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Separate estimation schemes for time-frequency overlapped micro-doppler signal in single channel infrared laser detection

Liren Guo, Yihua Hu*, Shilong Xu, Xiao Dong, Minle Li

State Key Laboratory of Pulsed Power Laser Technology, College of Electronic Engineering, National University of Defense Technology, Hefei 230037, China
Anhui Province Key Laboratory of Electronic Restriction Technology, Hefei 230037, China

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ABSTRACT

The micro-Doppler (MD) effect of weak vibration target is obvious in infrared laser detection. This provides the foundation for precise estimation of micro-motion parameters, and makes the target classification and recognition possible. The multi-targets or multi-scattering points existing in the detecting field will generate the single-channel multi-component (SCMC) signal in laser detection. Further, the similar micro-motion parameters will lead to the feature overlapping in time-frequency domain, which will increase the difficulty of parameter estimation. In this paper, a separate parameter estimator based on the maximum likelihood framework and singular value decomposition is proposed to deal with this mixed signal. First, an improved singular value ratio (SVR) spectrum with detailed period scanning is presented to locate the vibration frequency. The amplitude ratio information of each component is also extracted from the SVR spectrum. Then, the analytic expression of the maximum likelihood estimation (MLE) of micro-motion parameters is derived. To solve the high nonlinear problem in laser MD signal, a new likelihood function (LF) is designed in the derivation process. The Robustness and efficiency are both increased with this new LF. The Markov chain Monte Carlo (MCMC) sampling is employed to implement the MLE. Finally, the simulation results verifies the validity of the proposed method. The comparison with the Cramer-Rao bound shows the ability of accurate estimation of the proposed method.

1. Introduction

Micro-motions caused by engine vibration, blades rotation, and body procession will generate additional frequency modulation in the echo signal in moving target remote sensing, which is called the Micro Doppler (MD) effect [1]. Typical radar targets like vehicles, jets et al. possess unique micro-motion forms and specific range of micro-motion parameters [2,3]. These make the target classification and identification possible once the parameters are precisely estimated. For most MD effects generated by engine vibration, the amplitudes are in micrometer order or even weaker, which makes it hard to detected in radar [4]. Thus, the laser detection, which possess shorter wavelength, is irreplaceable in precise estimation of weak MD effect. Generally, the advantages on concealment, high atmospheric transmittance, and high output power of the infrared band make it the best choice for remote sensing lidar.

The core task in making use of the MD effect is the estimation of micro-motion parameters. There may be multiple targets or scattering points in the field of view in actual detection, and the parameters of micro-motion targets are always similar [5]. These make the laser MD echo a single channel multi-component (SCMC) signal with overlapped MD features in the time-frequency (TF) domain. The current researches on parameter estimation of the SCMC signal can categorized into the nonparametric and parametric class [6]. The first class is mainly based on TF distribution. The convenient exhibition of the instantaneous frequency(IF) law, which reveals the MD characteristics, makes the TF analysis a major research direction for the past decade. However, it has some inevitable limitations. The TF distribution of multi-component signal is seriously interfered by the window effect and the cross term [7]. Although the improved TF distribution can achieve better time and frequency resolution [8,9], they still suffer severe restrictions of the heavy burden of computation. The traditional methods such as direct peak-searching [10] will not be able to extract the features from the multi-component TF distribution. Thus, a curve tracking method based on the Viterbi theory is proposed in [11] to separate the IF laws successively. However, it requires a high signal to noise ratio (SNR) and performs poorly on breakpoints. Some parametric methods like the Radon and Hough transforms are also applied to the TF distribution to solve the SCMC problem [12]. These approaches can improve the robustness, but at the cost of increasing the calculation. The parameters

* Corresponding author.
E-mail address: skl_hyh@163.com (Y. Hu).

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are located in a blurry region but not a specific point, where the estimation precision is not guaranteed. Further, the two-parameter model is too simple for the practical signals.

The parametric methods for MD parameter estimation arose in recent years to improve the precision. The cyclostationary character is used to estimate the micro-motion frequency in [13]. But the half and diploid period is inevitable in the cycle spectra, which makes it unsuitable for multi-component signal. A high-order moment based method is proposed in [14] to estimate the micro-motion parameters. Although, this approach is faster than the class of image processing and orthogonal matching pursuit, it is still not ideal in real-time processing. Further, the anti-noise ability is poor when using broadband signal. The matched filter of sinusoidal frequency modulation (SFM) signal in [15,16] separate the SCMC signal by reconstructing each component using the estimated parameters. However, the grid search estimator is not able to achieve high precision and efficiency at the same time. Static parameter particle filter can precisely estimate the SFM parameters [17], but the particles should increase exponentially with the number of components to ensure the convergence. Furthermore, the BSS, EEMD, and LMD methods in signal processing are also employed [18–20]. They are well performed in a multi-channel or non-overlapping signal, while incapable of the frequency overlapping or one channel circumstance. Setlur [21] presents an iterative reweighted nonlinear least square method under the maximum likelihood scheme to estimate the MD parameters, which achieves the estimation precision next to the Cramer–Rao bound (CRB). But this algorithm has complex computation in each iteration and works only on single component signal at present. The maximum likelihood estimation (MLE) has been proved to be an optimal asymptotic unbiased estimator in theory [22]. The performance of MLE can achieve the CRB with adequate data and high SNR, which is far better than the traditional nonparametric estimators. Unfortunately, the current likelihood function (LF) is established for radar MD effect. The nonlinearity will be sharply increased when used in the laser MD signal [23]. The LF distribution will become the form of serried peaks rather than the ideal single and smooth peak [24], which may lead to incorrect convergence of the MLE implementation.

