Electromagnetic Reflection Field Detection Based on TEO

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Abstract. Active electromagnetic detection explores targets using electromagnetic reflection field of metal objects. In view of the detection of active electromagnetic by detecting target reflection field, a Teager energy operator (TEO) is adopted to improve the electromagnetic reflection amplitude and instantaneous frequency detection method, the method of theoretical description and simulation verification has also carried out in this paper. Results show that this method is able to track the change of the single frequency signal of electromagnetic reflection field with good effect. It is also able to provide full details of the judgment to confirm the target. This method is simple and convenient for real-time processing, and has good application value.

1. Introduction

Active electromagnetic detection is an effective means to detect metal objects. The electromagnetic detection system radiates the electromagnetic field actively and realizes the detection of metal objects by detecting the induction characteristics of the target in the electromagnetic field. When the electromagnetic detection system passes near the metal target, it will detect the amplitude change of the electromagnetic field, and judge and confirm the target, and the traditional analog circuit method commonly used detection method. Hilbert change method can be used in digital circuit processing, which is realized by FFT. It is simple and effective, but it requires a lot of computation, and it is a batch processing method, so it can not reflect the amplitude envelope change in real time, nor can it get the instantaneous frequency change.

When studying nonlinear voice modeling, Kaiser et al. proposed a simple Teager energy operator (TEO) signal analysis algorithm, which can be applied to analyze and track the energy of narrowband signals [1] and is very sensitive to the amplitude envelope of AM signals and the instantaneous frequency change of FM signals. In this paper, TEO is used to detect the electromagnetic reflection field signals, which can reflect the electromagnetic field amplitude envelope and instantaneous frequency in time, and has the advantages of simple calculation and good real-time performance.

2. Electromagnetic Reflection Field

When a metal object exist around the radiation source, the alternating radiation field will stimulate the metal object to produce a secondary eddy current field, which is opposite to the direction of the original radiation field. In addition, it can be equivalent to the radiation field generated by the mirror radiation source at the metal interface [2], as shown in Fig. 1, and can be called the “reflection field”.
Assuming that a magnetic dipole radiator is used as the radiation source, and that the radiator and the electromagnetic receiving device are vertically configured (the axial direction of the magnetic dipole radiator is perpendicular to the axial direction of the electromagnetic receiving device), then the intensity of the reflection field of the metal object detected by the receiving device is:

\[
H = \frac{3Ma(2z)}{4\pi R^3} K_r K_m K(l)
\]

Where, \( M \) is the radiant magnetic moment. \( K_r = e^{-\sqrt{1+2x+2x^2+4x^3/3+4x^4/9}} \) is propagation attenuation of electromagnetic field in water (magnetic dipole radial). \( K_r = \sqrt{1+v_m^2(1-S)^2}/[v_m + \xi + \sqrt{v_m^2(\sqrt{\xi^2+1} - \sqrt{\xi^2-1})}] \) and \( v_m = (\mu_1/\mu_2)^2 \left(4\omega\mu_2\sigma_2 z^2/9\right) \), \( S = \sigma_1\mu_2/\sigma_2\mu_1 \), \( \xi = \sqrt{1+(v_m S)^2} \). \( \sigma_1, \mu_1 \) is the electrical and magnetic conductivity of water. \( \sigma_2, \mu_2 \) is the electrical and magnetic conductivity of the metal object. \( K(l) \) is the external dimension coefficient of the metal object.

By adopting the vertical configuration method, and accurately adjusting the relative position of the electromagnetic receiving device and the radiation source, so that the receiving device is located on the axis of the radiation source, the primary magnetic field generated by the radiation source can be avoided, and only the electromagnetic reflection field of the metal object can be detected. Compared with the radiation field of the source, the reflection field is usually weak, so it is necessary to obtain a sufficiently large signal amplitude through filtering and amplification during detection, then sample and process it.

