A method of RCS Sequence extraction based on CAC + EMD

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Abstract. When the spatial object possesses the periodic motion, an obvious periodic phenomenon can be produced by its RCS sequence. Some methods such as Fast Fourier Transform Algorithm (FFT) and Circular Autocorrelation Function (CACF) can be used to judge the existence as well as the extraction of the sequence’s periodicity. Autocorrelation Function, Average Magnitude Difference Function (AMDF) and their combined transformation are essentially estimated by the correlation of their periodic signal. More than two periods of observation time is needed for accurate estimate. Furthermore, the requirement of the date rate is high and. Furthermore, such methods always accompanied by the errors of frequency multiplication and frequency division. In this paper, a periodic discriminant and estimation method combining cyclic autocorrelation and empirical mode decomposition is proposed. The periodicity of the original signal can be enhanced by the cyclic autocorrelation (CAC), and the signal component with the relatively complete periodicity can be obtained by the empirical mode decomposition (EMD). The periodic estimation of the measured data showed that the period estimated by CAC+EMD is more stable. In addition, this method is also effective in extracting the signal period with the weaker periodic phenomenon. In this paper, a periodic discriminant and estimation method combining cyclic autocorrelation (CAC) and empirical mode decomposition (EMD) is proposed (CAC+EMD), and a comprehensive comparison with the Single method is made, both CAC and CAC+EMD can extract the stable signal’s period effectively. With the gradual increase of noise discriminant effect of CAC+EMD on signal period is much better than CAC. Because CAC does not have the ability to process the non-stationary signal, so this method has a poor discriminant effect on signal period. As for the discriminant effect of CAC+EMD, there is no difference between stable signal and non-stationary signal.

1. Introduction
The Radar Cross Section (RCS) of the target is a measure index for reflecting the target’s ability to scatter radar signals. The periodicity of RCS sequence refers to the periodic change of RCS sequence caused by the periodic motion of the object, and the periodic movement phenomenon of spatial object includes spin of the spin-stabilized satellite, rolling of the failed satellite, periodic movement of the spare parts on the satellite, rolling of the ballistic missile body or debris, and the inching of the warhead, etc.[1-3].
In general, there are three kinds of envelope period extraction algorithms, including time domain algorithm, frequency domain algorithm and time-frequency hybrid domain algorithm. There are two main time domain algorithms, autocorrelation function method and average amplitude difference method, while frequency domain algorithm mainly includes cepstrum method[4]. As for time-frequency hybrid domain algorithm, its representative algorithm includes wavelet transform method, Hilbert-Huang transformation, Autocorrelation Function, Average Magnitude Difference Function (AMDF) and their combined transformation are essentially estimated by the correlation of their periodic signal. While the above-mentioned methods have many limitations. For example, the errors of frequency multiplication and frequency division always accompanied, the requirement data rate is high and one period of observation time can not estimate the periodic motion in a high accuracy[5-7].

2. The method of cyclic autocorrelation (CAC)

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\[
R(k) = \sum_{n=-\infty}^{\infty} x(n)x(n + k)
\]  

(1)

The properties of CAC are listed as follow:

(1) CAC is the even function;
(2) If the original signal has periodicity, CAC will possess the same periodicity, and the period is as same as the original signal.

It can be found from CAC's definition and properties that periodic signal's CAC has the same periodicity and there is a large peak at the integer multiple position of the cycle [8]. While the aperiodic signal's CAC does not have the above-mentioned properties. Thus, the discrimination of signal period can depend on detection of the peak value [9-11].

