A Micro-Motion Information Reconstruction Method Based on Compressed Sensing for Precession Ballistic Targets

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***Abstract*—For a wideband radar system adopting stepped frequency signal (SFS), the micro-motion parameter is usually obtained by time-frequency analysis of the echo HRRPs (high resolution profiles). The data to be collected mainly includes each sub-frequency echo in the slow-time domain, which brings a great burden to the signal generation equipment and data storage on the radar system. Because of the sparseness of the ballistic target scatters in high frequency area, this paper adopts the compressed sensing technique to reduce the sampling data by randomly transmitting the stepped frequency signal. The performance of the proposed method is analyzed by the precession target measurement experiment in the anechoic chamber. The experimental results show that for the nose cone, middle circular ring and bottom circular ring of experimental missile target, when the sampling rate is no less than 50%, 30% and 30% respectively, the reconstruction result is qualified for micro-motion parameter extraction.**

Keywords—Micro-motion; Compressed sensing; Stepped frequency signal;Precession Ballistic targets

I. INTRODUCTION

As a universally acknowledged feature for ballistic targets recognition, the micro-motion parameter measurements and analysis is of great significance [1]. In the microwave anechoic chamber experiments, the stepped frequency signal is usually adopted for wideband radar systems to obtain the HRRPs (high resolution range profiles), then signal processing methods such as time-frequency analysis can be adopted to obtain the micro-motion parameters [2]. The data to be collected mainly includes each sub-frequency echo data and the slow-time sampling data. The data volume is relatively large, which brings a great burden to the signal generation equipment and data storage on the radar system. In addition, if the sampling data is missing partly, the traditional processing method will also be invalid. Recently, compressed sensing theory has been introduced to the radar signal processing, and the ballistic target satisfies the sparse requirement for compressed sensing applications [3]. Currently compressed sensing is widely studied in radar (SAR or ISAR) imaging [4]-[6]. The common processing schedule is that first randomly under-sample the echoes then rebuild the whole imaging data in both range and aspect by sparse recovery. Since the micro-motion information is involved in the HRRP, and HRRP is the range information for ISAR imaging. Thus the similar theory can be applied for micro-motion parameter extraction. Considering the radar system adopting stepped-frequency signal, a series of randomly selected frequencies are transmitted. After obtaining the sparse echo, compressed sensing technique is applied to rebuild the HRRP. By repeating the above transmitting-processing schedule in slow-time domain, the slow time-HRRP spectrum is obtained. Based on this, micro-motion parameters extraction algorithm is used to find out whether the reconstruction HRRPs are effective and test the performance bounder of the proposed method. In actual applications, the algorithm is also applicable for the partly missing sampling data.

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II. THE MICRO-MOTION INFORMATION EXTRACTION FOR PRECESSION BALLISTIC TARGETS WITH TRADITIONAL STEPPED FREQUENCY SIGNAL

Precession is a combined motion of spinning and coning for ballistic target, which provides an effective feature for target recognition. For the precession ballistic target, the micro-motion model is shown in Fig.1. O is the target's center of mass, P is the vertex of the warhead. The ballistic target cones circling OZ axis. OZ is called the precession axis, the included angle of OP and OZ is called the precession angle. f_p is the target's precession frequency, r is the precession radius. According to the scattering properties of ballistic targets, the scattering centers are formed by three parts: the nose cone, the middle ring located in the joint part of the nose cone and the missile body and the bottom ring located in the missile body bottom[2],which are marked in red circles in Fig.1. The micro-motion information such as precession frequency is involved in the echoes modulated by the range change between the radar and these main scattering parts of the precession ballistic target.

