A robust detection method for micro-Doppler feature of rotating blades under low SNR

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Abstract: Rotation of rotor blades is typically micro-motion and would induce micro-Doppler modulation. However, accurate detection will become extremely difficult when the echo signal is corrupted by strong noise. This paper proposes a method to realize extraction of micro-Doppler feature from the rotating rotor blade echo signals with low signal-to-noise ratio (SNR). The proposed method is characterized by applying low-rank decomposition for saliency detection of spectrogram. MATLAB simulation results verify that the proposed method is effective in saliency detection of the spectrogram from rotor blade echo signals and is robust in estimating the maximum micro-Doppler shift under low SNR.

Keywords: spectrogram, micro-Doppler, saliency detection, Hough transform

Classification: Sensing

References

[1] V. C. Chen, The Micro-Doppler Effect in Radar, Artech House, Boston, 2011.
[2] B. S. Oh, X. Guo, F. Wan, K. A. Toh, and Z. Lin, “An EMD-based micro-Doppler signature analysis for mini-UAV blade flash reconstruction,” 2017 22nd International Conference on Digital Signal Processing, London, UK, pp. 1–5, Aug. 2017. DOI:10.1109/ICDSP.2017.8096105
[3] L. Stankovic, I. Orovic, S. Stankovic, and A. Moeness, “Compressive sensing based separation of nonstationary and stationary signals overlapping in time-frequency,” IEEE Trans. Signal Process., vol. 61, no. 18, pp. 4562–4572, Sept. 2013. DOI:10.1109/TSP.2013.2271752
[4] W. Kang, Y. Zhang, and X. Dong, “Micro-Doppler effect removal for ISAR imaging based on bivariate variational mode decomposition,” IET Radar Sonar & Navigation, vol. 12, no. 1, pp. 74–81, Jan. 2018. DOI:10.1049/iet-rsn.2017.0104
[5] L. Cirillo, A. M. Zoubir, and M. Amin, “Parameter estimation for locally linear FM signals using a time-frequency Hough transform,” IEEE Trans. Signal Process., vol. 56, no. 9, pp. 4162–4175, Sept. 2008. DOI:10.1109/TSP.2008.
1 Introduction

Micro-motion could cause side-band Doppler frequency shifts around the centre of Doppler shifted carrier frequency; which is called micro-Doppler effect [1]. The frequency modulation of micro-Doppler effect contributes mono-/multi-component of sinusoidal frequency modulation or multi-frequency pattern combination.

Extraction of the micro-Doppler features from echo signals can provide a basis for detection of flying targets. The empirical mode decomposition [2], compressive sensing [3] and variational mode decomposition [4] are the typical algorithms aimed to separate micro-Doppler contributions from multicomponent signals. These methods suffer huge computation loads when estimated data are high-dimensional. With applying time-frequency analysis, micro-Doppler parameters could also be estimated by mapping the time-frequency distribution onto the parameter space by a pattern recognition tool, such as Hough transform. The existing Hough transform based methods detect sinusoids produced by micro-Doppler effect [5, 6], which are easily submerged in background noise, thus they tend to lose robustness at low SNR. Instead of sinusoid detection, an envelope detection method realizes estimation of the maximum Doppler frequency by detecting location of the steepest negative slope of the envelope of the spectrum [7]. The method still suffers poor performance under low SNR without adopting effective noise suppression.

In this paper, we propose a method that estimates the maximum Doppler frequency by detecting frequency flashes, which have the strongest spectral amplitude in the spectrogram. The proposed method is Hough transform based and featured by saliency detection of the spectrogram: global low-rank decomposition is applied to obtain saliency map firstly, then the maximum micro-Doppler shift is estimated by detecting frequency flash lines. The rest of the paper is organized as follows. The rotor signal model is given and its spectrogram is obtained, followed with description of the proposed method. Simulation results validate the proposed method finally.
2 Signal model of rotating rotor blades

For a rotor with $N$ blades, the echo continuous wave (CW) signal from rotating rotor blades with a certain reflectivity could be given by [1]:

$$s(t) = L \times \exp \left( -\frac{j4\pi R_0}{\lambda} \right) \times \sum_{n=0}^{N-1} \text{sinc} \left( \frac{2L}{\lambda} \cos \beta \cos \left( 2\pi f_r t + \phi_0 + \frac{2\pi n}{N} \right) \right)$$

where $L$ is the blade length; $R_0$ is the distance between the radar and rotation center; $\lambda$ is the wavelength of the transmitted signal; $\beta$ is the elevation angle; $f_r$ is the blade rotate frequency; $\phi_0$ is the initial phase, $\phi_0 \sim U(0, 2\pi)$.

