Defence Science Journal, Vol. 63, No. 5, September 2013, pp. 521-523, DOI : 10.14429/dsj.63.4087

SHORT COMMUNICATION

Inverse Synthetic Aperture Radar Imaging for Micro-motion Target with Rotating Parts

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ABSTRACT

This paper establishes imaging model for rigid body micro-motion target with rotating parts, and derives the formulas of micro-Doppler induced by target with rotation. To obtain well-focused inverse synthetic aperture radar image of rigid body micro-motion target with rotating parts, low frequency filter algorithm is presented to separate the echoes of the rigid body from that of the micro-motion parts. The results of measured data confirm the effectiveness of the proposed method.

Keywords: Micro-Doppler, low frequency filter, inverse synthetic aperture radar image

1. INTRODUCTION

Micro-Doppler (MD) effect has received intensive interest for radar target identification in recent years, since it is regarded as a unique signature of the target and provides additional information that is complementary to the existing methods[1]. However, the existence of MD could also contaminate inverse synthetic aperture radar (ISAR) image due to the interference from the micro-motion parts, which represents interferential strip across Doppler direction[2]. Therefore, micro-motion signatures must be extracted and separated from the original returned signals to achieve well-focused ISAR image. Several micro-motion feature extraction and separation algorithms have been proposed[3-6]. High-resolution joint time-frequency algorithm incorporated with order statistics is developed for micro-motion feature extraction[3]. A method for separation of MD effect from the radar image based on chirplet transform is proposed[4]. The image processing algorithms such as Hough and extended Hough transform are introduced for separation of micro-motion features[5,6]. An algorithm utilizing the complex-value empirical mode decomposition to separate the echo of the unsymmetrical appendix parts from the main body is proposed[7]. However, these methods cannot overcome the intrinsic disadvantage of high computational load.

In this paper, we present a method for separating micro-motion parts caused signal from the signal caused by rigid body via low frequency filter algorithm. Based on the diversity of micro-motion parts and rigid parts on time-frequency plane, MD signatures can be extracted and wiped off from the original returned signals. Thus, well-focused ISAR image for rigid body by Range-Doppler (RD) algorithm is obtained, which avoids a high computational requirement.

2. PROBLEM FORMULATION

The point scattering model is usually applied in simplifying the analysis while preserving MD signatures. Without loss of generality, the imaging geometry of radar and a micro-motion target with a rotating scatterer is depicted in Fig. 1, where translational motion has been compensated[2]. According to Fig. 1, XOY denotes the imaging plane, and scatterers P and Q are corresponding to the rotating scatterer and rigid scatterer, respectively. Scatterer P rotates around O' with a constant angular velocity ω_P, rotation radii r_P and initial phase θ_P while scatterer Q rotates around imaging center O with a constant angular velocity ω_0, rotation radii R_Q and initial phase θ_Q. The dashed lines denote the imaging geometry when the target rotates a small angle.

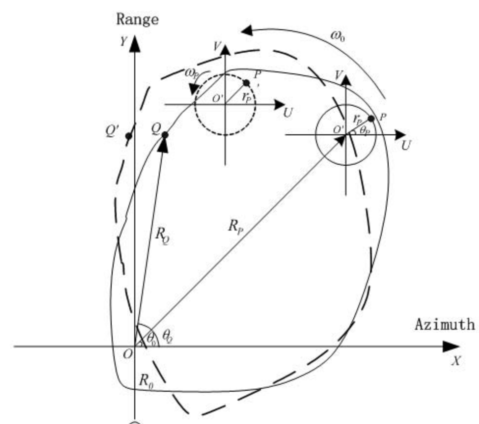

Figure 1. Imaging geometry of radar and a micro-motion target with a rotating scatterer

Suppose that radar transmits linear frequency modulated (LFM) signal, then the returned radar signal after stretch processing and fast-time-domain compression is expressed as:

$$s_c\left(r,t_m\right)=\sum_{i=1}^{K}\sigma_i T_1 \operatorname{sinc}\left\{\frac{2\pi B}{c}\left[r+R_{\Delta i}\left(t_m\right)\right]\right\}\exp\left[-\mathrm{j}\frac{4\pi}{c}f_0 R_{\Delta i}\left(t_m\right)\right] \tag{1}$$

Received 13 March 2013, revised 14 May 2013, online published 25 September 2013

where i is the scatterer index, K is the scatterer number, σ_i, c, T_1, B and f_0 denote scattering coefficient, light speed, pulse width, signal bandwidth and frequency, respectively. The range variable between i th scatterer and imaging center is $R_{\Delta i}(t_m)$, which is a function of slow time t_m.