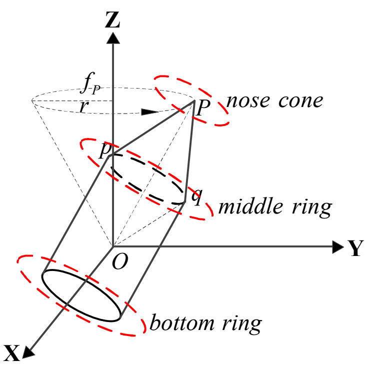

Fig.1. The precession model of ballistic targets

For the wideband radar system, the stepped frequency signal is usually adopted to extract the micro-motion parameter. The pulse train signal is formed by N frequencies, assume the center frequency of the first pulse as f_0, the center frequency of the i th pulse is $f_i = f_0 + \Delta f$, ($i = 0,1,\cdots N-1$) ,where

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Δf is the frequency interval of the adjacent two pulses. The stepped frequency signal can be expressed as

$$s(t)=\sum_{i=0}^{N-1} A_i rect(\frac{t-iT-\tau/2}{\tau})\exp(j2\pi f_i t) \quad 0\le t\le NT \quad (1)$$

Where A_i represents the pulse amplitude, τ is the sub-pulse width, T is the pulse repetition period, t is the time variable, and $rect(\frac{t}{\tau})=\begin{cases}1 & -\tau/2\le t\le \tau/2\\ 0 & otherwise\end{cases}$. Substitute the target distance R_t into (1), after down-conversion and low-filtering, the radar echo can be written as

$$s_r(t)=\sum_{i=0}^{N-1}\sigma_i rect(\frac{t-iT-\tau/2-2R(t)/c}{\tau})\exp(-j2\pi f_i\tau_d(t)) \quad 0\le t\le NT \quad (2)$$

Where σ_i is the echo amplitude, $\tau_d(t)=\frac{2R(t)}{c}$, c is the light speed. During the short transmitting time of a pulse train, the distance change caused by micro-motion can be ignored. Thus the echo time delay can be assumed as $\tau_d(t_m)=2R(t_m)/c$, where t_m is the initial time moment of the mth pulse train in slow-time domain. Sample the echo at time $t_i=iT+\tau_d(t_m)$, and the sampling signal is expressed as

$$s_r(i)=\sigma_i\exp(-j4\pi f_i R(t_m)/\mathrm{c}) \quad (3)$$

Assume $\sigma_i=1$ .Via IFFT to(3), the HRRP of the target can be obtained, written as $H(l,t_m)$.

$$H(l,t_m)=\frac{\sin(-\pi N\Delta f\tau_d(t_m)+\pi l)}{\sin(-\pi\Delta f\tau_d(t_m)+\pi l/N)}\exp(-2j\pi f_0\tau_d(t_m)+j\pi\frac{N-1}{N}(-2N\Delta f\tau_d(t_m)+l)) \quad (4)$$

Then

$$|H(l,t_m)|=\left|\frac{\sin(-\pi N\Delta f\tau_d(t_m)+\pi l)}{\sin(-\pi\Delta f\tau_d(t_m)+\pi l/N)}\right| \quad (5)$$

Where $|\bullet|$ represents the modular operation.

The peak value for (5)can be obtained at

$$l(t_m)=round(N\Delta f\tau_d(t_m)) \quad (6)$$

Where $round(\bullet)$ represents the rounding function.

Considering the three main scattering parts of precession ballistic targets, the peak value position can be written as l_{nc} , l_{mr} and l_{br} for the nose cone, the middle ring and the bottom ring respectively. Substitute them into(4), $H(l_{nc},t_m)$, $H(l_{mr},t_m)$ and $H(l_{br},t_m)$ are obtained. Then by time-frequency analysis, the micro-motion information can be obtained.

III. Micro-motion Information Reconstruction Based on Random Stepped Frequency Signal

In actual applications, vast sub-frequencies are required to realize high-resolution for traditional stepped frequency signal, which give a great burden to the radar transmitters. Hence a random stepped frequency signal can be presented based on compressed sensing theory which reduces the sub-frequency count. This signal contains M （$M<N$） sub-frequencies selected from the traditional stepped frequency signal.

The proposed signal can be expressed as

$$s^{'}(t)=\sum_{i=0}^{N-1}K_i A_i rect(\frac{t-iT-\tau/2}{\tau})\exp(j2\pi f_i t) \quad 0\le t\le NT \quad (7)$$

Where $K_i=\begin{cases}1 & the\ i\,th\,subfrequency is selected\\ 0 & otherwise\end{cases}$.

