A Novel Phase Compensation Method for ISAR Imaging in Wideband Radar

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Abstract: This paper is proposed to eliminate the negative influence of the Rotational Phase Component (RPC) on the performance of the Doppler Centroid Tracking (DCT) phase compensation method. Firstly, the coherent property between adjacent echo pulses sampled directly in Intermediate Frequency (IF) is analyzed in the paper. Then a coherent phase compensation method is developed to improve the Translational Phase Component (TPC) estimation accuracy of DCT. Compared to the Modified DCT (MDCT) algorithm, the proposed method achieves better phase compensation performance. Experimental results prove the effectiveness and efficiency of the proposed strategy.

Key words: Wideband radar; Phase compensation; Direct Intermediate Frequency (IF) sampling; Curve fitting

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宽带雷达 ISAR 成像相位补偿新方法

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摘　要：为了消除目标强散射中心的转动相位分量对传统多普勒中心跟踪(DCT)相位补偿方法性能的影响，该文提出了一种新的相位补偿方法。该方法通过分析得出中频直接采样回波信号脉间相参的特点，并利用相参性改进 DCT 相位补偿方法对平动相位分量估计的精度，从而提高相位补偿效果，改善 ISAR 成像的质量。相对于 MDCT 法，该方法能够达到更好的相位补偿效果。实测数据验证了该方法是一种可行、高效的相位补偿方法。

关键词：宽带雷达；相位补偿；中频直接采样；曲线拟合

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1　Introduction

Inverse Synthetic Aperture Radar (ISAR) can obtain the 2-D images of moving targets (such as aircraft, ship, satellite, *et al.*), and improve the target recognition performance[1]. Generally, ISAR aims at non-cooperative targets, this puts forward high request to motion compensation. The non-cooperative motion of radar target can be decomposed into rotational component and translational component. The rotational component is beneficial to ISAR imaging while the effects of translational component is just the opposite.

Among them, the proceeding of eliminate the influence of translational component on echo envelope is called envelop alignment, and proceeding of eliminate the influence of rotational component on echo phase is called phase compensation. ISAR imaging raises a high demand on the latter. Therefore, improving precision of phase compensation plays an important role in improving the quality of ISAR imaging. Centring on this, domestic and foreign scholars carried out many related researches for a long time and achieved a lot of fruits. All of them can be classified into two kinds: one is parameterization method and the other is non-parameterization method[2]. Among these numerous methods, Doppler Centroid Tracking (DCT) algorithm is adopted widely. DCT algorithm is the optimal one based on maximum likelihood criterion and can reduce the tracking loss

induced by scintillation and obscuring while tracking the whole object instead of whichever scattering point[3]. Also, it has fast calculation speed and is beneficial to real-time imaging. However, the DCT algorithm has poor Translational Phase Component (TPC) estimation accuracy because of the Rotational Phase Component (RPC). The Modified DCT (MDCT) algorithm eliminates the negative influence of the RPC on the estimation accuracy of the TPC by circular shifting, windowing and iteration steps[4]. Generally speaking, we need 8 to 10 times of iteration before obtaining good compensation performance. Consequently, the heavy computation load induced by times of iteration makes the MDCT method hard to be applied in engineering[5].

With the development of Analog-to-Digital Converter (ADC), direct Intermediate Frequency (IF) sampling for wideband radar comes true and is used widely in applications. Compared to STRETCH processing[6,7], direct IF sampling raises a high demand on sampling frequency. But it also brings obvious advantages[8]. One of them is coherent property of echo pulses. Coherent property between echo pulses plays an important role in ISAR imaging[9]. In this paper, we explore improving the translational component estimation accuracy of DCT with simpler operation by adopting the coherent property.

The remainder of this paper is organized as follows. In Section 2, the DCT algorithm is briefly introduced, as well as its limitation. Further, we analysis the coherent property of echo signal sampled directly in IF, and place an emphasis on the novel phase compensation method in Section 3. Experimental verification and conclusions are respectively given in Sections 4 and 5.

