Int. J. Electron. Commun. (AEÜ) 69 (2015) 903–914

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

# Micro-motion frequency estimation of radar targets with complicated translations

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ARTICLE INFO

*Article history:*
Received 30 August 2014
Accepted 18 February 2015

*Keywords:*
Micro-Doppler
Micro-motion
Parameter estimation
Complicated translations
Time-frequency squared difference sequences

ABSTRACT

Micro-Doppler (m-D) signatures induced by micro-motion dynamics, which are of great importance for target classification, have received increasing attention among the radar community. However, most of the existing m-D signature-extraction methods are based on the assumption that translations of radar targets have been completely compensated by other methods or they merely involve scenarios when radar targets undergo low order polynomial translations. These methods may become invalid for maneuvering targets with complicated translations. In this work, radar targets with micro-motion and complicated translations are considered. Inspired by the differential element method and the shift invariant difference operation, a micro-motion frequency estimation method based on piecewise translation compensation (PTC) and time-frequency squared difference sequences (TFSDS) is proposed. The PTC can compensate the translations of radar targets at the largest extent. After compensation, the TFSDS-based frequency estimator gives an estimation of micro-motion frequency; this estimator can remove the effect of residual translation and avoid the separation of the multicomponent radar echo. The combination of PTC and TFSDS enables us to extract the micro-motion frequency of radar targets with complicated translations without a prior knowledge. Experiments with synthetic and measured data confirm the effectiveness and good performance of the proposed method.



## 1. Introduction

The radar target undergoing micro-motion dynamics imposes a periodic time-varying frequency modulation on radar signals. This is known as the micro-Doppler (m-D) effect [1]. The m-D features, which reflect the unique dynamic and structural characteristics of the target, serve as additional target features for target recognition and classification that are complementary to those made available by existing methods [1–3].

Extraction of m-D feature for maneuvering space targets is a hot topic in recent years, application can be found in the research of ballistic warhead, decoy, etc. [4]. For such maneuvering targets which are always with high velocity and acceleration, their translations shift the m-D and disturb its periodicity. Furthermore, high accelerations lead to a large dynamic frequency range and even Doppler ambiguity. The complicated instantaneous frequency (IF) laws of radar signals introduced by complicated translations also cause m-D estimation bias. On the other hand, radar echoes of targets with micro-motion are nonstationary and multicomponent. As a result, when the acceleration is high enough, components of the radar echo become unresolvable in time-frequency (TF) domain because of their interferences. Therefore, it is essential to compensate the translation of the radar target for most applications to resolve the Doppler ambiguity and to improve the estimation precision of m-D.

Numerous m-D signature-extraction methods were proposed in the past decades. As for non-rigid radar targets, the main body signatures and m-D signatures are overlapped in the TF domain. Typically, signal decomposition methods which decompose radar signals into components associated with different parts of the radar target, e.g., chirplet decomposition, wavelet decomposition, empirical mode decomposition (EMD), can be carried out to extract m-D signature [5–7]. Another category of methods for extracting m-D signatures of non-rigid targets is based on the statistics of time-frequency distribution (TFD) [8]. In [8], an *L*-statistics-based method for m-D effects removal is proposed; it produces better focused images of the rigid body than the other TF-based approaches. The m-D signatures present periodicity on the TF plane, thus methods based on the periodicity of the TFD of radar signals can be developed to estimate the micro-motion period [9–12]. Taking advantage of this property, two approaches based on the

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http://dx.doi.org/10.1016/j.aeue.2015.02.011
1434-8411/

one-dimensional Fourier transform [9] and the two-dimensional Fourier transform [10] of the TFD are proposed to extract the micro-motion period (frequency), respectively. In [11], a similarity measure of the TFD is employed to estimate the micro-motion period, which can be applied to different types of m-D signals. In [12], a method based on the mixed m-D time-frequency data sequences is proposed to estimate micro-motion parameters of free rigid targets, including spin rate, precession rate, nutation angle and inertia ratio. The construction of mixed m-D TF data sequences plays a crucial role in the performance of the method. Recently, the authors show that the radar echo in the presence of translation presents circular periodicity in TF domain. In view of this, the circular correlation coefficients of the TFD are employed to characterize the circular periodicity of the TFD and to provide an estimate of the micro-motion period. But its performance for complicated translation remains to be tested [13]. The aforementioned methods are mostly based on the assumption that the target undergoes a low order (usually second order) polynomial translation or that the translation is compensated by other methods. As for translation compensation, the Doppler rate is used to remove the translation [14], but it merely compensates the translation for single scatterer-radar targets or it need to separate the multicomponent radar echo in the TF domain. In [15], a translation compensation method based on the minimization of the spectrum entropy of the radar echo is proposed; it can compensate high acceleration-translations without the separation of the multicomponent radar echo if the translation of the target can be approximated by a second polynomial function. An EMD-based translation compensation method which decomposes the IFs of the radar echo into intrinsic mode functions (IMFs) associated with the micro-motion and the translation is proposed in [16]. The proposed method in [16] can compensate the radar echo with multi-scatterers and seems to be effective for complicated translations. However, it becomes invalid when there is frequency aliasing in the TF domain. These methods may not be effective for scenarios when the radar target undergoes a complicated translation, especially when there is no a prior knowledge about the translation.