3. Teager Energy Operator (TEO)

3.1. TEO for Continuous Time Signals

An AM/FM signal with time-varying amplitude \( a(t) \) and time-varying phase \( \phi(t) \) can be expressed as \( x(t) = a(t)\cos\phi(t) \), instantaneous frequency is defined as \( \omega(t) = \dot{\phi}(t) = 2\pi f(t) \), then the TEO for continuous time signals is defined as[3]:

\[
\varphi_x[x(t)] = [\dot{x}(t)]^2 - x(t)\ddot{x}(t)
\]

Derivative is:

\[
\dot{x}(t) = \dot{a}(t)\cos\phi(t) - a(t)\sin\phi(t)\phi(t)
\]

Second derivative is:
\[ x(t) = \ddot{a}(t) \cos \phi(t) - 2\dot{a}(t) \sin \phi(t) \dot{\phi}(t) - a(t) \cos \phi(t) [\dot{\phi}(t)]^2 - a(t) \sin \phi(t) \ddot{\phi}(t) \]  

(4)

The change in modulation signals is much slower than the change in carrier, and \( a(t) \) can be seen as a constant, and the carrier frequency \( \omega(t) \) is usually slow, which can be considered constant, so there is \( \ddot{a}(t) = 0 \), \( \dot{\phi}(t) = 0 \), then:

\[ \varphi_2[x(t)] \approx [a(t) \phi(t)]^2 = a^2(t) \omega^2(t) \]  

(5)

The same as:

\[ \varphi_2[\dot{x}(t)] \approx a^2(t) \omega^4(t) \]  

(6)

So the instantaneous amplitude and frequency can be got as:

\[ a(t) = \frac{\varphi_2[x(t)]}{\sqrt{\varphi_2[\dot{x}(t)]}} \]  

(7)

\[ \omega(t) = \frac{\varphi_2[\dot{x}(t)]}{\sqrt{\varphi_2[x(t)]}} \]  

(8)

3.2. TEO for Discrete Time Signal

For discrete time signals, the TEO is defined as[4]:

\[ \varphi_2[x(n)] = [x(n)]^2 - x(n-1)x(n+1) \]  

(9)

Where, \( x(n) = a(n) \cos \phi(n) \), and the instantaneous frequency is \( \omega(n) = \phi(n) - \phi(n-1) \). The change of the modulation signal is much slower than the change of the carrier signal, which can be thought of as \( a(n) = a(n-1) = a(n+1) \) and \( \phi(n+1) - \phi(n-1) = 2\omega(n) \).

Define the derivative signal as \( y(n) = [x(n+1) - x(n-1)]/2 \), then:

\[ \varphi_2[x(n)] \approx a^2(n) \sin^2[\omega(n)] \]  

(10)

\[ \varphi_2[y(n)] \approx a^2(n) \sin^2[\omega(n)] \]  

(11)

Instantaneous amplitude and instantaneous frequency is:

\[ a(n) = \frac{\varphi_2[x(n)]}{\sqrt{\varphi_2[y(n)]}} \]  

(12)

\[ \omega(n) = \arcsin\left[ \frac{\varphi_2[y(n)]}{\sqrt{\varphi_2[x(n)]}} \right] \]  

(13)

Using the TEO in this paper, the instantaneous amplitude and instantaneous phase of the signal can be calculated in real time by only a few sampling points every time. When detecting the electromagnetic reflection field, the amplitude and frequency changes are reflected in real time, and the complete amplitude envelope and frequency values are obtained.
4. Experimental Verification

4.1. Simulation Experiment

4.1.1 Single Frequency Electromagnetic Field Signal Simulation
The radiation source and the electromagnetic receiving device are rigid connected, and the relative position is fixed. The device passes at the constant speed over the metal body, the radiation signal frequency is 600 Hz, the SNR is 20 dB. In figure 2, the vector strength of the reflection field, the single frequency reflection field signal detected by the electromagnetic receiver, the signal amplitude envelope and the instantaneous frequency of the signal are calculated using the TEO are shown.

![Figure 2 The single-frequency electromagnetic reflection field that pass over the metal object](image)

The source of radiation is above the metal object at 10s when it is close to the target, and the vector direction of the electromagnetic reflection field is perpendicular to the electromagnetic receiver at this moment. The amplitude of the test signal is zero. At $a(n) \approx 0$, the TEO of $\varphi_{x}[x(n)] \approx 0$ and $\varphi_{y}[y(n)] \approx 0$ cannot correctly calculate the instantaneous frequency, so by setting the threshold, the instantaneous frequency is not calculated when the amplitude is small. For observation, the frequency of the range in figure 2 is replaced by the frequency mean of other periods nearby.