2 DCT Algorithm and Its Limitation

DCT algorithm is the embodiment of target centroid tracking method proposed firstly by Prichet[10]. It tracks the target centroid and force the average Doppler to be zero. Its concrete implementation steps can be described as follows: After envelope alignment, calculate the weighted mean of adjacent echoes phase difference complex

exponential function on weighted amplitude. In other words, obtain the Doppler centroid phase difference complex exponential function[4] as follows:

$$\exp\left[j\Delta\zeta(m)\right] = \sum_{n=1}^{N} s_{m,n}^{*} s_{m+1,n} \left/ \left|\sum_{n=1}^{N} s_{m,n}^{*} s_{m+1,n}\right|\right. \quad (1)$$

where $m=1, 2, \cdots$ is the frame serial number, $s_{m,n}$ and $s_{m+1,n}$ are the sub-echoes of range bin n in the adjacent echoes (Frame m and Frame $m+1$), $\Delta\zeta(m)$ stands for the phase difference of adjacent echoes. This is the Doppler phase induced by envelope motion. Obtain the adjacent envelopes phase difference successively and establish Doppler centroid phase difference function. Calibrating the phase of all range bins using this function, we can complete the phase compensation. But the rotational component of target motion may reduce the translational phase estimation accuracy of DCT method. Ref. [4] proposed the MDCT algorithm which solves this problem based on circle shift operation. Unfortunately, the multiple iterations induce heavy computation load[5]. To solve this problem, we improve the estimation accuracy of DCT method by adopting the coherent property of echo pulses.

3 Phase Compensation Method Based on the Coherent Property of Echo Pulses

3.1 Phase property of STRETCH method

It is assumed that the carrier frequency is f_c, T_t is the pulse duration, t is time variable, and γ is the chirp rate. The amplitude of the Linear Frequency Modulation (LFM) signal is set to 1 for the convenience of analyzing. For STRETCH processing, the digital echo signals can be express in frequency domain as[9]:

$$S_{\mathrm{if}}(f_i, n) = T_t \,\mathrm{sinc}\left[T_t\left(f_i + 2\frac{\gamma}{c}R_\Delta\right)\right]\exp(-j4\pi f_c R_\Delta / c)$$
$$\cdot \exp\left[-j4\pi f_i R_\Delta / c\right]\exp(j4\pi\gamma R_\Delta^2 / c^2) \quad (2)$$

where c is the velocity of light, $R_\Delta = R_i - R_{\mathrm{ref}}$, R_i is the distance between the target and radar, and R_{ref} is the reference distance. The second exponential term is Residual Video Phase (RVP) term, and the third exponential term is the envelop "sideling" term when $R_\Delta \neq 0$. This two exponential phase term can be eliminated by phase

compensation at the envelope peak point when $f_i = -2(\gamma/c)R_\Delta$ [9]. The first phase term is the echo pulse phase brought by translational motion:

$$\phi_d = -4\pi f_c R_\Delta / c = -\frac{4\pi}{c} f_c (R_i - R_{\text{ref}}) \qquad (3)$$

As is shown in Eq. (3), the phase of STRETCH processing echo pulse is related to the radial distance R_i and the reference distance R_{ref}. R_{ref} is closely related to the time-delay of the narrowband echo, which is not precise enough. So the phase term in Eq. (3) can not be obtained precisely and finally induced the incoherence of STRETCH processing echo returns. Fig. 1 shows the phase difference curves of adjacent echo pulses in STRETCH processing by using DCT method in a phased array radar. As shown in Fig. 1, the phase difference curve has tough undulation and cannot reflect the motion state of the target. This is due to the coherence destroying in STRETCH processing.

3.2 Coherent property of direct IF sampling

As is known to all, most of modern radars use the phase and frequency information instead of amplitude only for their main function. The radar coherent property plays a more and more important role in the system performance. Coherent radar sets higher requirements on radar frequency source. The frequency and phase stability of frequency source is the precondition of coherence in coherent radar[11]. Based on the coherence mentioned above, we can ensure the coherent property of echo pulses sampling directly in IF by proper design of system parameters.
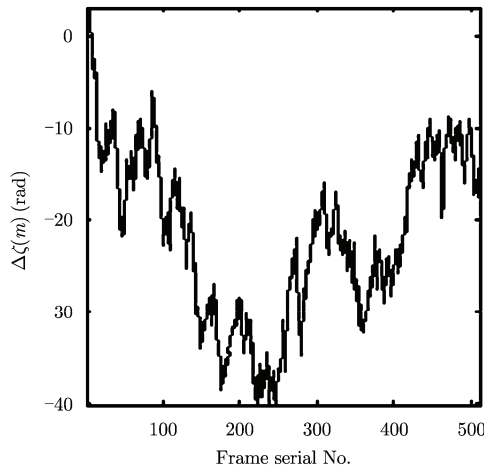

Fig. 1   Phase difference curves of adjacent echo pulses achieving by STRETCH processing