Its maximum micro-Doppler shift for a single blade is given by:

$$f_d = \frac{4\pi L f_r \cos \beta}{\lambda}$$

(2)

The echo signal $s(t)$ could be transformed into time-frequency domain through short-time Fourier transform (STFT). Its spectrogram $TF$ is a two-dimensional map of power spectral along the time axis:

$$TF(t, f) = |\text{STFT}(t, f)|^2 = \left| \sum_{m_i=-\infty}^{W-1} w(m_i) s(m_i + (t - 1)(W - O_i)) e^{-j2\pi km_i/W} \right|^2$$

(3)

where $w(\cdot)$ is the Hamming window function with length $W$, $m_i$ is the index of window position, $O_i$ is the overlap of two consecutive analysis windows, $k$ is the index for frequency $k\omega_0$ with $\omega_0$ representing the Fourier resolution and equals to $2\pi f_s/W$ for the sampling frequency $f_s$. Thus $TF \in \mathbb{R}^{W \times Q}$, $Q = \left\lfloor \frac{(N_s - O_i)}{(W - O_i)} \right\rfloor$, where $N_s$ is the total number of signals and $N_s = t_s f_s$ for observation time $t_s$.

With the sinc($\cdot$) in Eq. (1) in time domain to be turned into rete($\cdot$) in frequency domain by executing STFT, frequency flashes with a certain width are produced in the spectrograms.

Fig. 1 demonstrates two noise-free spectrograms from the rotating rotor with two blades and a single blade, respectively. When the number of blades is even, the frequency flashes occur in a symmetric spectrum and the frequency of flashes is twice the rotation rate. When the number of blades is odd, the frequency flashes occur in an asymmetric spectrum and the frequency is the same with rotation rate.

The micro-Doppler traces of rotating scatter points on the blade tip are sinusoids in general cases. While the incident ray is perpendicular to the blade, all scatter points along the blade’s surface mainly produce specular reflections, which are presented as frequency flashes. The frequency flashes range from 0 Hz to $f_d$ and have the strongest spectral amplitude in the spectrogram. Therefore, detection of frequency flashes could potentially be an effective choice.
3 The proposed method

We propose a detection method for the maximum Doppler frequency shift in this section. Processing of the proposed method mainly consists of saliency detection by low-rank decomposition and line detection by Hough transform.

Non-saliency information causes great interference to the extraction of micro-Doppler features in spectrogram. Since a data matrix could be decomposed into a low-rank matrix and a sparse matrix, the initial spectrogram $TF$ then can be expressed as:

$$TF = TF_s + E$$

(4)

where $E$ is the gross and sparse component of the noise residual, $TF_s$ is the low-rank component of the salient regions.

The problem is described as a nuclear norm minimization approach:

$$\min_{L,M} \|TF_s\|_s + \varepsilon |E|_1 \quad s.t. \quad TF = TF_s + E$$

(5)

where $\| \cdot \|_s$ is the nuclear norm; $| \cdot |_1$ is the $l_1$-norm; $\varepsilon$ is a positive weighting parameter that guarantees the exact recovery and $\varepsilon = Q^{-1/2}$.

