Analysis and Simulation of Extracting Radar Modulation Signal Based on CIC Filter

Wei Liu1,2, Minggang Tang3, Liming Liu1, Xiaxi Lu2, Chengqiang Luo1,2

1Army Engineering University, Shijiazhuang, Hebei Province, 050000, China; 2Huayin Ordnance Test Center, Huayin, Shaixi Province, 714200, China

Abstract. Aimed at the difficulty of extracting weak information such as projectile movement and precession during flight, this paper analyzes the characteristics of extracting the periodic motion information of the projectile from the original data, and designs the resampling and filtering methods based on the characteristics and measured data of a certain type of continuous wave radar system. This method achieves the purpose of non-destructive extraction of low frequency weak signals.

1. Introduction
During the flight, the projectile shaft will make complex swing around the centroid of itself. The movement status of the rotating projectile includes nutation, precession and rotation. The size and change trend of the nutation angle reflect the stability of its flight, affecting the range and the scattering. The periodic movement of the flying target within the radar beam will cause a change in the reflection intensity of the electromagnetic wave, which is similar to modulate the radar echo. Comparing to the scale information of the target, these modulated signals of the projectile itself are very weak. Based on the test data of a certain type of continuous wave radar, how to effectively extract these weak signals is the main content of this paper.

2. Analysis of radar measurement data
The information on the nutation and rotation of the projectile is included in the radar echo. After the continuous wave radar performs high-precision dense sampling on the echo signal, the modulation information is retained in the radar sampling data. However, these signals have very weak energy and low frequency relatively to the flying target, and it is difficult to process directly using the Fourier transform. For example, in a test with a maximum speed of 500m/s, the sampling frequency is 87KHz, and the characteristic frequency of the rotation and nutation of the projectile is only a few to several tens of Hertz. Tens of thousands of points need to participate in the operation if you want to restore the modulation information. And the feature frequency to be extracted will be missed after transforming the FFT because the frequency resolution is relatively large; adding that the energy leakage of the high frequency component will cover the low frequency weak signal; to sum up, all above factors will make it difficult to extract information such as rotation and nutation by directly using the FFT method. If you process direct sampling, it is alike adding an impulse rectangle window to the original data. In the passband, the spectrum produces periodic attenuation, which will have a large impact on low-frequency
signals with weak energy. Therefore, it is necessary to use resampling to reduce the data rate and increase the frequency resolution. Thus, designing a filtering method without any attenuation in the passband and re-sampling at the same time is the focus of this paper.

3. Filtering method of weak modulation signal

Resampling the radar original data is equivalent to filtering the radar signal, so that the high-frequency components are attenuated and the low-frequency components are retained as much as possible. Meanwhile, when resampling the radar original data, the stability of the passband to reduce the data rate should be ensured.

3.1 Design of filter

Digital filter technology is a general term for a series of techniques of extracting target signals by using digital processing methods. Figure 1 is a block diagram of the digital filter designed in this paper.

![Fig.1 Block diagram of the digital filter](image)

In this picture, for a sampling frequency of 87 kHz, the frequency resolution is 0.5 Hz, and 176 times extraction is proposed, and information within 1 kHz is reserved. In which, the CIC filter realizes 22 times extraction, the half-band filter realizes 8 times extraction, and the DSP performs digital signal processing.

3.1.1 Design of cascaded integrator comb (CIC) filter

Firstly, the characteristics of amplitude and phase frequency of the Integrator-Comb filter (IC) are studied. The total response of this type of filter frequency is:

\[ H_0(\omega) = \frac{\sin(\alpha D/2)}{\sin(\alpha/2)} e^{-jD(Q-1)/2} = D^Q \cdot Sa^Q(\frac{\alpha D}{2}) \cdot Sa^{-Q}(\frac{\alpha}{2}) \cdot e^{-jD(Q-1)/2} \]  

(1)

Similarly, the side lobe suppression of the Grade Q CIC filter can be found as:

\[ \alpha_s^Q = 20 \log \left( \frac{D}{A_1} \right)^Q = Q \cdot 20 \log \frac{3\pi}{2} = (Q \times 46) \text{dB} \]  

(2)

For example, when Q=6, the difference between the main lobe and the side lobe is: 80.8dB. Such stop band attenuation can basically meet the actual requirements. The characteristic curves of the amplitude and phase frequency of the CIC filter obtained by the formula (1) are as shown in Fig. 2.
Compared to traditional FIR decimation filters, CIC filters show the following several advantages:

1. Without multiplier;
2. No need to store filter coefficients (filter parameters are unity gain);
3. The CIC filter does not need to be stored. The number of intermediate delay registers can be obtained from equation (1), thus the characteristic curves of the amplitude and phase frequency of the CIC filter are shown in Fig. 2. The number is also very small and the structure is very formal, including two simple builds;
4. There is almost no external control or complex control.

Based on these characteristics, the design adopts CIC filter as the first-stage filter, and performs the first data extraction, which makes the subsequent filtering and digital signal process possible.

### Design of CIC Compensation Filter

The CIC filter is simple in structure and widely used in practical engineering. However, its amplitude response attenuation of passband is very fast, which can be solved by compensated through a shorter FIR filter. The amplitude frequency response is:

\[
G(f) = \left[ \frac{1}{DM} \sin \pi MF \right]^Q = \left[ \frac{1}{DM} \sin^{-1}(MF) \right]^Q
\]

The amplitude frequency curve after compensation of CIC filter is shown in Fig. 3.

