Inverse synthetic aperture radar imaging method of complex maneuvering target based on instantaneous autocorrelation function – chirp Fourier transform

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Abstract. As the maneuverability of aerial targets increases, in the process of using traditional imaging algorithms to image complex maneuvering targets, the results obtained will inevitably appear defocus and blurring. In order to achieve high-resolution imaging of complex maneuvering targets, the inverse synthetic aperture radar (ISAR) imaging method for complex maneuvering targets based on instantaneous autocorrelation function-chirp Fourier transform (IAF-CFT) is proposed in this work. The method first uses IAF to reduce the order of echo, and then chirp Fourier Transform is used to estimate the echo parameters. Finally, the CLEAN technology is adopted to reconstruct the echo and get the result of ISAR imaging. The simulation results prove the effectiveness of this method.

1. Introduction
Radar imaging technology can break through the influence of time and climate to obtain images of the target of interest, which has important research value. Unlike synthetic aperture radar (SAR) imaging, ISAR imaging cannot accurately learn the movement of the target. In order to overcome this problem, the traditional ISAR imaging theory proposes that translational motion of the target should be compensated firstly. After the translational motion compensation is completed, the target's motion can be described as a classic turntable model. At this time, the RD algorithm can be used to image the target [1]. However, the RD algorithm and the turntable model have obvious limitations, that is, the turntable model believes that the rotation of the target can be approximately regarded as a uniform speed. When maneuverability of the target is poor, this approximation is reasonable, but if the target has strong maneuverability, the target's rotation will no longer be uniform, and for non-uniform rotation models, the RD algorithm is difficult to obtain clear imaging result.

In order to achieve high-quality imaging of non-uniformly rotating targets, relevant scholars improved the echo model, that is to say, the echo of a maneuvering target can be regarded as an LFM signal. Based on this model, a variety of different imaging algorithms have been proposed, including WVD algorithm, RWT algorithm and CPF algorithm [2]. These algorithms all have good performance when maneuverability of the target is not particularly strong. However, with the continuous improvement of target maneuverability, existing maneuvering target imaging algorithms are gradually difficult to achieve better results, and the LFM signal model can no longer accurately describe the target echo. Therefore, the CPS echo model is further proposed [3,4].
In order to realize the ISAR imaging based on the CPS echo model, a complex maneuvering target imaging method based on IAF-CFT is proposed. The method uses IAF to reduce the order of the echo to make it become LFM signal, then CFT is adopted to estimate the chirp rate and quadratic chirp rate of echo, and finally the CLEAN technology is used to reconstruct the echo and image the target. The simulation results prove that this method can achieve high-resolution imaging of complex maneuvering targets.

2. Signal model
Suppose the transmitted signal is the LFM signal:

\[ s(t, t_m) = \text{rect} \left( \frac{t}{T_p} \right) \exp \left[ j 2\pi f_c t \right] \exp \left[ j \pi \mu t^2 \right] \]  

where \( \text{rect} \) represents the rectangular window function, \( t \) is the fast time, \( T_p \) is pulse Width, \( f_c \) is carrier frequency, \( \mu \) is chirp rate of transmitted signal, \( t_m = t + \hat{t} \) is the total time, \( t_m \) is the slow time.

The expression of the echo from a scattering center \( p \) of the target after Dechirp processing can be written as:

\[ s_r(t_r, t_m) = \sigma_p \text{rect} \left( \frac{t_r}{B} \right) \exp \left[ -j \frac{4\pi}{c} (t_r + f_c \Delta R_p(t_m)) \right] \]  

where \( \sigma_p \) is scattering coefficient, \( t_r \) is Redefined fast time. \( \Delta R_p(t_m) \) is The distance from the scattering center \( p \) to the center of the turntable, after the translational motion compensation, it can be expressed as:

\[ \Delta R_p(t_m) = y_p \cos \theta(t_m) + x_p \sin \theta(t_m) \]  

where \( y_p \) and \( x_p \) are the range coordinates and cross range coordinates of \( p \) respectively. For complex maneuvering targets, \( \theta(t_m) \) can be given as:

\[ \theta(t_m) = \omega t_m + \frac{1}{2} \alpha t_m^2 + \frac{1}{6} \beta t_m^3 \]  

where \( \omega \) is rotational velocity, \( \alpha \) is rotational acceleration, \( \beta \) is rotational jerk. Since the angle of rotation in ISAR imaging is small, according to Taylor series, \( \Delta R_p(t_m) \) can be rewritten as:

\[ \Delta R_p(t_m) = y_p + x_p \omega t_m + \frac{1}{2} \left( x_p \alpha + y_p \omega^2 \right) t_m^2 + \frac{1}{6} x_p \beta t_m^3 \]  

