Ballistic target intake feature extraction algorithm based on phase recovery

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Abstract: The movement is the main form of movement of the space ballistic target, and the recognition of the inmoving characteristic is the basis for judging the target attribute. By analyzing the echo phase form of a single intake scattering point, a phase recovery algorithm restores the phase change of narrow-band radar echo signal. The recovered phase is analyzed spectrally, so as to estimate the spin and velocity of the target. The simulation results prove the validity of the algorithm and have good robustness.

1. Introduction

The micro-motion signal phase of the ballistic target contains a wealth of target micro-motion information, however, the form of the micro-dynamic signal phase is often more complex[1-3],the typical phase change form has the vibration micro-motion echo signal and the sine variation form of the rotating micro-motion echo signal, the phase of theinmoving micro-motion signal echo is more complex, how to move the characteristic target's motion characteristic sitter from the micro-motion echo signal has become a hot spot for scholars in China[4-6].

Using the broadband system radar, the intake characteristics of the intake scattering point are extracted according to the relationship between the target time distance image and the intake distance [7]. Using orthogonal matching decomposition, the signal of the intake scattering point is reconstructed, and the intake target of the target is successfully extracted [8]. The above methods are based on the radar signal of the broadband system, the target's movement characteristics are estimated. Based on the ideal intake scattering model, based on narrow-band system radar, based on the separation of the signals at each micro-scatter point, a microdynamic feature extraction method based on phase recovery algorithm is proposed to estimate the motion characteristics of the intake scattering point.

2. Ideal intake scattering model

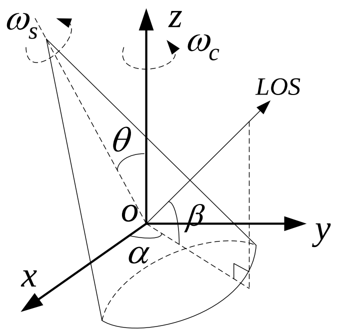

Figure 1 Ideal intake ballistic target model

Establish the precession model as shown in Figure 1. Take the intersection point o of the symmetry axis and the conic axis of the ballistic target as the origin, take the precession axis as the z axis, and take the plane where the precession axis and the conic axis are located at the initial time as the yoz plane to establish the rectangular coordinate system $oxyz$. *LOS* is the radar line of sight direction. Its azimuth angle in the coordinate system is α , and the pitch angle is β . The angle between the target symmetry axis and the cone rotation axis is θ . Suppose the distance from the far point o of the coordinate system to the radar is R_0 . According to the verification of the measured data and the experimental results of the microwave darkroom [9-11], there are only a few scattering centers of the precession target in the high-frequency electromagnetic environment, mainly the joint of the cone top and the bottom tail and the missile body. Suppose P is any precession scattering point on the projectile, its initial position in the coordinate system is (x_p, y_p, z_p) , its motion can be equivalent to rotating around the symmetric axis with the angular velocity ω_s , and rotating around the conical axis oz with the angular velocity ω_c . By the literature [12], the relationship between the radial distance of scattering point P and radar with time is

$$\begin{aligned} R(t) = R_0 &+ A_1 \sin[(\omega_s + \omega_c)t + \varphi_1] \\ &+ A_2 \sin[(\omega_s - \omega_c)t + \varphi_2] \\ &+ A_3 \sin(\omega_c t + \varphi_3) \\ &+ A_4 \sin(\omega_s t + \varphi_4) + A_5 \end{aligned} \tag{1}$$

Where

$$\begin{cases} A_1 = \dfrac{1}{2}\cos\beta(1+\cos\theta) \\ \qquad * \sqrt{x_p^2 + (y_p\cos\theta - z_p\sin\theta)^2} \\ A_2 = -\dfrac{1}{2}\cos\beta(1-\cos\theta) \\ \qquad * \sqrt{x_p^2 + (y_p\cos\theta - z_p\sin\theta)^2} \\ A_3 = \cos\beta(y_p^2\sin^2\theta + z_p\sin\theta\cos\theta) \\ A_4 = \sin\beta\sin\theta\sqrt{x_p^2 + (y_p\cos\theta - z_p\sin\theta)^2} \\ A_5 = y_p\sin\beta\sin\theta\cos\theta + z_p\sin\beta\cos^2\theta \end{cases} \qquad \begin{cases} \varphi_1 = \arctan(\dfrac{x_p\cos\alpha + y_p\sin\alpha\cos\theta - z_p\sin\alpha\sin\theta}{x_p\sin\alpha - y_p\cos\alpha\cos\theta + z_p\cos\alpha\sin\theta}) \\ \varphi_2 = -\arctan(\dfrac{x_p\cos\alpha - y_p\sin\alpha\cos\theta + z_p\sin\alpha\sin\theta}{x_p\sin\alpha + y_p\cos\alpha\cos\theta - z_p\cos\alpha\sin\theta}) \\ \varphi_3 = -\alpha \\ \varphi_4 = \arctan(\dfrac{y_p\cos\theta - z_p\sin\theta}{x_p}) \end{cases}$$