Transmit the random stepped frequency signal stated above, the sampled echo expressed in matrix form is

$$y=\phi s \quad (8)$$

Where $s=s(t-\tau)$, $\phi=\begin{bmatrix}1&0&0&\cdots&0\\0&0&1&\cdots&0\\0&0&0&\cdots&0\\\cdots&\cdots&\cdots&\cdots&\cdots\\0&0&0&\cdots&1\end{bmatrix}_{M\times N}$ is a $M\times N$ sub-frequency selection matrix, which is randomly selected M rows form the $N\times N$ unit matrix in accord with the value of K_i in (7).

Since the HRRP of the ballistic target is sparse in high frequency area, thus HRRP is the proper sparse signal for compressed sensing theory applications. The HRRP is obtained by IFFT operation of the echo samples, the echo samples can be expressed by the FFT operation of the HRRP.

$$s=\psi H_m \quad (9)$$

Where H_m is a $N\times 1$ matrix, represents target HRRP at t_m .

$$\psi=\begin{bmatrix}1&1&1&\cdots&1\\1&W_N^1&W_N^2&\cdots&W_N^{(N-1)}\\1&W_N^2&W_N^3&\cdots&W_N^{2(N-1)}\\\cdots&\cdots&\cdots&\cdots&\cdots\\1&W_N^{(N-1)}&W_N^{2(N-1)}&\cdots&W_N^{(N-1)(N-1)}\end{bmatrix}_{N\times N},$$

$W_N=\exp(-2\pi j/N)$, is a $N\times N$ FFT matrix.

Thus

$$y=\phi s=\phi\psi H_m=\Phi H_m \quad (10)$$

Where $\Phi=\phi\psi$, and ϕ is a unit selection matrix, ψ is the FFT matrix, thus Φ can be regarded as a matrix randomly selected from an orthogonal basis, which satisfies the RIP requirements for compressed sensing applications.

Consider the signal noise or jamming, then

$$y=\Phi H_m+n_m \quad (11)$$

Where n_m is a $M\times 1$ matrix, represents the noise signal at t_m .

The reconstruction of the HRRP can be obtained by solving the following sparse-recovery problem.

$$\hat{H}_m = \min \ \|H_m\|_0 \quad subject\ to\ \|\Phi H_m - y\|_2 \le \varepsilon \tag{12}$$

Where $\|\bullet\|_0$ represents the l_0 norm, and $\|\bullet\|_2$ represents the l_2 norm, ε is the threshold related to the noise power. For l_0 norm is discontinuous, l_1 norm is introduced to replace l_0 norm, saying $\hat{H}_m = \min \ \|H_m\|_1$. To solve the problem, algorithms such as convex optimization, Matching Pursuit (MP), Orthogonal Matching Pursuit (OMP) and Bayesian Estimation can be applied.

Applying the same processing schedule at different slow time $t_0, t_1 \cdots t_P$,where t_P is the ending observation time. The slow time- HRRP spectrum is obtained.

$$\hat{H} = [\hat{H}_0, \hat{H}_1, \cdots \hat{H}_P] \tag{13}$$

Then extract the peak value of $\hat{H}$, and the corresponding range in the spectrum is $\hat{R} = \arg \ \max(abs(\hat{H}))$. Then time-frequency analysis algorithms can be applied to $\hat{R}$ so as to obtain the micro-motion parameters of the precession ballistic targets.

IV. Microwave Anechoic Chamber Measurement Experiments

In this sub-section, a microwave-chamber experiment is conducted to prove the effectiveness of the proposed method above and analyze the algorithm performance.

A. Experiment system description

The experiment is conducted in the compact microwave anechoic chamber. In microwave anechoic chamber measurements, vector network analyzer (VNA) is used as transmit signal source and the echo processor. It is able to transmit stepped frequency signals, being the key part of the system. Connect the output of the VNA with the receiver and the antenna, and put the antennas on the focus of the collimator reflector, and isolate them by the transmitter-receiver isolation. Fig.2 shows the actual experiment scene.

(a) Front view (b) Back view

Fig.2. Experiment scene of space precession target

B. Experiment result analysis

The experiment on micro-Doppler of space precession target is conducted in the Microwave Lab of National University of Defense Technology. The geometric parameters of the target are shown in Fig.3. In this experiment, the target has no spinning, the precession frequency $f_p = 0.26Hz$.

