Laser Radar Range-Doppler Imaging and Simulation on High-speed Target

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Abstract. On the basis of the representation of the principle of Doppler imaging, an echo model of high-speed target illuminated by broadband linear frequency modulated (LFM) signal was established in this paper. For high-speed target, because of its nonlinear echo phase and time-varying Doppler frequency shift, the Doppler spectrum of the target acquired by the traditional Fourier method was ambiguous, and the same in the radar images of the target. Therefore, an adaptive Wigner-Ville time-frequency analysis method was presented in the paper, that is, the local fuzzy function could be obtained by applying the two-dimensional adding window Fourier Transform to signal’s Wigner-Ville distribution, which made the kernel function, not only be adaptive to time, but also to the frequency. Finally, the simulation results show that the method has a good time-frequency concentration, and effectively control the cross-term interference.

1. Introduction

In missile defense system, the detection and recognition of high-speed missile target is one of the main research work. Through conducting accurate imaging on the target, features like size and motion parameters of the target can be obtained, then, these high resolution features can be used in the recognition of the target. In radar imaging field\cite{1}, the laser range-doppler imaging radar is a rapidly developing high and new technology, which is being extensively applied in the field of aerospace and military applications. At present, laser high resolution and range-doppler imaging system can measure the distance and set direction of the target by using the laser scattering features, and identify the target through the target location, radial velocity and reflection characteristics of objects. That range-doppler algorithm (RDA)\cite{2-3} is a kind of algorithm to obtain the high resolution of longitudinal separation by broadband signals, and acquire the across high resolution by echo doppler bandwidth. When targets fly in high-speed maneuver flight, the echo of doppler frequency is time-varying during the observation, which is why we will get an ambiguous image if we use the traditional Fourier method to make observation on the targets. To conduct spectrum analysis on maneuvering targets, the method of time-frequency analysis not only can eliminate the fuzzy, but also can get target-instantaneous doppler imaging, which plays an important role in determining the flight attitude of the maneuvering target during observation. Therefore, the method has a great development potential.
2. Imaging principle of range-doppler

Laser range-doppler imaging is a kind of method to acquire the features of the locomotive information of targets, mainly based on the Doppler Effect resulted from the relative motion between radar and targets. The basic method of image is the range-doppler method, the longitudinal range resolution relies on broadband signals and the across resolution relies on doppler frequency of the echo\[^{4-5}\]. Range-doppler imaging diagram is shown in figure.1

![Range-doppler imaging diagram](image)

**Figure. 1** Range-doppler imaging diagram

3. Echo model of high-speed moving target

Laser radar broadband chirp signal can be expressed as the following \[^{6-7}\]:

\[
S(\hat{t}, t_m) = \text{rect}(\frac{\hat{t}}{T_p}) \exp \left[ j2\pi(f_c + \frac{1}{2}k\hat{t}^2) \right]
\]  

(1)

where \(\text{rect}(u)\) represents rectangular pulse; \(f_c\) center frequency; \(T_p\) the pulse width; \(k\) frequency modulation ratio of launch signal. Launch time \(t_m = mT\) represents slow time, \(\hat{t} = t - mT\) represents fast time.

The distance of some point target to the radar is \(R_n(\hat{t})\). Then, the echo signal of radar receiver can be expressed as follows:

\[
S_r(\hat{t}, t_m) = A\text{rect}(\frac{\hat{t} - 2R_n(\hat{t})/c}{T_p}) \exp \left[ j2\pi(f_c(t - \frac{R_n(\hat{t})}{c}) + \frac{1}{2}k(\hat{t} - \frac{2R_n(\hat{t})}{c})^2) \right]
\]

(2)

where \(A\) represents scattering intensity.

Through dechirp, the echo of target scattering point can be expressed as follows:
where $R_{ref}$ represents reference distance;

$$\phi_n (\hat{t}) = k\hat{t}(R_n (\hat{t}) - R_{ref}) + f_c (R_n (\hat{t}) - R_{ref}) - \frac{k}{c}[R_n^2(\hat{t}) - R_{ref}^2]$$

Assuming that target velocity is $V$, $R_n(\hat{t}) = R_{n0} + \hat{V}t$, here $R_{n0}$ represents the distance of the scattering point to radar at the starting time. Introducing into Eq.(3), the precise model of high-speed moving target can be got:

$$S'_y (\hat{t}, t_m) = S_y (\hat{t}, t_m) \exp\left[ - j2\pi \left( \frac{2f_c}{c} - \frac{4kR_{m0}}{c^2} \right)\hat{V}t \right] \exp\left[ - j2\pi \left( \frac{2kV}{c} - \frac{2kV}{c^2} \right)\hat{t}^2 \right]$$

Eq.(4) is shown that the last two phase will make range imaging to produce displacement and stretch, which will effect feature extraction of target structure.

