequency is fixed at 2600 Hz is consistent with the trend at 1700 Hz, as shown in Fig. 10(b). For the most unfavorable 29 Hz, when the signal-to-noise ratio is greater than or equal to −8 dB, the error rate is basically 0. Compared with the analysis of bit error rate in the case of intra band harmonic interference, the values have slightly changed, but the trend is consistent.

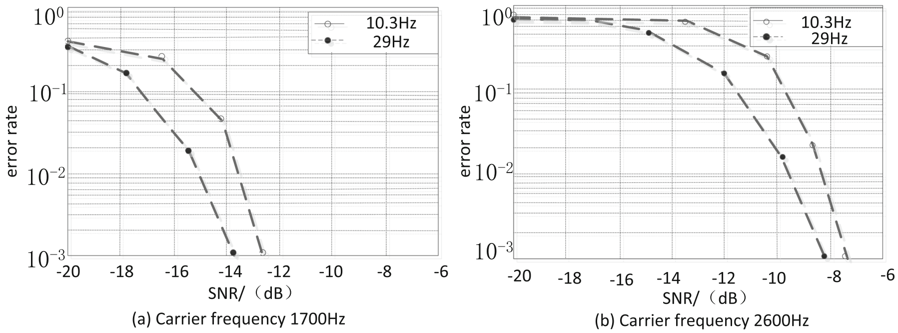


Fig. 10. Low frequency detection error rate under different carrier frequencies

After the above analysis, the frequency shift signal of railway can still be detected by the transient electromagnetic radar under the condition of offline noise interference of pantograph catenary equivalent to white noise.

3.5 Comparison of Bit Error Rate with Traditional Detection Methods

The above studies respectively aim at the bit error rate of railway frequency shift signal detection under different noise conditions. To demonstrate the superiority of the improved detection method, the bit error rates of the proposed method and different methods were measured by changing the noise intensity, as shown in Fig. 11. It can be seen from the figure that although the Bit error rate of the two methods decreases with the increase of the signal to noise ratio, compared with the curve trend of the two methods, the bit error rate of the proposed method is far lower than that of the traditional method under the same signal to noise ratio. Especially when the signal-to-noise ratio is about −20 decibels, the error rate of the proposed method is 0.1, while the error rate of traditional methods is as high as 1. From this, it can be concluded that the new detection method based on transient electromagnetic radar discussed in this article can accurately detect ZPW-2000 railway frequency shift signals under low signal-to-noise ratio conditions, while also having a low bit error rate.

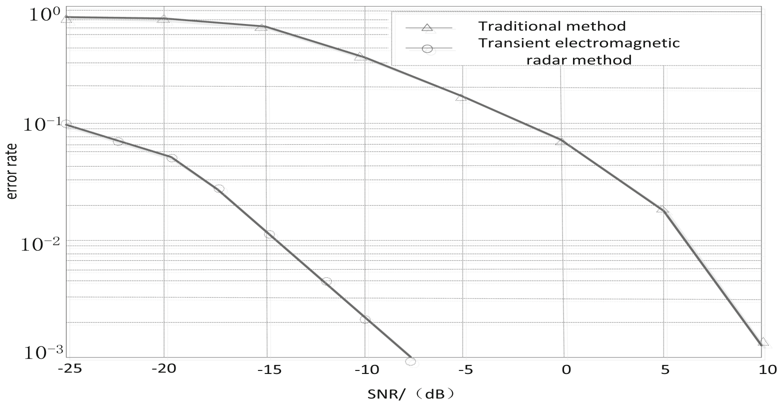


Fig. 11. Bit error rate curve of ZPW-2000 frequency shift signal

4 Conclusion

In summary, this article has completed the corresponding technical research on railway frequency shift signal detection and parameter estimation of transient electromagnetic radar. However, there are still many problems that need to be solved in the research content, mainly including the following parts: In the railway frequency shift signal detection method of transient electromagnetic radar, the test threshold is reduced through the method of equal division replacement, and there may be certain false alarms in the actual environment. In response to this problem, The algorithm in this article still needs further improvement; In the implementation of the transient electromagnetic radar detection method for modulation recognition, the types of modulation recognition for transient electromagnetic radar signals should be added in subsequent work to enhance the breadth of research. Further research is needed in this regard.

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