As for quasi-stationary periodic signal with nonstationary amplitude sequence, its amplitude sequence can be periodic continued by autoregressive-sliding model [12, 13]. This approach can effectively resolve the problem that the sum term decreases with the increase of the value of \( k \). Specifically, it is a method which similar to cyclic convolution to redefine CAC:

\[
R(k) = \sum_{n=1}^{N} x(n)x(\text{mod}(n + k), N)
\]  

(2)

Supposing autocorrelation function gets the maximum when \( k=k_0 \), then the period of the signal can be estimated as \( T=k_0/f_s \) (is denoted as sampling frequency). Autocorrelation function is a statistic of flexible second-order average of sample series, primary filtering has been carried out for noise interference with mixed signals. Thus, compared with the echo signal, autocorrelation function can display the periodic regularity of the signal more intuitively. The method of autocorrelation function has some advantages in anti-noise and simple operation, but it also has some shortcomings. For example, using this method often results in half and double extraction errors.
Figure 1. Original periodic signal and signal processed by CAC

3. The method of Empirical Mode Decomposition (EMD)

Traditional signal processing algorithms are based on Fourier transform. In general, Fourier transform is only suitable for stationary linear signals, and it will be limited when the signal changes irregularly. In 1996, N. E. Huang proposed that any complex signal can be decomposed into the sum of several eigenmode functions, and this algorithm is named empirical mode decomposition algorithm. Such algorithm makes the instantaneous frequency more reasonable. A new time-frequency analysis method was born, this method is based on the inherent mode signal and uses the instantaneous frequency to represent the characteristics of alternating signals. On this basis, in 1998, N. E. Huang and his colleagues proposed a relatively complete Hilbert-Huang transform signal analysis method, which has good localization properties in both time and frequency domains.

In the study of non-linear and non-stationary signals, transient information of signal, such as transient energy, transient envelope as well as transient frequency have become a hot topic. Specifically, the transient frequency is defined as follow:

\[
f(t) = \frac{1}{2\pi} \frac{d\varphi(t)}{dt}
\]

\(\varphi\) is denoted as transient frequency. However, the transient frequency solved according to the above definition are problematic in some cases, and meaningless negative frequencies may occur. After a thorough study of transient frequency, it is found that only signals satisfying certain conditions can obtain transient frequency of physical significance, and such signals are called intrinsic mode function (IMF) or intrinsic mode component.

The concept of IMF is proposed for obtaining the meaningful transient frequency, and there are two conditions should be satisfied:

1. The number of extreme point (including maximum and minimum points) in the whole signal should be equal to or one off zero-crossing point.

2. At any time point on the signal, the mean value of the upper envelope determined by all local maximum points and the lower envelope determined by all local minimum points equal to zero.

Generally, The number of IMF’s zero-crossing points on all time thresholds must be equal to the number of extreme points, or the difference must be less than or equal to 1, and the waveform should be symmetrical with local zero-mean. When IMF satisfies the above two conditions, there will be only one extreme point between the two zero-crossing points. So there is only one oscillation of the intrinsic modal component without the existence of complex superimposed wave.

EMD always be known as a screening process, and according to the signal characteristics, this screening process can adaptively decompose any complex signal into a series of IMF.

The screening process of EMD is as follows:
(1) Take the original signal $x(t)$ as the pending signal, and determine all local maximum and minimum points of the signal. Connect all the maximum points and minimum points with cubic spline curves respectively to obtain the upper and lower envelopes of $x(t)$. The mean values of the upper and lower envelopes are set as $m(t)$.

(2) Take $x(t)$ minus $m(t)$, and get the following form:

$$h_1(t) = x(t) - m(t)$$  \hspace{1cm} (4)

(3) Verify whether $h_1(t)$ satisfies two conditions for intrinsic modal components, if not, then set $h_1(t)$ as the pending signal and repeat step (2) until $h_1(t)$ becomes an intrinsic modal components, and take the following transformation:

$$c_1(t) = h_1(t)$$  \hspace{1cm} (5)

(4) After decomposing the first intrinsic mode component from the original signal, take $x(t)$ minus $c_1(t)$ and get the residual value sequence $r_1(t)$:

$$r_1(t) = x(t) - c_1(t)$$  \hspace{1cm} (6)

(5) Set as the "new" original signal and repeat the above-mentioned operation, the second (denoted as $c_2(t)$), the third (denoted as $c_3(t)$), and the nth (denoted as $c_n(t)$) intrinsic modal component can be obtained in turn, the circulation will be end until $r_n(t)$ satisfies the terminate condition (At this time, $r_n(t)$ is usually a monotone function).