As for the coherent pulse compression radar, in order to keep the coherent property of echo pulses sampled directly in IF, there are some constraints to the sampling frequency. We usually adopt pulse train sampling or pulse sampling in the present existing direct IF sampling systems[12]. Comparatively, pulse train sampling is more suitable for keeping coherence of echo pulses. In Ref. [13], two conditions for keeping coherence in pulsed radar are summarized:

(1) band-pass signal non-aliasing sampling rule

$$\begin{cases} \dfrac{2f_{\text{H}}}{m+1} \le f_s \le \dfrac{2f_{\text{L}}}{m} \\ f_s \ge 2B \end{cases} \qquad (4)$$

where f_s is the direct IF sampling frequency, f_{H} denotes the highest frequency of radar IF echoes, f_{L} the lowest frequency, B represents the bandwidth, and m stand for nonnegative integer;

(2) coherent requirement of adjacent pulses

f_s can be divided exactly by f_r, where f_r is the pulse repetition frequency. It means that $f_s = kf_r$. k is positive integer.

Then we'll proof the coherent property of echo signals sampled directly in IF bellow. The LFM signal used by radar can be expressed as

$$s(t) = \text{rect}\left(\frac{t}{T_t}\right) \exp\left[j2\pi\left(f_c t + \frac{1}{2}\gamma t^2\right)\right] \qquad (5)$$

The echo returns $s_r(t)$ can be written as

$$s_r(t) = \text{rect}\left(\frac{t - 2R_i/c}{T_t}\right) \exp\left\{j2\pi\left[f_c\left(t - \frac{2R_i}{c}\right) + \frac{1}{2}\gamma\left(t - \frac{2R_i}{c}\right)^2\right]\right\} \qquad (6)$$

After mixing process, the echo returns are converted down to IF signal $s_I(t)$, which can be express as

$$s_I(t) = \text{rect}\left(\frac{t - 2R_i/c}{T_t}\right) \exp(-j4\pi f_c R_i/c)$$
$$\cdot \exp\left\{j2\pi\left[f_I t + \frac{1}{2}\gamma(t - 2R_i/c)^2\right]\right\} \qquad (7)$$

where f_I stands for the centre frequency of IF echo signal.

$s_I(t)$ is treated by digital orthogonal demodulation, then we obtain the baseband signal $s_B(t)$

$$s_B(t) = \text{rect}\left(\frac{t - 2R_i/c}{T_t}\right) \exp(-j4\pi f_c R_i/c)$$
$$\cdot \exp\left[j\pi\gamma(t - 2R_i/c)^2\right] \qquad (8)$$

According to the stationary phase principle[14], we obtain the frequency domain expression of $s_{\mathrm{B}}(t)$ from Eq. (8).

$$S_{\mathrm{B}}(\omega) = \frac{1}{\sqrt{\gamma}} \mathrm{rect}\left(\frac{\omega}{2\pi\gamma T_t}\right) \exp\left[j\left(-\frac{\omega^2}{4\pi\gamma} + \frac{\pi}{4}\right)\right]$$
$$\cdot \exp\left(-j\frac{2R_i\omega}{c}\right) \exp\left(-j\frac{4\pi f_{\mathrm{c}}R_i}{c}\right) \tag{9}$$

Then the matched filter of signal expressed by Eq. (9) can be written as

$$H(\omega) = \frac{1}{\sqrt{\gamma}} \mathrm{rect}\left(\frac{\omega}{2\pi\gamma T_t}\right) \exp\left[-j\left(-\frac{\omega^2}{4\pi\gamma} + \frac{\pi}{4}\right)\right] \tag{10}$$

So the output signal of the matched filter can be expressed as

$$\begin{aligned} s_{\mathrm{p}}(t) &= s_{\mathrm{B}}(t) * h(t) \\ &= \frac{1}{2\pi} \int_{-\infty}^{+\infty} S_{\mathrm{B}}(\omega)H(\omega)\exp(j\omega t)\mathrm{d}\omega \\ &= \frac{1}{2\pi\gamma} \exp\left(-j\frac{4\pi f_{\mathrm{c}}R_i}{c}\right) \int_{-\infty}^{+\infty} \mathrm{rect}\left(\frac{\omega}{2\pi\gamma T_t}\right) \\ &\quad \cdot \exp\left(-j\frac{2R_i\omega}{c}\right)\exp(j\omega t)\mathrm{d}\omega \\ &= \frac{T_t}{2} \exp\left(-j\frac{4\pi f_{\mathrm{c}}R_i}{c}\right)\mathrm{sinc}\left[\pi\gamma T_t\left(t - \frac{2R_i}{c}\right)\right] \end{aligned} \tag{11}$$

We can see from Eq. (9) that, the phase of signal after matched filtering is

$$\phi_{\mathrm{d}}^{'} = -4\pi f_{\mathrm{c}}R_i / c \tag{12}$$

In Eq. (12), $\phi_{\mathrm{d}}^{'}$ is related to R_i only, and changes when changes take place in R_i. That means the echo phase keeps strict and stable relationship with transmitted signal phase, so the phase of adjacent echo returns is coherent.

