Parameters Estimation of Precession Cone Target Based on Micro-Doppler Spectrum

MingFeng Wang, AiJun Liu(✉), LinWei Wang, and ChangJun Yu

School of Information and Electrical Engineering,
Harbin Institute of Technology, Harbin 264209, China
mylaj@hitwh.edu.cn

Abstract. The micro-Doppler (m-D) provides valuable information for the motion parameters extraction and the target recognition of space targets. To address the issue of estimating the motion parameters of precession warhead targets, a new method based on the m-D spectrum of the top and the bottom of the cone is proposed in this paper. In this method, the m-D features of the cone target are firstly extracted by calculating the first-order moments of the time-frequency distribution of the echo signal. Then, the motion parameters of the target are roughly estimated by the Fourier transformation of the m-D curve. Based on the rough estimation, the search method is employed to estimate the motion parameters of the cone target precisely. The validity of the proposed method is verified by the analysis data.

Keywords: Procession cone target · micro-Doppler features · Search method Precession parameters estimation

1 Introduction

Space target recognition is a key part of ballistic missile defense system. From launch to landing, the flight phase of the ballistic missile includes boost stage, middle section, and reentry stage. In the boost phase and reentry stage, the target flying time is short, and the missile defense system must complete target identification in a short time to implement effective interception. There is still no reliable solution to this problem. While the middle section is the longest flight time of the missile, and the space environment is relatively simple. Therefore, the current research of ballistic missile identification mainly focuses on the middle section [1]. In order to improve the survivability of missile and interfere with the work of missile defense system, the ballistic missile will take penetration measures such as releasing decoys and electromagnetic interference. In addition, at the end of the boost stage, the warheads and the propeller rockets will produce some debris, including booster rockets, mother cabins, etc. Thus, the target group in the middle section of the trajectory includes warhead targets, debris, bait and false targets, which fly at roughly at the same speed to form a diffuse threat band. The task of identifying the target in the middle target is to determine the position of the warhead target from the target group.

Micro-motion feature are often used to identify warhead targets. In order to ensure the reentry angle of attack, the warhead target is usually oriented by spin in the middle

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flight. When a spinning warhead target is disturbed, such as the release of the decoy or the separation of the projectile and rocket, certain precession or nutation occurs. However, the non-attitude control systems such as bait, decoy and debris usually do not have regular micro-motion features. Because the micro-motion features of warhead target are of great value to distinguish warhead and decoy. Therefore, the extraction of target micro-motion features from radar echoes and the estimation of micro-motion parameters have received extensive attention in the radar community [2–4]. The main tasks can be divided into two categories: the first is to extract target micro-motion features from wideband radar echoes, and the other is to extract target micro-motion features from narrowband radar echoes. Although the theory and method of the target precession parameters based on wideband radar echo are more studied, the technologies of narrowband radar system are more mature. The m-D spectrum of the target [5] can be obtained by narrow band radar, so it is of great practical significance to study target precession parameter estimation algorithm based on m-D spectrum.

2 Radar Echo Signal Model of Precession Cone Target

Radar observation of the precession of the cone-shaped target is shown in Fig. 1. Establish reference coordinate system O-XYZ: take the target centroid as the origin, and take the cone precession axis as the Z axis, and the cone top direction is the Z axis forward. Define the Y-axis and the initial time cone symmetry axis coplanar, and perpendicular to the Z axis. The X axis is determined by the right hand criterion. The angle between the target symmetry axis and the Z axis is the precession angle θ. The target is spinning at an angular velocity wr, and simultaneously coning at an angular velocity wc. The azimuth of the radar line of sight in the reference coordinate system is v. α is the mean angle of view, which represents the angle between the radar line of sight and the Z axis of the precession axis.

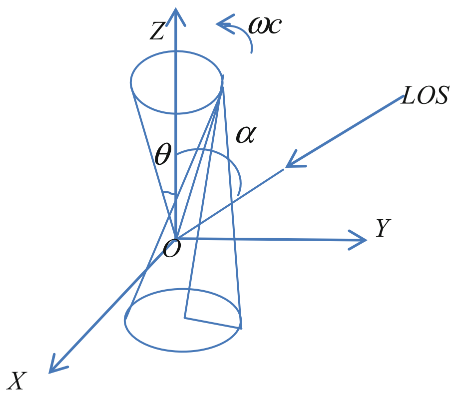


Fig. 1. The cone-shaped target model

As defined by the coordinate system, the unit vector of the precession axis in the reference coordinate system is: $\vec{e} = [0 \quad 0 \quad 1]^T$, the unit vector of radar sight in the reference coordinate system is: $\vec{n} = [\sin\alpha\cos v \quad \sin\alpha\sin v \quad -\cos v]^T$. Precession can be divided into two components, the rotation of a symmetrical axis and the rotation of the precession axis. Under the radar observation, the radial distance variation of P at any point of the precession cone target is investigated.

