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Analysis of micro-Doppler effect on rotating blades for radar-based UAV detection

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Abstract: *The micro-Doppler (MD) effect is an important feature in radar-based unmanned aerial vehicle (UAV) detection, as it is generated by rotating structures, namely the blades. In this paper, the MD effect of rotating blades is studied based on signal simulations. By discretizing the blades into cells, the influence of bandwidth, number of blades, blade length, and rotation speed on MD effect is investigated. Short Time Fourier Transform (STFT) is adopted to search for the time-frequency relationship of a certain range cell and extract the time-frequency features. The results show that increasing the bandwidth improves the resolution of the target while increasing the number of blades makes the spectrogram more complex because more information is required. The rotational speed is a prominent factor affecting the MD signature, with an increase in rotational speed producing significant periodicity with an increase in frequency shift, but the blade length has less effect on the MD signature, and the results obtained from simulations do not vary significantly for the three blade lengths. This paper provides essential theoretical and experimental references for parameter optimization for target identification in radar-based UAV detecting systems.*

Keywords: *Micro-Doppler effect, radar UAV detection, Short Time Fourier Transform*

1. Introduction

Radar signal processing is critical to modern military and civilian applications, especially for target detection and identification [1], and offers many features and benefits. Radar can measure a target's distance, speed, and position by emitting electromagnetic waves [2] and analyzing the reflected signals. Modern radars (e.g., drones, helicopter propellers, wind turbines) utilize radar to detect and identify rotating targets accurately. Among them, the MD effect on radar targets is a new technical method for accurate target identification that has been extensively studied in recent years. The MD effect is an extension of the Doppler effect, which is a physical phenomenon caused by the microscopic motion of objects and their components [3]. While the classical Doppler effect primarily provides information about the overall velocity of a target, the MD effect captures frequency modulations caused by rotation, vibration, and other complex target motions [4]. As the blades are rotating to provide power for the UAVS, MD effect provides a feasible technique to detect small UAVs, especially rotary wing UAVs with radars

In recent years, many studies have been conducted to investigate the application of the micro-Doppler effect in rotating target recognition. S. Vaněk. et al. [5] analyzed the Micro-Doppler effect of helicopter rotating propellers obtained from simulation data. In the paper, the reflected signals from helicopters with different numbers of propeller blades (3, 4, 6, and 8 blades) are simulated, and the Micro-Doppler effect is measured from these simulated data. However, the assumed conditions in the simulations may differ significantly from the natural environment, e.g., ambient noise and multipath effects may affect the accurate measurement of the Micro-Doppler effect. X. Fang and G. Xiao [6] discussed micro-Doppler characterization and small unmanned rotorcraft (SUR) extraction. They modeled the radar echo from the rotor blades as a sinusoidal frequency-modulated (SFM) signal. Then, a time-frequency distribution (TFD) was obtained using the Gabor transform, while a high-carrier frequency radar was introduced to separate the different sinusoidal curves in the TFD.

Subsequently, these sinusoids are detected by the Hough-Radon transform (HRT). However, this method involves multiple complex mathematical transformations (e.g., Gabor transform and Hough-Radon transform), which impose a computational burden when implemented in practical systems. C.

Bennett. et al. [7] modeled the kinematics and dynamics of UAV flight to capture changes in rotor speed. They aimed to generate realistic features consistent with the variations observed in actual radar measurements. However, their accuracy relies on accurate modeling of UAV kinematics and dynamics. The simulation results will be biased if the model fails to capture the complex dynamics in full, precise flight. Y. Cai. et al. [8] presented a thin-line electromagnetic (EM) model for multi-propeller UAVs, measured the Micro-Doppler modes of the propellers in an anechoic chamber, and used these experimental results to validate the thin-line model for individual propellers in the S- and X-bands. However, the experimental validation is mainly performed in an anechoic chamber, and more disturbing factors will exist in the actual application environment, requiring further validation of the model's applicability.