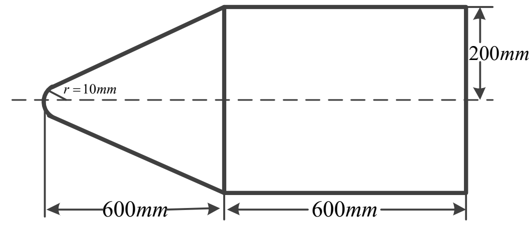


Fig.3. The geometric parameters of the target

Firstly, the traditional stepped frequency signal is simulated. The frequency range in this experiment is 9GHz-10GHz, the bandwidth is 1GHz and the frequency interval is 5MHz. by IFFT transform to the data collected, HRRPs can be obtained for target's current posture. Processing the HRRPs by time-frequency analysis, micro-Doppler of different structures can be obtained. The scattering property is reflected in the time-frequency energy distribution shown in Fig.4.

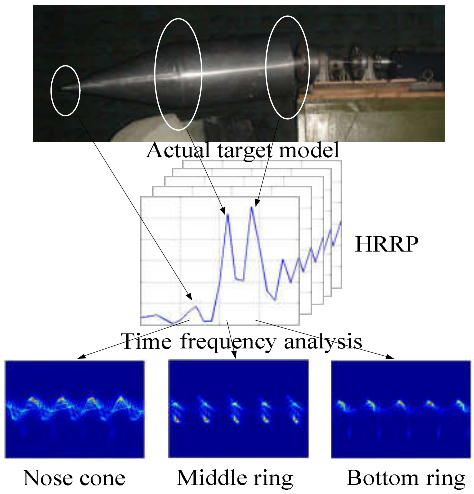
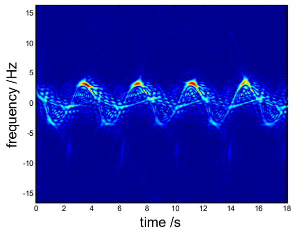


Fig.4. Measurement results analysis

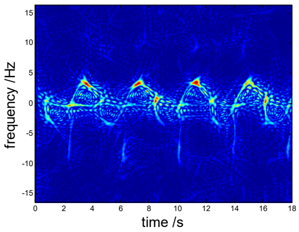
As shown in Fig.4, the time-frequency analysis result is obtained for traditional stepped frequency signal. Then some parameter extraction algorithms such as Hough transform can be applied to obtain the micro-motion parameter. However, it's not the emphasis of this paper, for detailed analysis, see [2]. In this experiment, it's aimed to analyze the performance of random stepped frequency signal. However, the network analyzer is unable to transmit the proposed signal. An equivalent method can be adopted by randomly sampling the echo of the stepped frequency signal in the frequency domain. The time-frequency analysis result of the three main scattering parts for the random stepped frequency signal is shown in Fig.5-Fig.7. Where (a) represents the initial time-frequency analysis result for the stepped frequency signal, (b)(c)(d) represents the time-frequency analysis result for the random stepped frequency signal with different decreasing sampling rates, where the decreasing sampling rates means the ratio of the selected frequency count to the initial frequency count.

(1) The nose cone

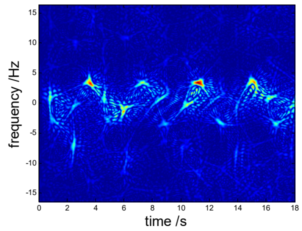
The echo amplitude of the nose cone is relatively weak, and the recovered HRRPs by OMP algorithm are unable to obtain the micro-motion parameters. Thus the convex optimization algorithm of higher reconstruction accuracy but relatively higher time costs is adopted instead. As shown in Fig.5, when the sampling rate is no less than 50%, the reconstruction HRRPs are qualified for micro- motion parameter extraction.



