Simulation Method of Semi-Measured Data of Radar Echo

Qiongdan Huang, Ruoyu Pan, Honggang Wang and Biao Li

***Abstract*—Owing to the problems such as the design of radar waveform using traditional method cannot be promptly applied in radar system, and to the difficulty and high cost in acquiring experimental data, we propose a simulation method of semi-measured data of radar echo based on measured echo data of conventional active radar. Specifically, we first design the radar waveform, and then conduct pulse compression and convolution algorithm to obtain the radar echo's semi-measured data combined with the newly designed waveform and measured echo data. Taking chaotic modulation multicarrier phase coded signal as an example, the radar echo's semi-measured data is simulated, and the signal processing and target detection are completed. The proposed method of semi-measured radar echo can overcome the inherent deficit induced by sophisticated mathematical simulation and modeling in generating radar echoes approximating to the real complex environment. In addition, our method provides effective data support for the design, analysis and performance evaluation of radar systems, and is convenient for rapid demonstration and exploration on the advantages of the designed radar waveform.**

***Index Terms*—Radar waveform, Semi-measured simulation, Multicarrier, Target detection**

I. INTRODUCTION

THE survivability and target detection ability of modern radar are affected by complicated battlefield environment involving comprehensive electromagnetic interference, target stealth, as well as low altitude and ultra-low altitude penetration [1-5]. Therefore, the performances of advanced contemporary radar in high resolution, anti-interference and anti-interception [6-7] is of critical necessity.

Performing as an important task of the radar system's front-end design, the waveform design is indispensably related with the aforementioned performances [8-10]. In practical engineering, the radar signals that are designed to meeting certain needs cannot be promptly applied to actual radar systems. The radar signal echoes must be simulated in combination with clutter environment to make the newly designed waveforms signal approaching the real echo signals, thereby verifying the performance of signal processing algorithm during the whole receiving and processing process as well as exploring the advantages of the designed radar signals [11,12].

The traditional simulation of radar echo data is the mathematical modeling based on the characteristics of radar target, clutter and noise, in which certain factors are considered involving the target-related time delay, Doppler shift, propagation attenuation, radar cross-section (RCS) flicker, clutter, noise and interference, etc. [13-15]. However, the actual radar echo reflecting the real detection environment is generally regarded complex, for which reason establishing an accurate mathematical model is not an easy task, not to mention various complex methods of mathematical modeling which require huge amount of calculation. Therefore, it is difficult to generate radar signals close to the real environment.

In this paper, we propose a semi-measured simulation method of radar echo signal based on measured echo data. Combining the designed radar waveform with the measured radar echo data, the designed waveform is integrated into the real radar echo signal to obtain the echo data of the radar signal detecting the actual environment. This kind of semi-measured radar echo provides necessary data support for the design, analysis and performance evaluation of radar system, which is convenient for rapid demonstrating and exploring on the advantages of the designed radar waveform. Meanwhile, our proposed method can effectively solve the engineering application problems of traditional echo simulation in terms of difficult application, huge expenditure, high engineering cost and long research period, etc.

II. DESIGN OF RADAR SIGNAL WAVEFORM

In designing radar waveform, larger signal energy enables higher detection ability, while larger randomness and modulation complexity satisfy the demand of anti-interference and anti-interception [16-18].

To realize higher modulation complexity, the multicarrier phase coded (MCPC) signal performs phase modulation on each subcarrier of the orthogonal frequency division multiplexing (OFDM) signal. Supposing that t_b is the bit duration, ω_n is the weighted number on the n-th carrier frequency in plural form, whose amplitude and phase is $|\omega_n|$

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and θ_n respectively, then we have $\omega_n = |\omega_n| e^{j\theta_n}$. The frequency difference between each subcarrier frequency is denoted as Δf, (Δf=1/t_b), which guarantees the orthogonality between subcarriers [19].

The mathematical expression of MCPC signal with N carrier numbers and M phase modulated bits is given by:

$$f_{\mathrm{MCPC}}(t) = \sum_{n=0}^{N-1} \omega_n s_n(t) \exp(\mathrm{j}2\pi n\Delta f t) \quad (1)$$

where

$$s_n(t) = \sum_{m=0}^{M-1} a_{n,m} r(t - m t_{\mathrm{b}}) . \quad (2)$$

In equation (2),

$$r(t) = \begin{cases} 1, & 0 \le t < t_{\mathrm{b}} \\ 0, & \text{otherwise} \end{cases} . \quad (3)$$

The phase code of the m-th symbol of the n-th subcarrier is $a_{n,m}=e^{j\varphi_{n,m}}$, the structure of MCPC signal is shown in Figure 1.