After pulse compression and correction of migration through the range cells (MTRC), the echo of a target with \( N \) scattering centers can be expressed as:

\[ s_r(f_r, t_m) = \sum_{p=1}^N \sigma_p \text{sinc} \left( B \left( f_r + \frac{2y_p}{c} \right) \right) \exp \left[ -j \frac{4\pi f_c}{c} \left( x_p \omega t_m + \frac{1}{2} \left( x_p \alpha + y_p \omega^2 \right) t_m^2 + \frac{1}{6} x_p \beta t_m^3 \right) \right] \]  

where \( \text{sinc} \) is the Sinc function.

3. Parameter estimation based on IAF-CFT
For ease of representation, let \( \rho_1 = x_p \omega \), \( \rho_2 = x_p \alpha + y_p \omega^2 \), \( \rho_3 = x_p \beta \). Taking into account that he echo of each scattering center have been focused in their respective range bins after MTRC correction, so \( s_r(\hat{t}, t_m) \) is processed separately by the range bins. Take the echo of one of the range bins to perform IAF, the result can be given as:

\[ r(t_m) = s_r(t_m + \tau_r) \cdot s_r^*(t_m - \tau_r) \]  

\[ = \sum_{p=1}^N \rho_p t_m \exp \left[ -j \frac{4\pi f_c}{c} \left( 2\rho_2 \tau_r t_m + \rho_3 t_m^2 \right) \right] + r_c(t_m) \]
where $r_\tau$ is the delay constant, $^*$ is the conjugate operation, $A_p$ is the amplitude of each component of the echo in the selected range bin, and $r_\tau(t_m)$ is the cross term after IAF processing. Any of its components can be written as:

$$r_\tau(t_m) = \exp \left[ -\frac{4\pi f_c}{c} \left( \rho_1 - \xi_1 + \tau, \rho_2 + \tau, \rho_3 - \tau, 2 \xi_3 \right) t_m \right] \cdot \exp \left[ -\frac{4\pi f_c}{c} \left( \rho_1 - \xi_1 + \tau, \rho_2 + \tau, \rho_3 - \tau, 2 \xi_3 \right) t_m \right] \cdot \exp \left[ -\frac{4\pi f_c}{c} \left( \rho_1 - \xi_1 \right) t_m^2 \right]$$

(8)

where $\xi_1, \xi_2, \xi_3$ are the rotation parameters of another scattering center. It can be seen that after IAF processing, the self-term of echo has been reduced to an LFM signal, and the cross term is still CPS.

Perform CFT$^5$ on the echo processed by IAF, the specific approach is:

$$CFT\left(f_d, \gamma \right) = \int r(t_m) \cdot \exp \left[ -j2\pi \left( f_d t_m + \frac{1}{2} \gamma t_m^2 \right) \right] dt_m$$

(9)

where $f_d$ represents the sampling sequence of frequency domain corresponding to $t_m$ after Fourier transform, and $\gamma$ is the chirp rate, its value range should include all possible values of $\rho_3$.

Incorporating (7) into (9) the result can be obtained as:

$$CFT\left(f_d, \gamma \right) = \sum_{p=1}^{N_c} \sigma_p \delta \left( f_d + \frac{4f_c \rho_2 \tau_c}{c} \right) \delta \left( \gamma + \frac{4f_c \rho_3}{c} \right) + CFT_c \left( f_d, \gamma \right)$$

(10)

where $\delta$ is the Dirac function, $CFT_c \left( f_d, \gamma \right)$ is the result of CFT processing of the cross term. It can be seen that after CFT, each component of the self-term achieves two-dimensional focusing, and the peak position is determined by $\rho_2$ and $\rho_3$. However, due to the cubic phase, the cross term cannot be focused.

4. Complex maneuvering target imaging based on IAF-CFT

According to the analysis in the previous section, the process of the complex maneuvering target ISAR imaging method based on IAF-CFT can be given as follow.

Step 1: Perform translational motion compensation and correction of MTRC for the echo.

Step 2: Select the echo of a certain range bin and calculate its IAF.