The position of P in target body coordinate system is $\vec{r}_0 = [x \quad y \quad z]^T$, and P in the reference coordinate position is $\vec{r}_1 = [X \quad Y \quad Z]^T$. Because of the precession of the target body, the coordinate transformation from the ontology coordinate system to the reference coordinate system is composed of three parts: the initial transformation matrix, the spinning transformation matrix and the coning transformation matrix. The initial conversion transformation matrix refers to the conversion of the target initial position to the reference coordinate system. As defined by the coordinate system, the reference coordinate system is obtained by the θ angles around the X axis from the initial time ontology coordinate system. The initial transformation matrix can be expressed as follows.

$$R_{\text{int}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix}. \tag{1}$$

At time t, the rotation matrix caused by the cone rotation can be represented as

$$R_c(t) = \exp(\hat{w}\,t). \tag{2}$$

where $\hat{w} = wc\,\hat{e}$ and $\hat{e}$ is the skew symmetric matrix formed by the unit vector $\vec{e}$ of the precession axis. According to the Rodrigues equation, the cone rotation transformation matrix (2) can be simplified as

$$R_c(t) = I + \hat{e}\text{sinwct} + \hat{e}^2(1 - \text{coswct}) = \begin{bmatrix} \cos wct & -\sin wct & 0 \\ \sin wct & \cos wct & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{3}$$

Similar to the coning transformation matrix, the rotation matrix of the target spins about the symmetry axis can be expressed as

$$R_s(t) = I + \hat{u}\sin wrt + \hat{u}^2(1 - \cos wrt). \tag{4}$$

where $\hat{u}$ is the skew symmetric matrix formed by unit direction vector $\vec{u}$ of the spin axis, the spin axis is the target symmetry axis. In the target body coordinate system: $\vec{u} = [0 \quad 0 \quad 1]^T$. Combining (4), the spin transition matrix can be obtained

$$R_s(t) = \begin{bmatrix} \cos wrt & -\sin wrt & 0 \\ \sin wrt & \cos wrt & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{5}$$

Then the position of P in the reference coordinate system is

$$\vec{r}(t) = R_C(t) \bullet R_{init} \bullet R_s(t) \bullet \vec{r}_0. \tag{6}$$

Therefore, the radial distance from the radar to P is

$$\vec{r}(t) = R_0 + [R_C(t) \bullet R_{init} \bullet R_s(t) \bullet \vec{r}_0]^T \bullet \vec{n}. \tag{7}$$

Assuming that the scattering characteristics of the target can be represented by N equivalent scattering centers. Considering that the scattering center is an isotropic echo model, and σ_n is the scattering intensity of the nth scattering center. The fundamental frequency form of the forward target radar echo can be expressed as

$$s(t) = \sum_{n=1}^{N} \sigma_n \exp\left\{ j2\pi f_0 \frac{2r_n(t)}{c} \right\}. \tag{8}$$

According to the definition of m-D, the electron micrograph of the nth scattering center of the precession target is

$$f_{mD}^{n} = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} = 2\frac{f_0}{c}\left[\frac{d}{dt} r_n(t)\right]. \tag{9}$$

3 Precession Parameter Estimation

3.1 Initial Value Estimation of Precession Parameters

It can be seen from the above, the radar baseband echo signal of the precession target is

$$s(t) = \sum_{n=1}^{N} \sigma_n \exp\left\{ j2\pi f_0 \frac{2r_n(t)}{c} \right\}. \tag{10}$$

Then the time-frequency analysis is done with short time Fourier transform (STFT):

$$|S(t,f)| = \sum_{n=1}^{N} |S_n(t,f)|^2 + 2\sum_{a,b=1,a\neq b}^{N} |S_a(t,f)||S_b(t,f)| \cos(Kr_a(t) - Kr_b(t)). \tag{11}$$

$$S_n(t,f) = 2\Delta\tau\sigma_n \exp(-jKr_n(t)) \exp(-j2\pi ft) \sin c\left[2\pi\Delta\tau\left(f - f_{mD}^{n}(t)\right)\right]. \tag{12}$$

where $K = 4\pi f_0/\lambda$, $2\Delta\tau$ is the width of the window function for STFT [6]. According to [7, 8], the instantaneous frequency of the signal is the first-order moments of the time-frequency distribution:

$$f(t) = \frac{\int f|s(t,f)|^2 df}{\int |s(t,f)|^2 df}. \tag{13}$$

$$f(t) = \frac{\int f|s(t,f)|^2 df}{\int |s(t,f)|^2 df} = \frac{1}{|A|^2}\left(4\Delta\tau^2 AA_k^2 \sum_{n=1}^{N} f_{mD}^n(t)\right). \tag{14}$$

