Time-frequency characteristics based motion estimation and imaging for high speed spinning targets via narrowband waveforms

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Abstract This paper focuses on the motion parameters estimation and inversed synthetic aperture radar (ISAR) imaging for the high-speed spinning targets via the time-frequency characteristics. Assuming that the translational motion is compensated with the available motion compensation techniques, then the residual part of translational motion and the spinning motion are estimated with high precision based on the time-frequency characteristics. Combining with the procedure of the motion estimation, a novel coherent time-frequency spectrum intensity redistribution method, coherent single range Doppler interferometry (CSRDI), is proposed, which provides higher resolution and sustain lower signal to noise rate (SNR) than the current approach. Numerical simulation confirms the validity and high precision of the proposed approaches.

Keywords ISAR, time-frequency characteristics, CSRDI, motion estimation, high speed spinning targets

1 Introduction

It usually occurs that a flying target or some parts on a target are rotating along with the bulk translational motion, such as space debris, flying missiles, airscrews of airplane and so on. This rotating motion introduces additional time-varying Doppler modulation on the echoes. For these targets, conventional ISAR imaging approaches are invalid due to the violation of the rigid body assumption. However, spinning targets detection and imaging is essential to some special applications, such as missile defense, targets classification and recognition, etc. Based on the assumption that the translational motion can be completely removed and the spinning angular velocity is estimated via autocorrelation precisely, a few methods for spinning targets imaging have been proposed. In the case of wideband signal transmitted, the profile after range compression is in a sine form. Using curve estimation techniques to detect these sine profiles, the target’s geometric parameters can be extracted. The general Radon transform (GRT) [1] and extended Hough transform (EHT) [2] are successfully applied to build spinning targets three-dimensional (3D) image. Both of them, however, suffer from the high computational load because the curve parameters are searched in a four-dimensional space. Another shortcoming of wideband imaging approaches is

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the sensitivity to translational motions, which may distort the sine profiles seriously. Actually, the spinning motion modulates not only the range profile but also the azimuth phase distribution of the returned signal. If a narrow-band waveform is transmitted, the range profile is still within a single range cell after translational motion compensation. Single range matched filtering (SRMF) [3] utilizes a matched filtering bank to focus the signal. It is efficient since the matched filtering processing is implemented by fast Fourier transform (FFT). However, the imagery focal is spatially variant and noise sensitive. Single range Doppler interferometry (SRDI) [4] algorithm makes use of the magnitude distribution of the time-frequency spectrogram to estimate the shape of spinning debris. Using an integral along the sine curves, two-dimensional (2D) image is reconstructed. However, SRDI is low in resolution and invalid in the case of low SNR, because it is an un-coherent integral and time-frequency spectrums of different scattering centers affects the focal seriously. Contrasting to the wideband waveform, the narrowband signal owns many advantages in signal to noise ratio (SNR), estimation performance and observing distance. For conventional targets imaging, there are available some motion compensation methods [5–7]. However, the high-speed spinning targets are usually along with high-speed translational motion and very maneuvering. The residual translational motion after conventional motion compensation usually is non-negligible. Residual translational motion should be compensated precisely, which may significantly distort both the sine profiles and the time-frequency distribution. Thus precise estimation of the translational motion is required for fully focusing imagery.

In this paper we focus on the precise translational motion estimation and 2D imaging for the high-speed spinning targets via narrowband waveforms. Suppose that the raw compensation removes most of the translational motion. However the residual part still significantly modulates the time-frequency spectrum of the returns, the assumption in the current algorithms fails. The 2D autocorrelation function in the time-frequency domain is utilized to estimate the spinning period and residual acceleration with high precision. Furthermore, the coherent single range Doppler interferometry (CSRDI) algorithm is presented in detail. It utilizes a coherent integral to redistribute the spectrogram in the time-frequency domain. CSRDI provides higher resolution than SRDI does, also it is more robust with low SNR. In the proposed formation the residue translational acceleration and spinning period are estimated from the time-frequency autocorrelation function, and the 2D image is obtained by CSRDI together with velocity compensation using the focal entropy. The paper is organized as follows. We first present the high-speed spinning turntable signal model with residual translational motion. Then we present detailed mathematical derivation of the residual acceleration and spinning rate estimation via the 2D time-frequency autocorrelation spectrogram. The CSRDI algorithm is presented in detail, whose performance is analyzed by comparing with SRDI. Simulation is provided with some conclusions drawn at last.

2 Signal model

A high-speed spinning 2D turntable model is shown in Figure 1. The residual translational velocity and acceleration are assumed to be \( v \) and \( a \) respectively. The target center is set to be the origin and the change of line of sight (LOS) angle is assumed to be neglectable compared with the spinning motion during the short coherent processing interval (CPI). The rotating speed is denoted by \( \omega_s \). The instantaneous range of a scatterer at \((R_i \cos \theta_i, R_i \sin \theta_i)\) is given by

\[
R(\tau_m) = R_0 + v \tau_m + \frac{\tau_m^2}{2} + R_i \sin(\theta_i + \omega_s \tau_m),
\]

(1)

where \( R_0 \) is the constant part and \( \tau_m \) is the sampling time (slow time). Supposing that a narrow-band signal with a bandwidth \( B_c \) and carrier frequency \( f_c \) is transmitted, the echo can be written after the downconversion to the baseband as follows:

\[
s_i(K_r, \tau_m) = A_i \cdot \exp[-jK_r R(\tau_m)],
\]

(2)

where \( A_i \) represents the reflection coefficient, \( K_r \in [K_{rc} + \frac{2\pi B_c}{c}, \frac{2\pi B_c}{c}] \) represents the wavenumber range, \( w(K_r) = \text{rect}\left(\frac{(K_r - K_{rc})c}{2\pi B_c}\right) \) is the corresponding window function, \( K_{rc} = \frac{4\pi f_c}{c} \) is the wavenumber center.