Type (1) the relationship between the scattering point and the radar radial distance f_c and the forward parameters of the target is clearly demonstrated, assuming that the narrow-band radar transmits a single-frequency pulse signal, the narrow-return wave signal received by the radar can be represented as a base-back wave signal after orthogonal dual-channel demodulation.

$$s_b(t) = \sigma \exp(j\frac{4\pi f_c}{c}R(t)) \tag{2}$$

Where σ is the scattering coefficient of the scattering point P . As can be seen from the formula, the phase $\phi = \frac{4\pi f_c}{c}R(t)$ and $R(t)$ of the incoming echo signal is proportional to the indirect relationship, so ω_c the spectral analysis of the phase of the target echo signal can be obtained, ω_s , , $\omega_s + \omega_c$ and $\omega_s - \omega_c$ frequency components.

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3. Micro-feature extraction based on echo phase recovery algorithm

The recovery of the phase of the target echo $s(t)$ signal is the key in this section, starting with a two-channel separation of the target echo signal and extracting the mixed phase of the target.

$$\phi_h = \arctan(\frac{image[s(t)]}{real[s(t)]}) \tag{3}$$

in the form, $image[\bullet]$ is the imaginary part function $real[\bullet]$ is the real part function. Since the value field of the Arctangent function is $(-\frac{\pi}{2}, \frac{\pi}{2})$, a aliasing occurs when the phase of the signal is beyond the interval, and the aliasing formula can be summarized as

$$\phi_{hfz} = \begin{cases} \mathrm{mod}(\phi, \pi), & \mathrm{mod}(\phi, \pi) < \frac{\pi}{2} \\ \mathrm{mod}(\phi, \pi) - \pi, & \text{others} \end{cases} \tag{4}$$

Where, mod is the residual function When a mix occurs, the echo signal phase is distorted, from which valuable information cannot be extracted. In order to accurately extract the micro-motion information contained in the signal phase, the output phase must first be demixed and stacked, and it can be seen by formula(4) that When the residual result of real phase and tangent function period at a certain time is greater than $\pi/2$, the output phase of the formula(3) will mutate. Thus, the solution-stacking formula can be written as

$$\phi_{zs}(t) = \phi_{zs}(t-1) + \Delta\phi_h(t) \tag{5}$$

Where

$$\Delta\phi_h(t) = \begin{cases} d\phi_h(t), & -\frac{\pi}{2} < d\phi_h(t) < \frac{\pi}{2} \\ d\phi_h(t) - \pi, & d\phi_h(t) > \frac{\pi}{2} \\ d\phi_h(t) + \pi, & d\phi_h(t) < -\frac{\pi}{2} \end{cases}$$

, Moreover, $d\phi_h(t) = \phi_h(t) - \phi_h(t-1)$ is the difference between the output phase at the time t and the output phase at the time $t-1$, $\phi_{zs}(t)$ is the recovered real phase, $\phi_{zs}(0) = \phi_h(0)$.

After the phase is demixed and stacked, the microdynamic parameters can be estimated using the formula (5) and the equation (1). It is easy to know that the phase size of the echo signal is determined by the sine curves of four different frequencies, the frequency of these sine curves is related to the spin and cone frequency of the target, as well as the difference between the two, that is ω_c, ω_s, $\omega_s + \omega_c$ and $\omega_s - \omega_c$. The recovered phase signal is analyzed in frequency spectrum, and filtered out the zero-frequency component slot slates to obtain four different frequency peaks. In general, the spin speed of the ballistic target is greater than the target's cone spin speed, the spectrum of the target phase is analyzed, the two largest frequency points that occur peak sit corresponding to the angular frequency $\omega_s + \omega_c$ and ω_s, the value of the two frequency points are recorded as $\hat{f}_1$, $\hat{f}_2$. Angle speed ω_c and ω_s can be estimated by frequency points.

$$\begin{cases} \hat{\omega}_c = 2\pi\left(\hat{f}_1 - \hat{f}_2\right) \\ \hat{\omega}_s = 2\pi\hat{f}_2 \end{cases} \tag{6}$$

The following are the specific steps for the extraction method of the ideal intake target micro-movement feature based on phase recovery:

Step1: A two-channel separation is accepted to the radar echo, with a distorted signal phase with a mix of outputs (3).