Step 3: Use CFT to estimate the parameters of the strongest scattering center of the range bin:

$$\left\{ f_{\text{do}}, \gamma_m \right\} = \arg\max \left[ CFT\left(f_d, \gamma \right) \right]$$

(11)

$$\hat{\rho}_2 = -\frac{c f_{\text{do}}}{4 f_c \tau_c}, \quad \hat{\rho}_3 = -\frac{c \gamma_m}{4 f_c}$$

(12)

where $f_{\text{do}}$ and $\gamma_m$ is the coordinate of peak after CFT.

Step 4: Use the above estimated parameters to estimate the $\rho_1$ of the strongest scattering center:

$$\phi(t_m) = \exp \left[ j\frac{4\pi f_c}{c} \left( \frac{1}{2} \hat{\rho}_2 t_m^2 + \frac{1}{6} \hat{\rho}_3 t_m^3 \right) \right]$$

$$\left\{ f_m \right\} = \arg\max \left[ \text{FT}_c \left[ s(t_m) \cdot \phi(t_m) \right] \right]$$

(13)

(14)

$$\hat{\rho}_1 = -\frac{c f_m}{2 f_c}$$

(15)

where $f_m$ is the coordinate of maximum of (14).

Step 5: Use the least square method to calculate the amplitude of the echo of the strongest scattering center:

$$\hat{\sigma}_p = (\Phi^H \Phi)^{-1} \Phi^H s$$

(16)
\[ \Phi = \exp \left( -j \frac{4\pi f_c}{c} \left( \hat{\rho}_n t_n + \frac{1}{2} \hat{\rho}_n^2 t_n^2 + \frac{1}{6} \hat{\rho}_n^3 t_n^3 \right) \right) \]  

Step 6: Reconstruct the echo according to above parameters:
\[ s_n(t_r,t_m) = \hat{\sigma}_p \text{rect} \left( \frac{t_r}{B} \right) \exp \left( -j \frac{4\pi f_c}{c} \hat{\rho}_n t_n \right) \exp \left( -j \frac{4\pi t_r}{c} \hat{\gamma}_p \right) \]

where \( \hat{\gamma}_p \) is determined by the \( f_r \) of the selected range bin, it can be given as: \( \hat{\gamma}_p = \frac{c f_r}{2} \).

Step 7: Eliminate the reconstructed scattering center echo from the total echo:
\[ s_{\omega}(t_r,t_m) = \hat{\sigma}_p \text{rect} \left( \frac{t_r}{B} \right) \exp \left( -j \frac{4\pi f_c}{c} (f_r + t_r) \right) \left( \hat{\rho}_n t_n + \frac{1}{2} \hat{\rho}_n^2 t_n^2 + \frac{1}{6} \hat{\rho}_n^3 t_n^3 \right) \]
\[ s_r(t_r,t_m) = s_{\omega}(t_r,t_m) - s_{\omega}(t_r,t_m) \]

Step 8: Repeat steps 3 - 7 until the total energy of the range bin is less than 5% of the initial energy.

Step 9: After processing steps 2 - 8 for all range bins, perform two-dimensional Fourier transform on the reconstructed signal to achieve ISAR imaging:
\[ S_{\text{img}}(f_r,f_{\omega}) = \text{FT}_r \left[ \text{FT}_n \left[ s_r(t_r,t_m) \right] \right] \]

5. Verify with simulation
The proposed method is verified by a simulated aircraft. The simulated target has 330 scattering points, and its specific shape is shown in figure 1:

![Fig. 1 Simulated target](image)
It can be seen that the results obtained by the RD algorithm is obviously defocused, which proves that the maneuvering of the target will seriously reduce the performance of the traditional imaging algorithm. Although the result obtained by the SPWVD algorithm improves the imaging quality to a certain extent, there is still a blur between some scattering centers.

The proposed method is used to image the simulated target and the result is shown in figure 3:

It can be found that compared with traditional methods, the proposed method can obtain clearer ISAR imaging results of complex maneuvering targets.

6. Conclusion
In this work, an ISAR imaging method for complex maneuvering targets based on IAF-CFT is proposed. This method firstly reduces the order of CPS through IAF, then CFT is adopted to estimate the rotation parameters, and finally CLEAN technology is combined to reconstruct the echo and image the target. The simulation results prove that the proposed method is superior to traditional methods.

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