Eq. (11) shows that, for the 1-D range profile of matched filtering after direct IF sampling, phase compensation means to eliminate the exponential term written as $\exp(-4\pi f_{\mathrm{c}}R_i / c)$ which truly reflects the phase variation induced by translational motion of the target. The exponential term's variation between pulses reflects the phase shift induced by target motion. Even though there may be accelerated motion during observation, the phase transformation curve induced by motion should be continuous and smooth because of the inertial. The non-ideal factors such as system distortion and radio propagation path just superimpose little ripple on the smooth curve.

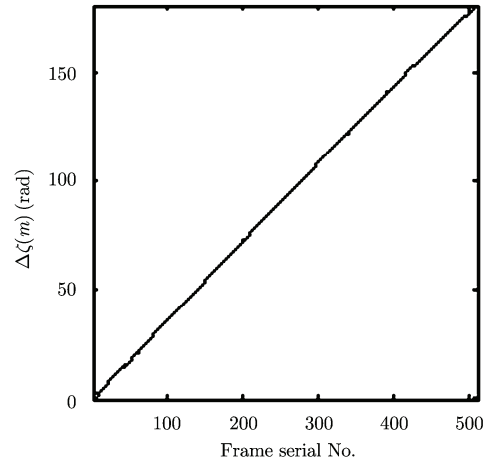Fig. 2 shows that the phase difference curve of

Fig. 2   Phase difference curves of adjacent echo pulses achieving by direct IF sampling

adjacent echo returns sampled directly in IF is continuous and approximate smooth. The little ripple is induced by the non-ideal factors such as system distortion and radio propagation path. Also we can find from the figure that the phase difference has an increasing trend. This indicates the accelerated motion of the target.

3.3 Coherent phase compensation method

Based on the coherent property of direct IF sampling, we can smooth the phase difference curve using the least squares curve fitting method, and eliminate the phase error. Then we achieve the accurate phase difference curve and can improve the phase compensation effect.

The concrete steps of the algorithm are shown bellow:

Step 1   Estimate the Doppler centroid phase difference complex exponential function shown in Eq. (1) using DCT method, so we can obtain the phase difference curve of adjacent echo returns (curve of $\Delta\zeta(m)$);

Step 2   Do the curve fitting using the least squares curve fitting method, then we achieve the accurate phase difference function $\Delta\zeta^{'}(m)$;

Step 3   Reconstruct the phase compensation exponential function $C(m)$ using $\Delta\zeta^{'}(m)$. So $C(m)$ can be express as

$$C(m) = \exp\left(j\sum_{m=1}^{m-1}\Delta\zeta'(m)\right) \tag{13}$$

Step 4   Implement the phase compensation by multiplying the 1-D range profile data with the corresponding $C(m)$.

Seen form the steps above, the algorithm proposed in this paper is on the basis of DCT method, and improves the translational phase estimation accuracy using one-time curve fitting. It resolves the heavy computation load problem in Ref. [4] and is fit for engineering application.

4   Experimental Verification and Analysis

In order to verify the algorithm analyzed above, we compare it with unmodified DCT method and MDCT method in this section. Aircraft echo data sampled by an experimental phased array radar is adopted. Fig. 3 shows the difference between pre- and post curve fitting. This figure indicates that there are errors between the phase estimated by DCT method and that induced by target motion. The difference, which is just the negative influences of the RPC and other system factors on the TPC estimation accuracy, is lies within the scope of ± 0.6 rad. ISAR imaging is processed after phase compensation using the phase difference function achieved by the least squares curve fitting method. It is important to choose a proper polynomial order when using curve fitting in Step 2 of the algorithm. Experimental shows that, in order to reflect the actual phase change induced by motion of the space or air targets as much as possible, the polynomial order should be set to 3.

Fig. 4(a) shows the ISAR image obtained using unmodified DCT method, while Fig. 4(b) are the ISAR image obtained by adopting the MDCT method and Fig. 4(c) via the novel phase compensation algorithm proposed in this paper. It is seen from the figure that, the imaging focus effect of Fig.