The original data can be decomposed into the sum of intrinsic modal components and residual components by the method of EMD:

$$r_1(t) = x(t) - c_1(t)$$  \hspace{1cm} (7)

$r_n(t)$ represents the average tendency of the signal.

EMD has two advantages in extracting signal’s period:

1. EMD can filter out the high frequency noise and retain the signal envelope to enhance the stability of periodic discrimination and extraction.

2. EMD has a good effect on non-stationary signal processing. When the signal envelope changes non-stationary, it can also extract the envelope stably.

4. The method of CAC+EMD

The periodicity of the original signal can be enhanced by CAC, and the signal component with a relatively complete periodicity can be decomposed by EMD. In this paper, we used method of CAC, EMD and CAC+EMD to handle the original signal which presented in Fig. 1, and the results have been shown in Figure. 2 and Figure. 3.
Figure 2. Decomposed by EMD after CAC operation

Figure 3. Spectrum of cyclic autocorrelation signal (a), spectrum of original signal decomposed by EMD (b) and spectrum of cyclic autocorrelation signal decomposed by EMD (c).

5. Experimental verification

Verification of simulated signal: Simulations generate sinusoidal signal with random noise, and the periodic estimation of the signal is performed by the combination of CAC +EMD. The performance of the algorithm is tested by two signal forms. \( s_1(t) = \sin(2\pi ft + \phi_0) + n(t) \) denoted as signal A, \( s_2(t) = \sin(2\pi ft + \phi_0) + n(t) + 2(t - 1)^2 \) denoted as signal B. The sampling frequency is 500 Hz, the signal length is 2s, the frequency is 2Hz and \( \phi_0 \) is the initial phase which generated randomly. \( n(t) \) is the noise of the Gauss distribution and the values of standard deviation are \( [0.1, 0.5, 1, 2, 4, 5, 6, 8, 10, 12, 14] \), the number of samples is 1000. The information forms under different standard deviations are shown in Fig. 4.
From Figure 4 it can be found that the periodicity of the signal is greatly weakened when the noise standard deviation is greater than 4, and it is difficult to judge the periodicity of the signal. The results of periodicity discrimination and periodicity estimation of signals by different algorithms are listed as follow.

| standard deviation | Signal A | Signal B |
|--------------------|----------|----------|
|                    | The accuracy of CAC+EMD(%) | The accuracy of CAC(%) |
| 0.1                | 100      | 100      |
| 0.5                | 100      | 100      |
| 1                  | 100      | 100      |
| 2                  | 100      | 99.7     |
| 4                  | 97.1     | 74.4     |
| 5                  | 83.3     | 37.1     |
| 6                  | 57.8     | 14.6     |
| 8                  | 20.7     | 2.1      |
| 10                 | 8.1      | 0.6      |
| 12                 | 3.2      | 0.2      |
| 14                 | 2.3      | 0.2      |

It can be found from Table 1 that when the noise is small, both CAC and CAC+EMD can extract the stationary signal’s period. As the noise increases, CAC+EMD is superior to CAC in discriminating signal period. As for the non-stationary signals, because CAC does not have the ability to process non-stationary signals, so it has a poor discrimination effect on signal period. While the discriminant result of CAC+EMD method is not much different from that of stationary signal.
Verification of measured signal: The target sequence with periodic phenomenon is shown in Fig. 5. CAC+EMD and CAC were performed to discriminate and extract the period.

Figure 5. The target sequence with periodic phenomenon

Figure 6. CAC+EMD period estimation method

Figure 7. CAC period estimation method
The sliding window is analyzed with 40s window with the step of 4s. Fig. 6 and 7 show the periodic estimation result of CAC+EMD and CAC on the measured data. The frequency of 0 indicates that the signal in this section is non-periodic. As for CAC+EMD, the experiments has proved that there is little difference in processing results for stationary or non-stationary periodic signals. Furthermore, such method can also discriminate and extract the signal period effectively.

6. Conclusion
In this paper, a method for extracting RCS Sequence Period based on CAC+EMD has been proposed. The experimental result has proved that such method has the advantage in processing non-stationary signals. As for the discriminant effect of CAC+EMD, there is no difference between stable signal and non-stationary signal.

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