The instantaneous frequency of the target is equal to the linear superposition of the m-D frequency of the scattering points of the target. Through the spectral analysis of $f(t)$, we can get wr, wc, $wr + wc$. According to the prior knowledge of the space cone target, there is $wr + wc > wr > wc$, so the initial value of the spinning angular velocity and the coning angular velocity of the target can be determined as $\widehat{wr1}$, $\widehat{wc1}$. At this point, the accuracy of the estimated spinning frequency and coning spin frequency is limited by resolution, and the frequency resolution of the time-frequency plane is

$$\Delta f = 1/T. \tag{15}$$

where T is the accumulation time.

3.2 Optimal Value Estimation of Precession Parameters by Search Method

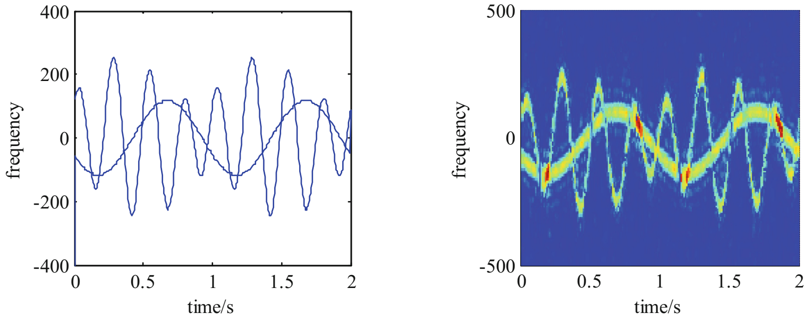
Based on the initial values, radar parameters and the observation time of the target, the maximum estimation error is determined as Δwc and Δwr. Suppose that $\widehat{wc} \in \left[\widehat{wc1} - \Delta wc, \widehat{wc1} + \Delta wc\right]$, $\widehat{wr} \in \left[\widehat{wr1} - \Delta wr, \widehat{wr1} + \Delta wr\right]$, and $\hat{\theta} \in [0, 90°]$. For any point P (*x, y, z*) on the target, the distance of the point and the echo signal can be obtained according to (7) and (8) respectively. Then the mean square error (MSE) of the echo signal and the real echo signal under this search parameters is calculated. When the estimate is consistent with the true value, the MSE reaches the minimum; otherwise, the MSE will increase. Therefore, the optimal estimation parameters can be determined according to the MSE of the estimated value and the true value $\widehat{wr1}$, $\widehat{wc1}$, and θ.

4 Simulations

The simulation circumstance is set up as follows: the radar frequency f_0 = 10 GHz. For the cone target, it is 2 m high, the bottom radius is 0.2 m, the distance between the center of mass and the center of the base is 0.4 m, the spin frequency is 3 Hz, the coning frequency is 1 Hz, and the precession angle θ = 18°. The azimuth angle of the radar line of sight in the reference coordinate system α = 50°, and the mean angle of view v = 270°. The precession parameters of the cone target are estimated by using the cone vertex P1 (0, 0, 1.6 m) and the bottom edge scattering point P2 (0, −0.2 m, −0.4 m). The radar sampling frequency is 1 kHz, the signal accumulation time is 2 s, and the Gaussian white noise is added to the echo, and SNR = 10 dB.

(1) Comparison of the calculated m-D spectra and the m-D spectra obtained by STFT.

The m-D spectrum of the precession target obtained by the simulation in Fig. 2 is basically consistent with the calculated m-D derived by the ideal formula. Thus, the correctness of the precession model can be explained, which lays a good theoretical foundation for the extraction of the following precession parameters.



a) The calculated m-D spectrum

b) The m- D spectrum of the echoes after STFT

Fig. 2. The calculated m-D spectrum

(2) The first-order moment method is used to estimate the instantaneous frequency of signals and to estimate the spinning and coning frequencies by Fourier transform roughly.