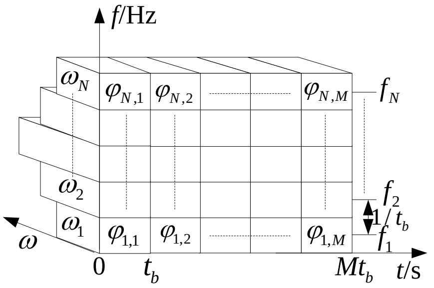

Fig. 1. Schematic diagram showing structure of MCPC signal

The advantages of the orthogonal structure of MCPC signal are that not only will less interference occur between carrier frequencies, but also the frequency resources will be fully utilized, enabling high range resolution of the synthesized large bandwidth. Moreover, the subcarrier phase coding will induce the difference between subcarriers, which increases the flexibility of the designed signal.

We presuppose that the phases $\varphi_{n,m}$ in $a_{n,m}=e^{j\varphi_{n,m}}$ are chaotic biphasic codes, thereby designing the chaos based MCPC signal.

Supposing that c_n (n=1, 2, 3, …) is the chaotic biphasic code set [20], then the relationship between phase $\varphi_{n,m}$ and c_n can be expressed as:

$$\varphi_{n,m} = c_{M(n-1)+m} . \quad (4)$$

The expressions for chaos based MCPC signals can be written as follows:

$$f_{\mathrm{MCPC}}(t) = \sum_{n=0}^{N-1} \omega_n \sum_{m=0}^{M-1} a_{n,m} r(t - m t_b) \exp(\mathrm{j}2\pi n\Delta f t) \quad (5)$$

Sampling the signal $f_{\mathrm{MCPC}}(t)$ ($t=nt_{\mathrm{b}}/N$), and then replacing n in equation (5) with k, we therefore obtain:

$$f_{\mathrm{MCPC}}(n) = \sum_{k=0}^{N-1} w_k \sum_{m=0}^{M-1} a_{k,m} r(n\frac{t_{\mathrm{b}}}{N} - m t_{\mathrm{b}}) \exp(\mathrm{j}2\pi \frac{kn}{N}) . \quad (6)$$

In the above equation,

$$r(n) = R_N(n) = \begin{cases} 1, & n = 0 \sim N-1 \\ 0, & else \end{cases} . \quad (7)$$

we therefore have

$$f_{\mathrm{MCPC}}(n) = N \times \mathrm{IDFT}\left\{ \sum_{m=0}^{M-1} w_k a_{k,m} r(n\frac{t_{\mathrm{b}}}{N} - m t_{\mathrm{b}}) \right\} . \quad (8)$$

It can be seen from the above equation that the chaos based MCPC signal can be realized by conducting fast Fourier transform (FFT).

III. Simulation Method of Semi-Measured Data of Radar Echo

The existing radars active on duty mostly use linear frequency modulation (LFM) signal, which is the most easily obtained measured signal.

The mathematical expression of LFM signals is presented as follows:

$$f_{\mathrm{LFM}}(t) = \frac{1}{\sqrt{T}} \exp\left(\mathrm{j}\pi k t^2\right)\left[u(t) - u(t - t_\tau)\right] , \quad (9)$$

where t_τ is the pulse width, B is the bandwidth, $k=B/t_\tau$ is the slope of frequency modulation, $u(t)$ is the unit step signal. The mathematical expression of the LFM echo signal is:

$$f_r(t) = rect(\frac{t - t_r}{t_\tau}) \quad (10)$$
$$\times \exp[j(2\pi(f_c + f_d)(t - t_r) + \pi k(t - t_r)^2 + 2\pi(m-1) f_d T_r)]$$

where t_r is the echo delay, T_r is the pulse emission period, m denotes the echo of the m-th period, $2\pi(m\text{-}1) f_d T_r$ denotes the compensation of the Doppler frequency at the m-th period.

The radar echo signal can be expressed as:

$$x(t) = s(t) + n(t) + c(t) , \quad (11)$$

where $x(t)$ is the radar echo, $s(t)$ is the target echo, $n(t)$ and $c(t)$ are the noise and clutter, respectively.

In the scenario of detecting the real environment, the radar echo that transmits LFM signal to detect the real environment belongs to the signal form of LFM, regardless it is the echo of target or of clutter. If a signal is newly designed whose performance needs to be evaluated in terms of signal processing and target detection when transmitting the designed signal, the existing measured data echo of LFM signal can be used. Specifically, by removing the LFM information through pulse compression, the newly designed signal can be implanted into the echo data by conducting convolution operations, thus accomplishing the simulation of semi-measured radar echo data. The simulation steps of semi-measured radar echo data are presented as follows.