Aiming at m-D feature extraction of radar targets with complicated translations, a micro-motion frequency estimation method based on piecewise translation compensation (PTC) and time-frequency squared difference sequences (TFSDS) is proposed in this paper. The PTC can compensate the translation of the radar target at the largest extent. After that, a TFSDS-based frequency estimator gives an estimation of micro-motion frequency, which can remove the effect of residual translation and avoid the separation of the multicomponent time-varying and intersecting micro-Doppler components. The remainder of this paper is organized as follows. In Section 2, the general model of the m-D of the radar target with a translation is introduced. Next, the derivation of the estimation algorithm is presented in Section 3, including the methodologies of PTC and TFSDS. Experiments with synthetic and measured data of cone-shaped targets validate the proposed method in Section 4.

## 2. The micro-Doppler model

In optical region, a radar target can be modeled as a set of point scatterers and thus its radar echo is the combination of returns from these point scatterers. The motion of a scatterer is composed of the translation of the target (also refer to as macro-motion, which is identical for all scatterers) and its individual micro-motion. The typical micro-motions whose forms are sinusoidal functions with respect to the micro-motion frequency are employed during the derivation, while the form of translation is arbitrary and unknown.

Assuming that there are $L$ scatterers on the target, the radial distance of the $l$th scatterer from radar associated with micro-motion can be expressed as:

$$r_{M\_l}(t) = A_l \sin(2\pi f_m t + \varphi_l) + r_{l0} \quad (1)$$

where $A_l$ is micro-motion amplitude, $f_m$ is micro-motion frequency, $\varphi_l$ is initial phase, $r_{l0}$ is the initial distance to radar. And total radial distance of the $l$th scatterer is

$$r_l(t) = r_T(t) + r_{M\_l}(t) \quad (2)$$

where $r_T(t)$ is the radial distance associated with the translation of the target.

In general, the baseband signal of the returned radar signal can be expressed as

$$s(t) = \sum_{l=1}^{L} \sigma_l(t) \exp\left(\frac{j4\pi r_l(t)}{\lambda}\right)$$
$$= \exp\left(\frac{j4\pi r_T(t)}{\lambda}\right) \sum_{l=1}^{L} \sigma_l(t) \exp\left(\frac{j4\pi r_{M\_l}(t)}{\lambda}\right) = s_T(t) s_M(t) \quad (3)$$

where

$$s_T(t) = \exp\left(\frac{j4\pi r_T(t)}{\lambda}\right) \quad (4)$$

$$s_M(t) = \sum_{l=1}^{L} \sigma_l(t) \exp\left(\frac{j4\pi r_{M\_l}(t)}{\lambda}\right) \quad (5)$$

$s_T(t)$ is the translation modulation part, $s_M(t)$ is the micro-motion modulation part, $\sigma_l(t)$ denotes the RCS of the $l$th scatterer, $\lambda$ is the wavelength of the carrier wave and $L$ is the number of scatterers. The Doppler frequency of the $l$th scatterer is given by

$$f_l(t) = \frac{2}{\lambda}\frac{dr_l(t)}{dt} = \frac{2}{\lambda}\frac{dr_T(t)}{dt} + \frac{2}{\lambda}\frac{dr_{M\_l}(t)}{dt} = \frac{2}{\lambda}\frac{dr_T(t)}{dt}$$
$$+ \frac{4\pi f_m A_l}{\lambda} \cos(2\pi f_m t + \varphi_l) \quad (6)$$

where $(2/\lambda)(dr_T(t)/dt)$ is the translation Doppler, $(4\pi f_m A_l/\lambda)\cos(2\pi f_m t + \varphi_l)$ is the m-D.

The Doppler frequency of the $l$th scatterer can be simplified as follows:

$$f_l(t) = A'_l \sin(2\pi f_m t + \varphi'_l) + f_{trans}(t) \quad (7)$$

where $f_{trans}(t) = (2/\lambda)(dr_T(t)/dt)$ denotes the translation Doppler, $f_m$ is the micro-motion frequency of the target, and $A'_l = 4\pi f_m A_l/\lambda$ and $\varphi'_l = \varphi_l + \pi/2$ are the amplitude and initial phase of the m-D, respectively. As indicated in (3), (6) and (7), the radar echo of the radar target with micro-motions is a multicomponent amplitude and frequency modulated (AM-FM) signal.

## 3. The proposed estimation algorithm

Because of the multicomponent and time-varying frequency modulation properties, radar echoes are overlapped in the TF domain, which makes it difficult to separate components associated with different scatterers. On the other hand, approaches based on the assumption that radar targets undergo a low order polynomial translation may become invalid for radar targets with complicated translations.

Our approach contains two main steps: (1) PTC and TFD generation; (2) TFSDS-based micro-motion frequency estimation. At the first stage, the translation is compensated by PTC accompanied by a special TFD Generation strategy. The special TFD Generation strategy can reduce the end effect of TFD which results from the segmenting of the radar echo. After that, the TFSDS is utilized to