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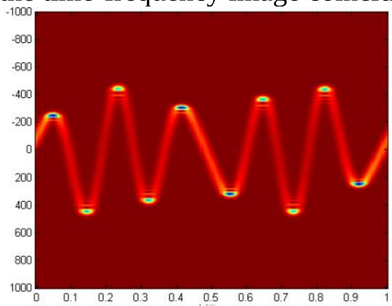
Step2: Destack the seisted signal phases based on the equation (5) to obtain a signal phase without a mix $\phi_{zs}(t)$

Step3: The spectral analysis of the real phase is performed, the maximum frequency point corresponding to the peak is searched, and the target spin angle frequency and cone-rotation frequency are estimated based on the formula (6).

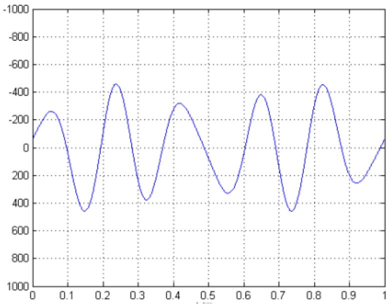
4. Simulation experiments

Assuming that there are P independent intake scattering points in space, the initial Euler angle of the local coordinate system and the reference coordinate system is $30°, 0°, 0°$. The azimuth of the taper axis in the reference coordinate system is at the angle of $60°$. The initial position coordinates of the scattering point under the local coordinate system are $(0.3, 0.4, -0.5)$. The cone spin angle speed is $10\pi\ \mathrm{rad}/s$, the cone spin angle speed $4\pi\ \mathrm{rad}/s$. The unit direction of radar line of sight in the local coordinate system is $(\sqrt{3}/4, 3/4, 1/2)$, the coordinates of the local coordinate system in the radar origin coordinate system are $(2000, 3000\sqrt{2}, 5000)$, assuming that the frequency of the radar transmit signal is $4\mathrm{GHz}$, the signal-to-noise ratio of the echo signal is $5dB$, according to the setting of the simulation parameters to simulate the echo signal of the intake scattering center.

Figure 2(b) is the micro Doppler theoretical curve in the ideal intake and scattering center, and Figure 2(a) is the result of time-frequency processing of the simulation signal, which shows that the curve in the time-frequency image coincides with the theoretical value.



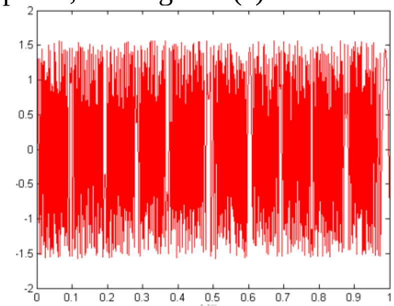
(a) time-frequency analysis results



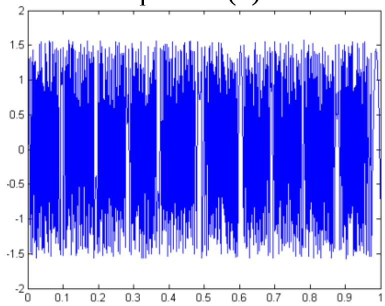
(b) Theory micro Doppler

Figure 2 MicroDoppler Results for Echo Signals

Based on the alias (3) output simulation echo signal's aliasing phase, Figure 3(b) is the output aliasing phase, and Figure 3(a) isthe result of the ideal phase of the equation (4).



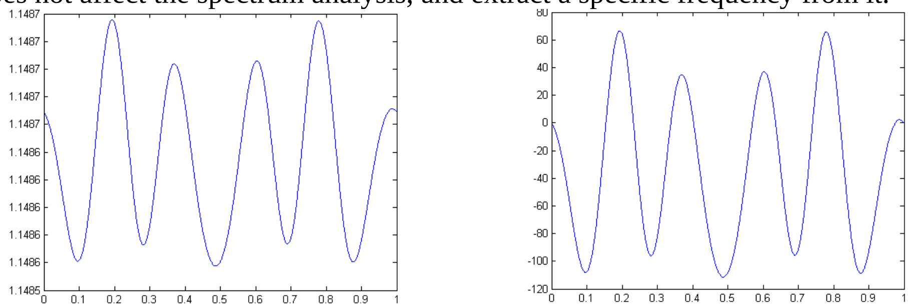
(a) The aliasing phase of the output of the mixed formula



(b) The aliasing phase of the output of the anathema function

Figure 3 Mixed Phase Comparison

According to the formula (5), The resulting distortion phase is de aliased,, phase recovery results are shown in Figure 4 (b), Figure 4(a) is a theoretical phase, from the figure, the recovery algorithm can only restore the change in the signal phase, can not fully restore the true value of the out phase, but the result does not affect the spectrum analysis, and extract a specific frequency from it.