Following steps are carried out to extract the micro-Doppler features:

1. Calculate the global saliency map $TF_s$ by accelerated proximal gradient (APG) approach [8].
2. Calculate the optimum threshold value $T_0$ by iterative threshold method [9], and segment $TF_s$ based on the threshold value $T_0$ to obtain the binary saliency map $TF_b$.
3. Remove all connected pixels that are fewer than the empirical threshold $p_n$ from the binary saliency map $TF_b$. Through doing so noise pixels remained after saliency detection could be eliminated. The $p_n$ is set to the mean number of pixels that are contained in connected noise pixels in $TF_b$ without target signal.
4. Divide $TF_b$ along the zero frequency into the upper image $TF_i$ and the lower image $TF_d$ for uncertain symmetry of the spectrogram caused by the unknown rotor blade number.
5. Calculate the length set of the line segments of frequency flashes $L_i$ and $L_d$ in $TF_i$ and $TF_d$ respectively using Hough line detection [9].
Within the short observation interval, the rotor is assumed to rotate at a constant rate. Then the frequency flashes have the same length in $TF_i$ and $TF_d$. The estimated maximum micro-Doppler shift $\tilde{f}_d$ is:

$$\tilde{f}_d = \frac{\omega_0 \times L_i + L_d \pi}{\eta}$$  \hspace{1cm} (6)

4 Simulation results

Simulations are conducted to demonstrate performance of the proposed method using MATLAB. The echo signal is generated based on Eq. (1) by setting $\lambda$ to 0.015 m, $R_0$ to 7 km, $f_s$ to 200 KHz and $t_s$ to 0.05 s. For the rotating rotor blades, $f_r = 300$ Hz, $\beta = 0^\circ$, $L_a = 0.2$ m. We set the blade number to 2 for model M1, M2 and M3, and the blade number to 1 for M4, to demonstrate the influence of frequency flash density on feature extraction. We then set the blade length to 0.1 m, 0.2 m, 0.3 m and 0.2 m for M1, M2, M3 and M4 respectively to demonstrate the influence of frequency flash length to feature extraction. To realize trade-off between time resolution and frequency resolution, we set $W$ to 512 and $O_t$ to 8 in STFT, $p_n = 8$ in the step 3.

Fig. 2(a) illustrates the original spectrogram $TF$ for M2 at SNR = $-5$ dB. The micro-Doppler sinusoid produced by scatters on the blade tip are buried in strong noise and the frequency flashes are also polluted by strong noise pixels. Fig. 2(b) demonstrates the binary saliency map $TF_b$ after saliency detection. The extracted salient regions of the frequency flashes are very clear in the spectrogram.

Furthermore, Monte Carlo simulations are run 100 times under different values of SNR and the Root Mean Square Error (RMSE) for each SNR is calculated. Performance for the proposed method is compared with two conventional methods: Envelope detection [7] and Hough detection [9]. The Hough detection binarizes $TF$ by iterative threshold method then detects lines by Hough transform. Compared to the Hough detection, the proposed method further processes $TF$ by low-rank decomposition before image binaryzation.

Fig. 3(a) demonstrates that the proposed method achieves the best performance for M2 and M4 and the performance converges into 4% at SNR = $-7$ dB and $-6$ dB respectively, followed with the performance of Hough detection and which

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**Fig. 2.** Spectrogram with noise and result of saliency detection

(a) Spectrogram for M2  
(b) Binary saliency map for M2
converges at SNR $= -2$ dB and $-3$ dB. Envelope detection does not reach its convergence performance within the investigated SNR range. In Fig. 3(b), we notice that the target RMSE reaches 4% at SNR of $-4$ dB for M1, $-7$ dB for M2 and $-10$ dB for M3. These results suggest that longer flashes contribute to a higher estimation accuracy.

Interestingly, Hough detection achieves superior performance for M4 than for M2, which suggests that the lower frequency flash density for M4 has produced detection gain. However, the proposed method for M2 performs better than M4, which suggests that longer frequency flash length could improve saliency detection and lead to a better performance of Hough line detection.

5 Conclusion

We propose a method to extract micro-Doppler feature from the rotor blade echo signal. The proposed method is Hough transform based and is characterized by saliency detection of the spectrogram; in particular, to improve robustness at low SNR, low-rank decomposition is applied in obtaining saliency map. Simulation results have verified the proposed method’s effectiveness in detecting saliency in the spectrogram and robustness in estimating the maximum micro-Doppler shift under low SNR.

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