### Simulation verification of digital receiver

Assuming that with a distance of 10km from the radar, a target is flying at 300m/s, the signal-to-noise ratio is -120dBm, and the radar carrier frequency is 10.54GHz, the generated Doppler frequency is 20kHz, and the target characteristic frequency is 60Hz. Then the radar echo signal can be expressed as:

\[
s(t) = \cos(2\pi f_d t + \phi_d) + \cos(2\pi f_d t + \phi_d) + \text{randn}(t)
\]
In the equation, $f_0=60\text{Hz}$ is the characteristic frequency of the target, $f_d=20k\text{Hz}$ is the Doppler frequency produced by the target. $\text{randn}(t)$ is Gaussian noise. The echo signal of the target is shown in Figure 4.

In this design, the decimated integral comb (CIC) filter has a decimation rate of 22, and the number of data points after the signal passes through the CIC filter is 7909. The delay of the CIC filter is $M=1$, the stopband attenuation is no more than $-65\text{dB}$, and the passband frequency is $f_p=4.5\text{kHz}$. Fig.5 and fig.6 show the signal after CIC filter and the frequency response of CIC filter.

The role of the CIC compensation filter is to flatten the frequency response within the passband while limiting the low frequency gain. The passband frequency of the compensation filter is $f_0=10^3\text{Hz}$, and the stopband attenuation is no more than $-70\text{dB}$. The frequency response of the filtered signal and the filter is shown below. It can be seen from Fig. 7 that the high-frequency component of the signal is enhanced, and the amplitude-frequency characteristic of the filter in Fig. 8 is slightly raised in the back-passband, which indicates that the designed compensation filter achieves the intended purpose.
In order to further reduce the amount of data, a half-band filter is used in the final stage of filtering. The decimation rate is 8, the passband frequency is \( f_p = 500 \text{Hz} \), and the stopband attenuation is no more than -80 dB. The filtered signal and the amplitude-frequency curve of the filter are shown in the figure below.

![Fig.9 The signal after half band filter](image)

![Fig.10 The frequency response of the half band filter](image)

After the signal passes through the half-band filter, the number of data points becomes 988 points, which can be transmitted to the DSP calculation module for Fourier transform. At this time, the 1024-point FFT is adopted and the frequency resolution is 0.48 Hz. FFT for the signal is processed, and the obtained spectrum is shown in Figure 11.

![Fig.11 Signal spectrum diagram after filter](image)

According to the above figure, after the signal is downsampled and filtered, the characteristic frequency is 60.01 Hz, 0.01 Hz away from the standard frequency of 60 Hz. In addition, the characteristic frequency of 6 Hz and 600 Hz are also brought into the simulation process, and the obtained signal spectrum are shown in Figure 12 and figure 13, which illustrates that the target information can also be extracted under extreme conditions.

![Fig.12 The spectrum diagram of target signal (90m/s)](image)

![Fig.13 The spectrum diagram of target signal (9000m/s)](image)

From what has been mentioned above, the digital receiver achieves a sampling rate of 176 times, with the number of data points is less than 1000, the cutoff frequency of the passband is about 1 kHz, and the stopband attenuation is less than -80 dB. The total characteristic curve of amplitude-frequency of the digital receiver is shown in Figure 14 and Figure 15, Moreover, the CIC, CIC compensation and
half-band filters used in this paper are essentially FIR filters which realize the linear phase filtering. The design purpose of reducing the sampling rate and extracting the target information is achieved. Therefore, the method can be applied to the extraction of weak information such as the rotational speed and the nutation angle.

Fig.14 The superposition of amplitude-frequency response of these three filters

Fig.15 The amplitude-frequency response curve of digital receiver

4. Conclusions and prospects
In this paper, a filtering method for radar signals is designed to ensure the smoothness of the passband and reduce the data rate, which is suitable for further deepening of radar data. The problems to be further studied are: the establishment of radar detection environment clutter and target fluctuation model to ensure that the radar effectively extracts target feature information; the characteristic parameters of the flying bullet, such as rotation, attitude, orbit, and trajectory differentiation, are included in the radar echo. The modern spectral estimation method and non-stationary signal processing method can be used to mine the target information in the echo and enhance the test capability of external ballistics trajectory

References
[1] (US) Skolnik M.I. Introduction to radar systems. Beijing: Electronic Industry Press, third edition. 2006, 7 Pages130-133
[2] Zhang Mingyou. Digital array radar and software radar. Beijing: Electronic Industry Press. 2008, 2
[3] Shen Fumin, Jia Yongkang. Deblurring technique in phase ranging. Journal of Xidian University, 1997, 3, Vol.24, No.1. Pages 52-57
[4] Xu Bangjian. Key theory and algorithm research and hardware and software design of multi-frequency continuous wave ranging radar. [Ph.D. thesis], Changsha: National University of Defense Technology. 2001
[5] Weibel Azimuth&Elevation Monopluse Doppler Tracking Radar System General Description. 2007
[6] William S.M., David F.M., and James B.Y.T . Resolution of a Ambiguity Problem in Multiple Frequency Spectral Estimation . IEEE Transactions on Aerospace and Electronic Systems . 2004, 1, Vol.31, No.1 . 2-7P
[7] Artis J.P. , Kemkemian S. The radar in the automotive domains[J]. Annalesdes Telecommunications/Annals of Telecommunications. 2005. 60(3-4): 326-356P