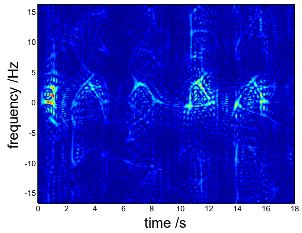
(a)initial time-frequecy analysis result



(b)decreasing sampling rate 70%



(c)decreasing sampling rate 50%

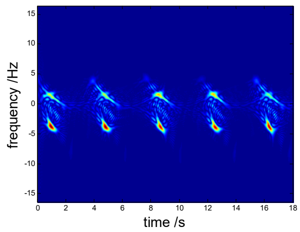


(d)decreasing sampling rate 30%

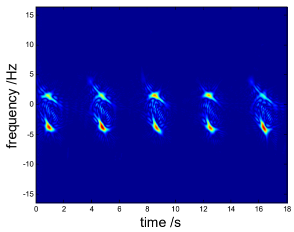
Fig.5. The nose cone

(2) The middle ring

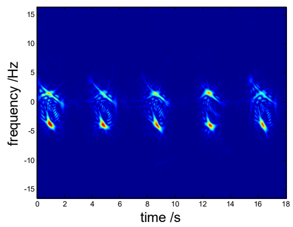
The echo amplitude of the middle ring is relatively strong, and OMP algorithm of less time costs is qualified in this case. From Fig.6, when the decreasing sampling rate is no less than 30%, the reconstruction time-frequency spectrum is qualified for the micro-motion extraction.



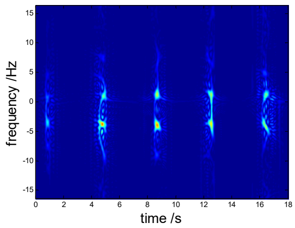
(a)initial time-frequecy analysis result



(b)decreasing sampling rate 50%



（c）decreasing sampling rate 30%

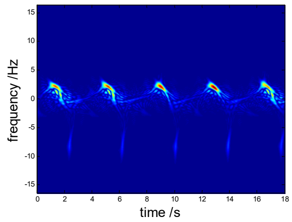


（d）decreasing sampling rate 20%

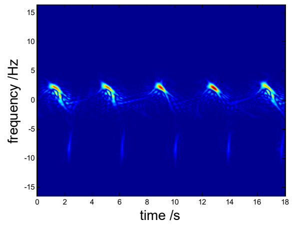
Fig.6. The middle ring

(3) The bottom ring

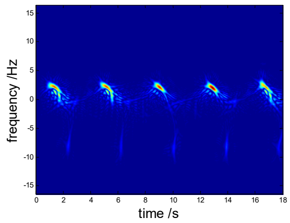
Similar to the middle ring, OMP algorithm can be adopted. As shown in Fig.7, when the decreasing sampling rate is no less than 30%, the reconstruction time-frequency spectrum is qualified for the micro-motion extraction.



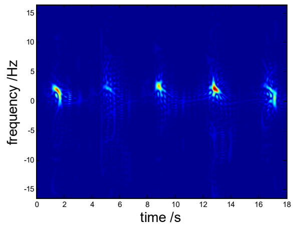
(a)initial time-frequecy analysis result



(b)decreasing sampling rate 50%



(c) decreasing sampling rate 30%



(d) decreasing sampling rate 20%

Fig.7. The bottom ring

From the experiment above, some conclusions can be made.

(1) When the decreasing sampling rate is no less than a certain threshold, the time-frequency analysis result for the random stepped frequency signal is qualified for micro-motion parameter extraction of the ballistic target, which proves the effectiveness of the proposed method.

(2) As the microwave-chamber experiment shows, the reconstruction requirement of the middle ring and the bottom ring is relatively low, when the decreasing sampling rate is only 30%, the reconstruction HRRPs can be used to extract the micro-motion parameters. However, the reconstruction requirement of the nose cone is relatively high, by adopting the better reconstruction algorithm with high time costs sacrifice, a decreasing sampling rate higher than 50% is qualified for the micro-motion extraction. The echo power of the nose cone is relatively weak, which is easily influenced by the measurement noise, thus a higher reconstruction condition is required.

V. Conclusion

In this paper, a micro- motion information reconstruction method based on compressed sensing is proposed instead of the traditional stepped frequency signal for precession ballistic targets. However, a relatively simple analysis of the method is conducted in this paper, for it mainly verifies the feasibility of compressed sensing theory applied in the micro-motion information extraction. A deeper analysis for more indicators of the reconstruction accuracy and micro-motion parameter estimations should be conducted. Moreover, the sub-frequency selection criterion for a more accurate micro-motion information reconstruction remains to be studied in the future.

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