Step 1. Conduct pulse compression on the measured echo data without target. Supposing that the $h_m(t)$ shown in equation (12) is the pulse response of the matching filter, then the result of pulse compression is the output of the signal $f_{\mathrm{LFM}}(t)$ being processed through the system $h_m(t)$, which is finished by convolution operations.

$$h_{\mathrm{m}}(t) = f^*_{\mathrm{LFM}}(t_0 - t) . \quad (12)$$

The output of $f_{\mathrm{LFM}}(t)$ after pulse compression can be expressed as:

$$h(t) = conv(f_{\mathrm{LFM}}(t), h_{\mathrm{m}}(t)) = \int_{-\infty}^{+\infty} h_{\mathrm{m}}(\tau) f_{\mathrm{LFM}}(t - \tau) \mathrm{d}\tau = \int_{-\infty}^{+\infty} f_{\mathrm{LFM}}(t - \tau) f^*_{\mathrm{LFM}}(t_0 - \tau) \mathrm{d}\tau . \quad (13)$$

The purpose of conducting pulse compression is to effectively trade off radar detection ability with resolution to ensure range resolution of radar. Under the circumstance of no target, the radar echo is a combination of clutter and noise, which is the concrete reflection of the environment it detects.

The result of pulse compression converts the LFM echo signal's wide pulse into narrow ones. The data obtained after pulse compression can be regarded as a radar transmitting narrow pulse to detect the environment, which is equivalent to the echo data obtained by emitting narrow pulse.

Similarly, if the environment detected by the radar is regarded as a system, the echo data after being pulse compressed can therefore be regarded as the system's pulse response excited by narrow pulse. This pulse response contains the delay and amplitude information of the clutter in the environment, which effectively characterizes the detected environment.

Step 2. By convoluting the designed waveform $f_n(t)$ with the pulse compression result $h(t)$, we obtain $f_{\mathrm{n}}^{'}(t)$, which is expressed as

$$f_{\mathrm{n}}^{'}(t)=\int_{-\infty}^{+\infty} f_{\mathrm{n}}(\tau)h(t-\tau)\mathrm{d}\tau \cdot \tag{14}$$

The principle of the above operation is to use the new signal to act upon the environment system $h(t)$. The result of convolution output can be taken regarded as the echo data obtained by using the designed signal to detect the environment.

Step 3. Generate the target echo data $f_t(t)$ based on the newly designed waveform $f_n(t)$, then add the term $f_t(t)$ with the $f_{\mathrm{n}}^{'}(t)$ obtained in Step 2 to obtain the echo data $f_{\mathrm{t}}(t)+f_{\mathrm{n}}^{'}(t)$ that contains the target.

Step 4. Generating the random noise $n_0(t)$, then adding the term $n_0(t)$ with the signal generated by Step 3, we to obtain the semi-measured radar echo data $f_r(t)$, which is expressed as

$$f_r(t)=f_{\mathrm{t}}(t)+f_{\mathrm{n}}^{'}(t)+n_0(t) \cdot \tag{15}$$

IV. Simulation Result

According to the steps presented in Section III, the simulation results of chaos based MCPC semi-measured radar echo and its signal processing procedure are demonstrated as follows.

The transmitting waveform of a radar is LFM signal, whose measured data within an echo period of a frame is shown in Figure 2.

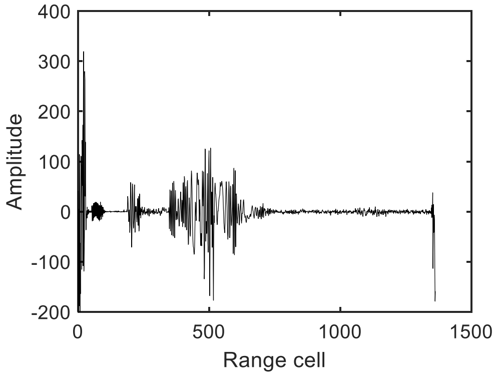

Fig. 2. Measured echo data within one period

Step1. The pulse response of complex environment system is obtained by conducting pulse compression on the echo data, whose result is shown in Figure 3.