The signal distribution of radar transmission and reception in time-frequency is shown in figure.2.

Figure.2 illustrates that in pulse duration position, the static or low target scattering point relative to the radar is unchanged. For a stationary point, after a delay of $2R/c$, the time-frequency curve of its echo signal is parallel to the time-frequency curve of radar launch signal. If this scattering point is in high-speed motion, in pulse duration position, because of the constant change of the position of the target, the echo signal delay and the slope of time-frequency curve will change greatly.

4. Time-frequency adaptive method

The time-frequency adaptive optimal kernel (TFAOK) time-frequency representation (TFR) regards Wigner-Ville distribution of signal as a two-dimensional signal, and every bit in the time-frequency plane optimizes its kernel function, which makes the kernel functions have adaptive characteristics in the time-frequency plane. The method of time frequency domain adding window can gain partial ambiguity function, and this local characteristic is able to restrain the cross-term interference. TFAOK TFR has a good cross inhibitory ability.

Wigner-Ville distribution is Fourier transform of the time-varying autocorrelation. It can be expressed as follows:
The fuzzy function of signal is expressed as follows:

$$WVD(t, f) = \int s'_f \left( t + \frac{\tau}{2} \right) s'_f \left( t - \frac{\tau}{2} \right) e^{-j2\pi ft} d\tau$$  \hspace{1cm} (5)$$

The fuzzy function of signal is expressed as follows:

$$AF(\theta, \tau) = \int s'_f \left( t + \frac{\tau}{2} \right) s'_f \left( t - \frac{\tau}{2} \right) e^{-j\theta} dt$$  \hspace{1cm} (6)$$

Reference to the thought of adding window Fourier transform, this paper put forward that, for Wigner-Ville distribution, the method of the two-dimensional adding Window Fourier Transform could make the fuzzy function have time characteristic and frequency local characteristic, and could define local ambiguity function. The fuzzy function with the characteristic of time-frequency localization can be expressed as follows:

$$AF(\theta, \tau, t, f) = \iint WVD(u, v) \cdot A(u - t, v - f) e^{-j\theta t + j\tau f} dudv$$  \hspace{1cm} (7)$$

Variables $t$ and $f$ give the center of two-dimensional window function. Wigner-Ville distribution and window function can be multiplied, which can limit integral area in the neighborhood of $\omega$ and $t$. Thus, TFAOK TFR is expressed as follows:

$$p(t, f) = \iint AF(\theta, \tau, t, f) \phi_{opt}(\theta, \tau; t, f, s) e^{j\alpha - j2\pi ft} d\theta d\tau$$  \hspace{1cm} (8)$$

Where $\phi_{opt} = \max_{\phi} \iint |AF(\theta, \tau)\phi(\theta, \tau, t, f, s)|^2 d\theta d\tau$

5. The simulation analysis

This paper verified the correctness of the above analysis with simulation data, and got a clear 2-D image of the target. The following are the selected simulation:

the distance between radar and target is $R_0 = 20km$; the speed of the target is $v = 10km/s$; the bandwidth is $B = 800MHz$; the pulse width is $T_p = 100\mu s$; and the pulse sampling rate is $f_s = 100MHz$.

Assuming that the target model is an aircraft shape model consisting of 12 scattering points, and the scattering intensity are unitary to 1.

![Fig.3 The range imaging of traditional method](image-url)
6. Conclusion
This paper mainly makes a study on the range-doppler imaging of LFM signal of laser radar. For high-speed target, because of its nonlinear echo phase and time-varying Doppler frequency shift, the Doppler spectrum of the target acquired by the traditional Fourier method was ambiguous, and the same in the radar images of the target. Therefore, this paper puts forward a new solution to the problem with the thought of speed supplement. In the consideration of the characteristics of the target in high-speed motion, the adaptive Wigner-Ville time-frequency analysis method can be used to eliminate fuzzy and coke caused by the high-speed radial motion. Finally, the simulation results show that this method has good time-frequency aggregation, and can effectively control the cross-term interference, and extract doppler spectrum characteristics and frequency spectrum characteristics from radar echo as well. The method not only can overcome the image blurring and the limit of the Doppler being constant in the traditional high speed target imaging, but also can get a clearer image, so as to provide new evidences for target identification.

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