4(c) is better than that of Fig. 4(a). So, the method proposed in this paper is effective and feasible.

The performance of phase compensation directly affects the quality of ISAR image which can be quantitatively evaluated by image entropy[15−17]. Therefore, image entropy is adopted for the performance evaluation of phase compensation in this section. With the same other algorithms (such as distortion compensation, envelope alignment, image reconstruction, *et al.*), the better phase compensation performance, the higher image quality and lower image entropy. On the other hand, the worse phase compensation performance, the lower image quality and higher image entropy.

We accomplished the phase compensation for the aircraft echo returns mentioned above by using unmodified DCT method, MDCT algorithm and the strategy proposed in this paper respectively. Then the ISAR image entropies are obtained and shown in Tab. 1.
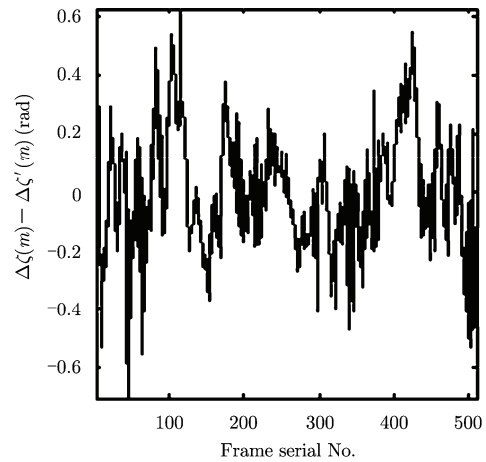

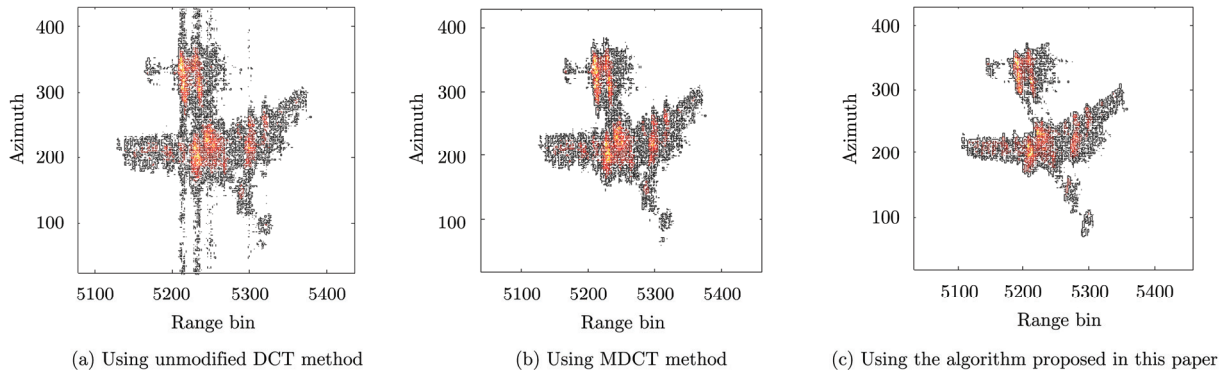Fig. 3   Difference between pre- and post fitting

(a) Using unmodified DCT method   (b) Using MDCT method   (c) Using the algorithm proposed in this paper

Fig. 4   ISAR imaging results of three methods

Tab. 1   Entropies of the three ISAR images obtained by using three phase compensation methods respectively

Phase compensation method	ISAR image entropy
Unmodified DCT method (Fig. 4(a))	8.7392
MDCT method (Fig. 4(b))	8.7174
Method proposed in this paper (Fig. 4(c))	8.6270

As is shown in Tab. 1, the ISAR image obtained by adopting the unmodified DCT method has the highest image entropy, while the ISAR image obtained by using the algorithm proposed in this paper has the lowest entropy. This indicates that the phase compensation method proposed in this paper has the best performance.

In a word, compared with the MDCT method, our method improves the unmodified DCT method and achieves better performance of phase compensation.

5   Conclusion

The coherence plays a more and more important role in radar system performance. Employing the coherent property of echo pulses, we can make better phase compensation in ISAR imaging. In this paper, the coherent property of echo pulses sampled directly in IF is obtained by analyzing, and a novel phase compensation algorithm is proposed to improve the translational phase estimation accuracy in DCT method, and then improve the quality of ISAR image. Experimental results prove the effectiveness and efficiency of the proposed strategy.

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