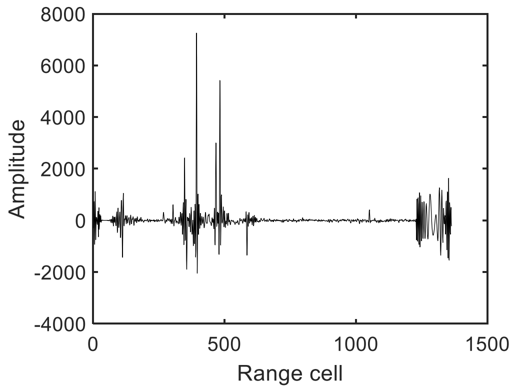

Fig. 3. Pulse compression result of measured echo data

Step 2. Design the chaos based MCPC signal, whose ambiguity diagram is shown in Figure 4. By convoluting the designed radar signal with the pulse compression result $h(t)$ obtained in Step 1, the $f_{\mathrm{n}}^{'}(t)$ is therefore obtained, whose diagram in time-domain is shown in Figure 5.

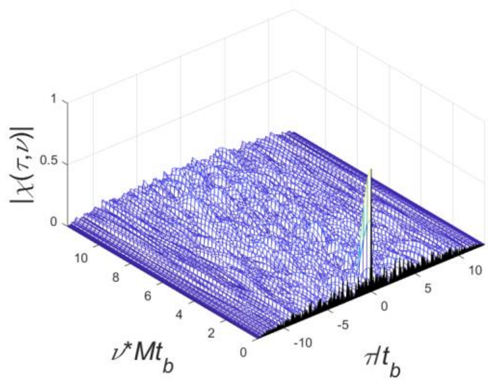

Fig. 4. The ambiguity function of chaos based MCPC

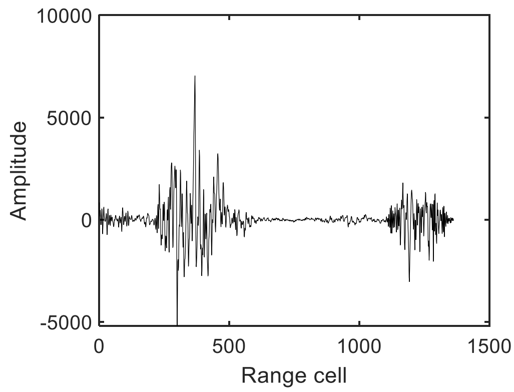

Fig. 5. Semi-measured data of the environment within one period

Step 3. Generate the target echo data based on the designed waveform $f_n(t)$ (i.e., integrate the time shift characterizing the target range with Doppler frequency shift characterizing the target velocity into the designed radar waveform). Then add the generated target data $f_t(t)$ with the semi-measured echo data $f_{\mathrm{n}}^{'}(t)$ of the environment generated in Step 2 to obtain the echo data $f_{\mathrm{t}}(t)+f_{\mathrm{n}}^{'}(t)$ which contains the target. Figure 6 shows the echo data containing the target in 10 periods.

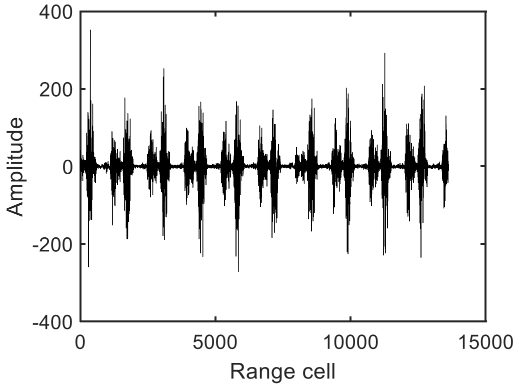

Fig. 6. Semi-measured data of the environment in 10 periods

Step 4. Generate the random noise $n_0(t)$ with -5dB signal-to-noise ratio (SNR), then add it with the signal generated in Step 3 to obtain the semi-measured simulation result $f_r(t)$. $f_r(t)$ in 10 periods, as shown in Figure 7. For baseband echo signal, after conducting pulse compression (shown in Fig. 8), moving target indicator (MTI) (shown in Fig. 9) and moving target detection (MTD) (shown in Fig. 10), the output result of the 24th narrow band filter of MTD is therefore obtained, which is shown in Figure 11. It can be seen from Fig.11 that one target occurs at the range cell of 1050.