There is a certain noise in the signal, which makes the instantaneous frequency calculation results fluctuate, so that it can be improved by smoothing the calculation results.

4.1.2 Impact Factor Analysis
In the practical application, the detection signals use the discrete time signals by sample, and the influences of the sampling rate are simulated in this paper.

The simulation conditions are the same as 4.1, and the sampling rate are 10 kHz and 40 kHz, and the results of amplitude and instantaneous frequency are shown in figure 4 and figure 5.
As you can see, the calculation results are not good when the sampling rate is 40 kHz, the main reason is the sampling rate is too high when the noise exists, which will make the two approximate conditions of $a(n) = a(n-1) = a(n+1)$ and $\phi(n+1) - \phi(n-1) = 2\phi(n)$ no longer satisfied, causing a large fluctuation in the calculation results of the TEO. Therefore, the sampling rate should not be too high to satisfy the use.

The effect of the SNR is also simulated, the sampling rate is 10 kHz, and the simulation conditions are the same as the 4.1, and the SNR are 20dB and 14dB, the amplitude and instantaneous frequency of the calculation are shown in figure 6 and figure 7.
Obviously, the higher SNR reduces the calculation result error. The results of the instantaneous frequency calculation are also more likely to be affected by the sampling rate and the noise ratio, because the error of the inverse triangle function is calculated in the instantaneous frequency calculation of the discrete time signal. And the error of $\phi \_n [x(n)]$ and $\phi \_n [y(n)]$ is amplified, and $\omega(n)$ is the normalized digital angle frequency, the actual time domain frequency is $f(n) = f_\text{g} \omega(n) / 2\pi$, and the increase of sampling rate increases the error. Therefore, band-pass filtering can be carried out according to the prior knowledge of the frequency range to maintain a high SNR and make the calculation results more accurate.

4.2. Laboratory Experiment

4.2.1 Experimental Method

The verification experiment in this paper is carried out in a special laboratory. In the experiment, in the range of the magnetic field of the radiator, except for the detected metal objects, the rest of the equipment are non-magnetic substances. Radiator uses wire rod that can also be replaced as a coil, select the appropriate capacitor through the signal source and power amplifier can be obtained stable frequency of the magnetic field. Using a highly sensitive receiver, the position relationship between the radiator and receiver is adjusted to reduce the interference of the radiator magnetic field along the axis of the radiator magnetic field source. During the experiment, the relative position of the radiator and the receiver is kept unchanged, the steel trolley is passed under the bracket of the radiator and the receiver with the rope, and the signal changes are observed on the acquisition system connected to the receiver. The system block diagram is shown in Figure 8, and the real objects in the experiment site are shown in Figure 9.
4.2.2 Analysis of Experimental Results

In the experiment, a 600 Hz single frequency signal is used as the transmitting signal. The trolley passes through the magnetic transceiver from below the bracket, and the NI acquisition board card is used to obtain the signal that the sampling frequency is 3 kHz. The obtained received signals processed by TEO are shown in Figure 10.

It can be seen from the figure that, in this experiment, the time of generate the reflection field is between 3.5s to 4.5s when the trolley passes through the magnetic field. The variation of the amplitude and frequency of the reflection field obtained by the calculation method of TEO is basically consistent with the actual situation. It should be noted that the reflected field signal obtained is quite different from the situation in the simulation experiment, because in the actual experiment, the position relationship between the radiator and receiver cannot be completely adjusted to completely cancel the interference of the transmitting field. That is to say, in actual laboratory experiments, there is always interference.
from the transmitting field to the received signal, but TEO can still detect the changes of the transmitting field well.

5. Conclusion
This paper studies the TEO is used in the electromagnetic reflection field detection method, the simulation results show that TEO in extracting electromagnetic reflection amplitude envelope and instantaneous frequency has good real-time performance and detection effect, which can timely reflect the change of the amplitude and frequency, calculate simply and has good application prospect in the active electromagnetic detection.

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