Since $R_0 \gg R_Q$, the variable $R_{\Delta Q}$ of the rigid scatterer Q can be written as:

$$R_{\Delta Q}(t_m) = R_Q \sin(\omega_0 t_m + \theta_Q) \tag{2}$$

Since the main body holds $\omega_0 t_m \ll 1$, we can conclude that $\cos(\omega_0 t_m) \approx 1$ and $\sin(\omega_0 t_m) \approx \omega_0 t_m$. Then $R_{\Delta Q}(t_m)$ can be written as:

$$\begin{aligned} R_{\Delta Q}(t_m) &= R_Q \cos(\theta_Q)\sin(\omega_0 t_m) + R_Q \sin(\theta_Q)\cos(\omega_0 t_m) \\ &= x_Q \sin(\omega_0 t_m) + y_Q \cos(\omega_0 t_m) \\ &\approx x_Q \omega_0 t_m + y_Q \end{aligned} \tag{3}$$

where $x_Q = R_Q \cos(\theta_Q)$, $y_Q = R_Q \sin(\theta_Q)$ are coordinates of scatterer Q.

For a small accumulation angle, the Doppler frequency of scatterer Q can be approximated as:

$$f_{dQ}(t_m) = \frac{2}{\lambda}\frac{dR_{\Delta Q}(t_m)}{dt_m} = \frac{2x_Q\omega_0}{\lambda} \tag{4}$$

Since $R_0 \gg R_P$ and $R_0 \gg r_P$, the variable $R_{\Delta P}(t_m)$ of rotating scatterer is:

$$\begin{aligned} R_{\Delta P}(t_m) &= R_P \sin(\omega_0 t_m + \theta_0) + r_P \sin(\omega_P t_m + \theta_P) \\ &= R_P \cos(\theta_0)\sin(\omega_0 t_m) + R_P \sin(\theta_0)\cos(\omega_0 t_m) + r_P \sin(\omega_P t_m + \theta_P) \\ &= x_{O'} \sin(\omega_0 t_m) + y_{O'} \cos(\omega_0 t_m) + r_p \sin(\omega_P t_m + \theta_P) \\ &\approx x_{O'}\omega_0 t_m + y_{O'} + r_p \sin(\omega_P t_m + \theta_P) \end{aligned} \tag{5}$$

where $x_{O'} = R_P \cos(\theta_0)$ and $y_{O'} = R_P \sin(\theta_0)$ are coordinates of the rotating center O'.

The Doppler frequency of rotating scatterer P can be written as:

$$f_{dP}(t_m) = \frac{2}{\lambda}\frac{dR_{\Delta P}(t_m)}{dt_m} = \frac{2x_{O'}\omega_0}{\lambda} + \frac{2\omega_P r_P}{\lambda}\cos(\omega_P t_m + \theta_P) \tag{6}$$

From the analysis above, the MD produced by the rotating scatterer P would appear as a sinusoid, while the Doppler produced by the rigid scatterer Q is a straight line.

3. MD SEPARATION

From Eqns. (4) and (6), we can conclude that the time-frequency distribution of the rigid scatterer is a straight line with a very small frequency which is a fixed value, since ω_0 is usually quite small; the time-frequency distribution of the rotating scatterer is a sinusoid, whose frequency distributes in the whole frequency axis. The accumulated peak value of the rotating scatterer is usually less than that of the rigid scatterer, because of the migration through range cell of the rotating scatterer, which makes the energy distributes on multi range cells. Thus, energy threshold can be applied for separation of returned radar signals from rotating scatterers and rigid scatterers. However, when the back-scattering coefficient of the rotating scatterer is far more than that of the rigid scatterer, the accumulated peak value of the rotating scatterer may be more than that of the rigid scatterer. So the illusive rigid echoes may appear with only energy threshold to separate MD. Since the frequency of the rotating scatterer distributes in the whole frequency axis, and its amplitudes gradually augment from low frequency to high frequency, which makes the frequency of illusive rigid echoes locates at high frequency region; while the frequency of the rigid scatterer locates at low frequency region, so the frequency threshold can be applied together with the energy threshold to separate radar returned signals from rotating scatterers and rigid scatterers. By disposing with the two thresholds, illusive rigid echoes can be restrained on one hand, on the other hand, frequency search extension minishes which reduces computational complexity. Thus, well-focused ISAR image can be obtained with separated rigid returned signals by applying RD algorithm. From the analysis above, the low frequency filter algorithm is described as follows:

(1) Compute the spectrums of each range cell;
(2) Search the maximum amplitude of the spectrums during the frequency extension $[-f_T, f_T]$, the corresponding frequency is thus the frequency $f_{\max 1}$ of the rigid scatterer;
(3) Design a band-stop filter with central frequency $f_{\max 1}$, and filter the estimated spectrum of the rigid scatterer from the original spectrum;
(4) Repeat step 2 and step 3 until the estimated energy of the rigid scatterer falls below a threshold;
(5) Transform the residual spectrum into time domain, which is the returned signal of micro-motion scatterers;
(6) Subtract the MD signal from the original echoes and obtain the rigid echoes.