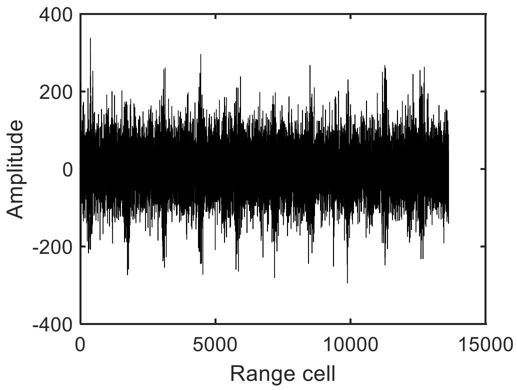

Fig. 7. Semi-measured data with noise and target in 10 periods

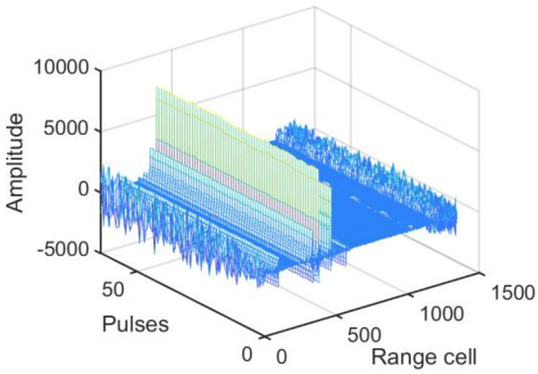

Fig. 8. Pulse compression result

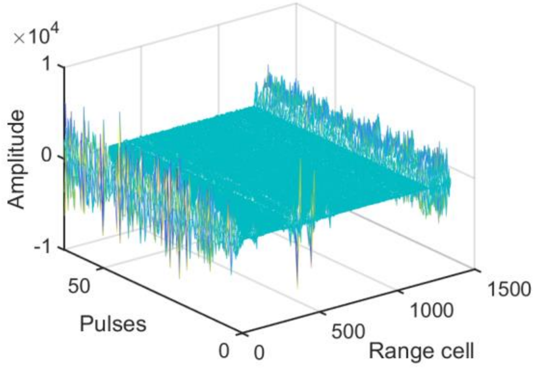

Fig. 9. MTI result

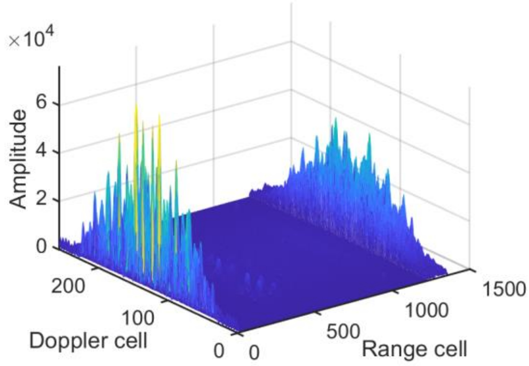

Fig. 10. MTD result

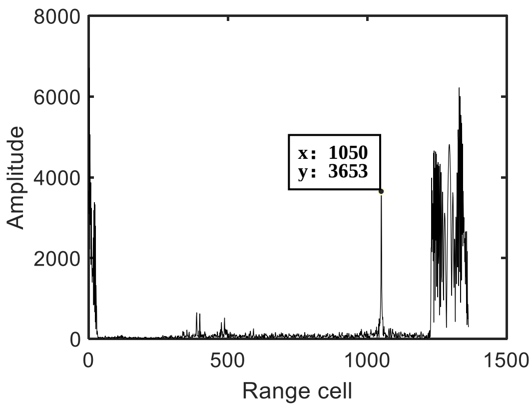

Fig. 11. The 24th narrow band filter output of MTD

Adopting image processing method to detect the MTD results of each frame, the final detection result is shown in Figure 12.

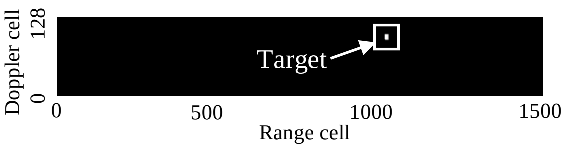

Fig. 12. Detection result

V. Conclusion

In this paper, the designed chaos based MCPC signal is used as an example to verify our proposed simulation method of semi-measured data of radar echo. The echo data generated by the proposed method can embed the designed signal into the measured data of radar echo in a convenient way, which is more realistic and reasonable than using the conventional mathematical modeling methods. The simulation method of semi-measured data of radar echo can easily obtain more real radar echo data when the radar system is not adequately prepared, thereby facilitating the test and evaluation of subsequent radar signal processing. In addition, our simulation method can provide effective data support to the radar systems in terms of early design, analysis and performance evaluation, which helps expedite the research and development process while reducing the engineering cost.

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