In this paper, a separate micro-motion parameter estimator based on the MLE scheme is proposed to deal with the overlapped SCMC signal. The singular value ratio (SVR) spectrum is used to estimate the vibration frequency, where the accuracy is highly improved with detailed scanning of the period. The difference between radar and laser MD effect in weak vibration detection is analyzed. Then, a new LF for laser MD signal is designed based on the characteristic of the spectrum energy distribution. The effect is equivalent to smoothing the pdf distribution generated by the traditional LF. Furthermore, the spectrum based LF possess strong anti-noise ability since the uniform distribution character of the white noise. The Markov chain Monte Carlo (MCMC) sampling is implemented to realize the MLE according to the derived analytical expression. It solved the problem of multidimensional integration by joint parameter estimation, and avoided the error transfer at the same time. The feasibility of the algorithm is verified by the simulation result. Compared with the Cramer-Rao bound (CRB), the proposed method shows the advantage on accurate estimation of the SCMC laser MD signal.

2. Mathematic model of SCMC laser MD signal

According to the electromagnetic scattering theory, electrically large target scattering possesses a local effect in optical region, where each scattering cell can be treated independently and the entire scattering can be equivalent to the sum of these local scattering points. For laser detected MD signal, it is reasonable to employ this equivalent point scattering theory as the wavelength is far smaller than the target size.

V.C. Chen first established the mathematical models of the micro-Doppler signals based on the point scattering theory. A laser MD model

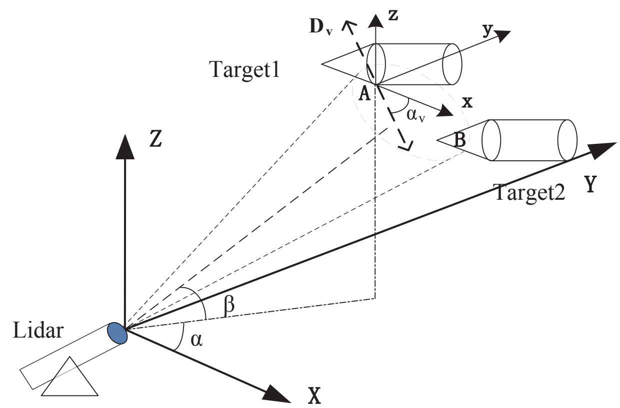

Fig. 1. Geometry of laser micro-Doppler model.

is shown in Fig. 1. The lidar is in the origin position of the fixed coordinate system ***XYZ***. ***xyz*** is the reference coordinate system of the targets that is parallel to ***XYZ***. Assuming two targets exist in the lidar field, a scattering point A of one target is vibrating along the vector of $\vec{\mathbf{D}}_{\mathbf{v}}$. The α, β, and α_v are the azimuth and pitch angle from target to lidar and the azimuth angle of vibration, respectively. Then, the baseband signal of multi-component MD effect in single channel lidar can be expressed as

$$s_{md}(n) = \sum_{k=1}^{K} A_k \cdot \exp\left\{ \mathrm{j}\left[\frac{4\pi D_{vk}\cos\beta\cos\alpha\sin(2\pi f_{0k}\ \mathrm{n}+\rho_{0k})}{\lambda} + \theta_k \right] \right\} + w(n) = e(n) + w(n) \quad (1)$$

where K is the number of components, A_k and θ_k are signal amplitude and initial phase of the kth component. $f_{0k} = f_{vk}/f_s$, where f_s denotes the sampling rate, and D_{vk}, f_{vk}, and ρ_{0k} are the amplitude, frequency and initial phase of the kth micro motion, respectively. λ is the laser wavelength, and $w(n)$ denotes the noise. Without loss of generality, those angles can be set to 0 for simplicity.

3. Separate estimation for SCMC laser MD signal

3.1. Micro-motion frequency estimation based on SVR

According to the Singular value decomposition theory, only the first singular value is not zero when the ratio between each row vector is a constant. For the periodic signal, if we build it in a matrix form and set the number of columns close to the length of signal period, the singular value ratio σ_1/σ_2 would be a larger value. σ_1 and σ_1 are the first and second singular value, respectively. The SVR spectrum describes the variation of SVR over the number of columns [25]. Thus, the signal period can be detected by finding the maximum value from the SVR spectrum. In general, the Laser micro-Doppler effect possesses the form of SFM signal. This periodic modulation gives the baseband signal a same periodical characteristic. Then, the SVR spectrum can be employed to extract the micro-motion period, which is exactly the signal ρ_{0k} modulation period.

The SVR methods may fail when the signal matrix is built directly on the complete samples. Because the error between the number of columns and the real period will accumulate as the rows increases. To avoid this problem, an improved SVR spectrum with specific number of columns and detailed cycle scanning is proposed. The matrix can be built as

$$\mathrm{S} = \begin{bmatrix} s(d_0+1), & s(d_0+2), & \dots, & s(d_0+L) \\ s(d_1+1), & s(d_1+2), & \dots, & s(d_1+L) \\ \vdots & \vdots & \ddots & \vdots \\ s(d_M+1), & s(d_M+2), & \dots, & s(d_M+L) \end{bmatrix} \quad (2)$$

In Eq. (2), $d_m = round(m\cdot d)$, $m = 0, 1, \dots, M$, where d denotes the