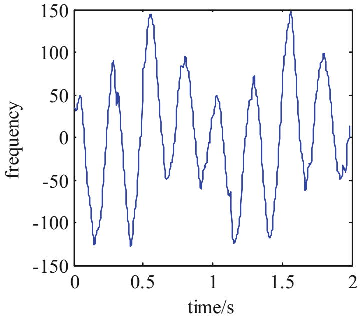


Fig. 3. Estimation of instantaneous frequency

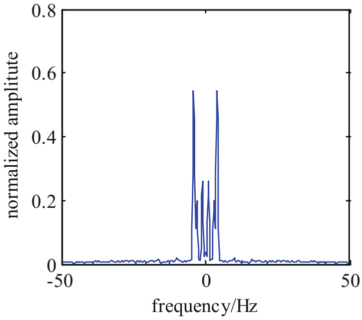


Fig. 4. A rough estimation of spinning frequency and coning frequency

Figure 3 shows the instantaneous frequency of the signals. The three amplitude maximum are selected. The above theory shows that they correspond to the spinning frequency, coning frequency and the sum of the two frequencies respectively. According to a priori knowledge of the spatial cone target, the spinning frequency and the coning frequency is greater than the spinning frequency, and the spinning frequency is greater than the coning frequency. Figure 5 is obtained by partial amplification of Fig. 4. Therefore, the spinning frequency 3 Hz and the coning frequency 1 Hz can be estimated roughly.

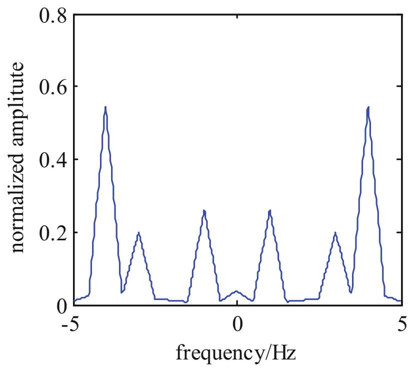


Fig. 5. The amplification of Fig. 4

(3) Accurate estimation of precession parameters by search method.

When the signal accumulation time is 2 s, the frequency estimation error is 0.5 Hz. The spinning frequency is searched in the range of 0.5 to 1.5 Hz based on the above-mentioned rough estimation of the spinning frequency and the coning frequency, and the spinning frequency is searched in the range of 2.5 to 3.5 Hz. The precession is searched in the range of 0–90°. The frequency step is 0.05 Hz, and the precession angle step is 1°.

As can be seen from Figs. 6, 7 and 8, the minimum of the MSE of the estimate and the true values is obtained at the spinning frequency of 3 Hz. Therefore, the spinning frequency of the cone target can be accurately estimated to be 3 Hz, which is exactly

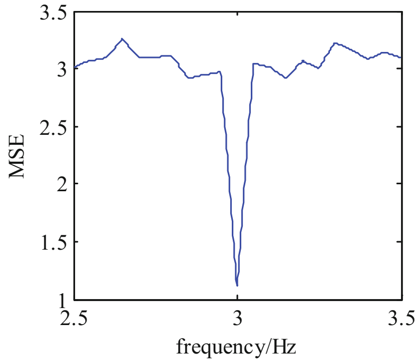


Fig. 6. Estimation of spinning frequency

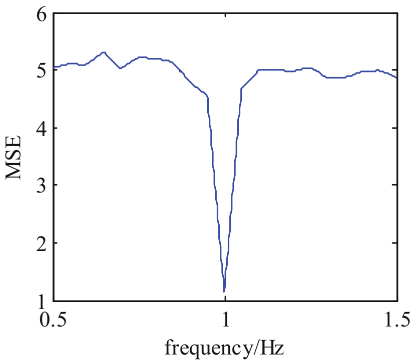


Fig. 7. Estimation of coning frequency

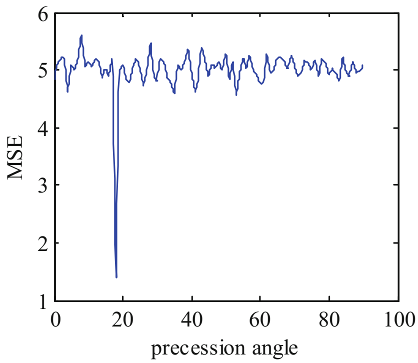


Fig. 8. Estimation of precession angle

the same as the model parameter set. Similarly, the coning frequency and precession angle of the cone target are 1 Hz and 18° respectively.

In general, the spinning frequency, coning frequency and precession angle estimated by the search method are exactly the same as those set in the model. The method provided in this paper can be effectively used in estimating the parameters of precession cone target.

5 Conclusion

In middle section of flight phase, for the common warhead with cone top and cone bottom, only the cone top scattering center and an equivalent scattering center on the cone bottom can be visible. A new method for estimating the precession parameters of a cone target based on the m-D spectrum of two scattering centers is proposed. The specific expressions of the m-D spectrum of the target cone top and the cone bottom scattering center of the precession cone are theoretically analyzed and deduced, and then a new method for estimating the parameters of the target precession is designed. Finally, the validity of the proposed method is verified by the simulation data.

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