A conclusion can be drawn that the proposed algorithm minishes the frequency search extension, which has the property of requiring less computational burden.

4. EXPERIMENTAL RESULTS

The raw radar data in this paper is the ISAR measured data of An-26 airplane. Ground radar operates at 400 MHz and transmits a pulse waveform with a pulse repetition frequency 400 MHz. Figure 2(a) is the RD image after translational motion compensation, from which we can see the clear MD interferential strip induced by the rotating airscrews. The spectrums of separated rotating scatterers and rigid scatterers are shown in Figs. 2(b) and 2(c), respectively. After MD separation with low frequency filter algorithm, the RD image of the rigid body is shown in Fig. 2(d), which demonstrated that the MD interferential strip is wiped off.

5. CONCLUSIONS

This study establishes the turntable model of micro-motion rotating target, and derived mathematical formulas solving micro-Doppler modulations induced by rotation. Based on the differences in frequency, the low frequency filter algorithm is proposed to separate the rigid echoes and MD echoes, which is computational efficient. The validity of the proposed algorithm has been proved by experimental data.

ACKNOWLEDGEMENT

This work was supported by a grant from School Project of Yuncheng University (No. YQ-2011034)

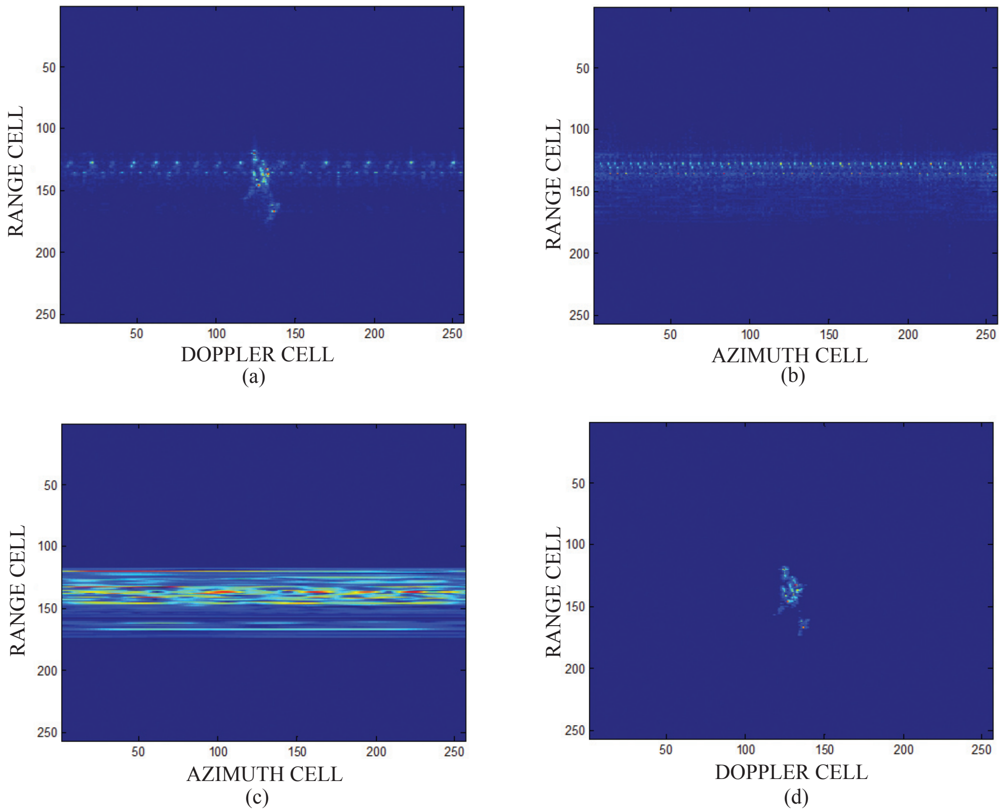

Figure 2. RD image of experimental data (a) RD image after translational motion compensation, (b) The spectrum of separated rotating scatterers, (c) The spectrum of separated rigid scatterers, (d) RD image of the rigid body.

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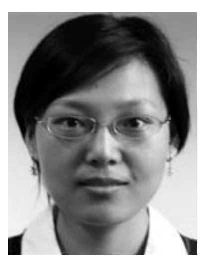
CONTRIBUTOR



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