(a) The theoretical phase of the echo signal (b) Restored signal phase

Figure 4 Echo Signal Phase Comparison

The recovered phase is spectrally analyzed, the results are shown in Figure 5, and the frequency point corresponding to the peak in the graph is searched to estimate the spin angle speed and cone angle velocity of the target according to the formula (6).

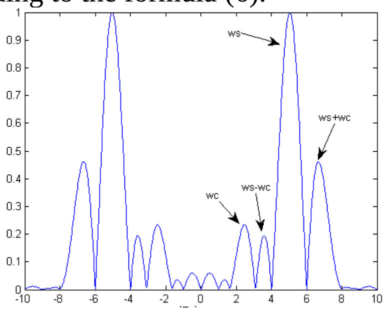


Figure 5 Recovery Phase Spectrum Analysis Results

The figure above clearly shows the four peaks, they correspond to the angular velocity, ω_s , $\omega_s+\omega_c$, ω_c , $\omega_s-\omega_c$ and extract the maximum two frequency points in the figure above, $\hat{f}_1=6.92$ and $\hat{f}_2=5.05$. The estimated parameter results are shown in Table 1.

Table 1 Intake Parameter Estimation Results

	Spin angle speed ω_s (rad/s)	Cone angle speed ω_c (rad/s)
Estimate	10.1π	3.74π
True value	10π	4π

From the results of the table above, we can see that the value estimated by the algorithm is very close to the real value, so the forward information of the ballistic target can be extracted effectively by the phase recovery algorithm.

5. Summary

The movement characteristic recognition of ballistic target is the basis for judging the target attribute, while in the middle of the ballistic target flight, the warhead is generally moving in order to carry out attitude control. The algorithm proposed in this paper can estimate the inmoving characteristics of the moving target under the narrow-band system, and the simulation experiment shows that the method proposed in this paper can still estimate the moving parameters of the target more accurately under the low signal-to-noise ratio, which provides a basis for the identification of the ballistic target.

References

[1] Micro Doppler Effect in Chen's Radar.
[2] Chen Radar Micro Doppler Signature Application Progress of the Application of the "C"//IEEE Antenna Measurement and Application Method: 2014.1-4.
[3] Chen V C, Li F Y, He S and other micro Doppler signature analysis Radar, Sonar and Navigation IEE Program, 2003, 150 (4): 271-276.
[4] DAVID L. Ballistic Missile Defense (J) Electronic Defense Journal, 2006, 29 (1): 46-52.
[5] S. Victoria. U.S. Missile Defense System (M) California: Prager Security International, 2010: 44-78.
[6] Cohort 311_121O/Team LCS, Missile Defense in 21st Century Procurement Environment: Explore LCS Mission Packs supporting BMDs. Naval Graduate School, Monterey, California, 2013:1-8.
[7] Reten, Liu Jin busy, Yu Fuping, Hu Guoping. New method extraction based on the ballistic target intake characteristics of time-distance images. Signal processing, 2012, 28 (1):73-79
[8] Luo Ying, Zhang Qun, Kingdom Zheng, Pipe, Pai and Qing. Broadband radar micro-movement feature extraction method based on the decomposition of the complex image OMP. Radar Journal, 2012, 1 (04): 361-369.
[9] Feng Dejun, Liu Jin, Dan Mei. The characteristics of the target RCS cycle in the middle of the trajectory and its estimation method. Journal of Astronautics, 2008, 29 (1): 362-365.
[10] Xiao Jinguo, Duran, Han Xun, etc. The intake cone skirt target instantaneous micro Doppler frequency extraction method based on parametric time frequency analysis. Journal of Electronics and Informatics, 2016, 38 (1): 90-96.
[11] Kang Ma, Wang Chunhua, Yu Ming, etc. Study on the characteristic extraction of the movement cycle of ballistic targets. Modern Radar, 2010, 32 (11): 29-32.
[12] Liu Weijian, Chen Jianwen. The method of extracting the characteristics of the trajectory-type target movement cycle is studied. Modern Radar, 2009, 31 (7): 63-68.