This paper aims to analyze the effects of various parameters, such as bandwidth, number of blades, blade length, and rotation, on speed and the MD effect in a multi-target scenario. Based on the point target model, the blade is firstly discretized into points with centimeter level interval. Then, the reflected signals are simulated by calculating the time delay of each point. STFT is applied to extract the time-frequency features of a certain range cell. The results provide a theoretical basis for a deeper understanding of the MD for radar-based UAV detecting systems. The paper is organized as follows. The basic principle is provided in Section 2. The proposed method is shown in Section 3. Results are discussed in Section 4. Conclusions are drawn in Section 5.

2. The basic fundamental

2.1 Micro-Doppler Effect

The micro-Doppler effect [9] occurs when the spinning rotor modulates the frequency of the radar wave, producing a significant MD shift. Extraction of the MD effect usually relies on time-frequency analysis techniques, which analyze the signal simultaneously in both the time and frequency domains to capture the frequency shifts caused by slight movements of the target. One of the most commonly used time-frequency analysis methods is [10-11] STFT, which obtains localized signal features in time and frequency by splitting the signal into several small time windows and performing a Fourier transform on the signal within each window. The steps to perform the Fourier transform are as follows:

(1) Split the received radar signal into multiple time windows.

(2) Fourier transformed the signals in each time window, and their spectra were calculated.

(3) The spectra from each time window are combined to form a time-frequency spectrogram.

2.2 Reflected radar signal of point target model

Linear frequency modulation (LFM) signal is one of commonly used signal in radar systems as it provides high-range resolution within a limited bandwidth due to their excellent immunity to interference and simplicity of implementation [7]. The formula for the LFM signal is shown in equation (1):

$$s(t-t0)=rect(Tp)\cdot exp\left(j\cdot 2\cdot \pi\cdot\left(f_c(t-t0)+\frac{1}{2}K_r(t-t0)^2\right)\right) \tag{1}$$

Where f_c is the carrier frequency, which is the center frequency of the radar signal., t denotes fast time. T_p is the pulse duration, which defines the time width of the radar signal. $t0$ represents the time delay from a certain point target. K_r is the frequency modulation rate, described as follows in equation (2).

$$K_r=\frac{B}{T_P} \tag{2}$$

Where B is the bandwidth of the radar signal.

3. Proposed Method

3.1 Parameter Settings

In this paper, the critical radar parameters are set as below: (1) T_p: 5 μs; (2) f_c: 3 GHz; (3) PRF: 20 kHz;

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3.2 Rotary blade modeling

The motion of the blade is described by its positional information at the moment of time t. The coordinates of the center of rotation are set to be $rot_center = (x_{center}, y_{center})$, and the radius of blades are R. The center of rotation is at position (0,1000), and the radar is at (0,0). The blade's position at moment t is as in equations (3) and (4).

$$x(t) = x_{center} + Rcos(\omega t + \varphi_0) \tag{3}$$

$$y(t) = y_{center} + Rsin(\omega t + \varphi_0) \tag{4}$$

Where ω is the angular velocity of the blade, and φ_0 is the initial phase angle of the blade, which defines the blade at the starting position.

3.3 Pulse Compression

The received signal needs to be processed by pulse compression. Pulse compression correlates the echo signal with the transmitted signal using matched filtering. First, a Fast Fourier Transform (FFT) is performed on the received echo signal to convert the time domain signal into a frequency domain signal. Next, the conjugate complex of the transmit signal is calculated and multiplied with the frequency domain representation of the echo signal [12]. Finally, an inverse Fourier transform (IFFT) is performed on the result to obtain the time domain signal after pulse compression. The mathematical formula for pulse compression is usually expressed as equation (5).

$$s_{pc}(t) = s_{tx}(t) \otimes s_{rx}(t) = IFFT\left(FFT\left(s_{tx}(t)\right) \cdot conj\left(FFT\left(s_{rx}(t)\right)\right)\right) \tag{5}$$

where $s_{tx}(t)$ is the transmitter signal, $s_{rx}(t)$ is the received signal, $\otimes$ denotes the convolution operation, $IFFT$ is the inverse fast Fourier transform, FFT is the fast Fourier Transform.

3.4 Time-Frequency Analysis

The time-frequency spectrograms obtained by the short time Fourier transform can visualize the micro-Doppler effect caused by the rotating blades, revealing their angular velocity, rotational period, and other motion characteristics. The mathematical formulation of STFT is shown in Equation (6).

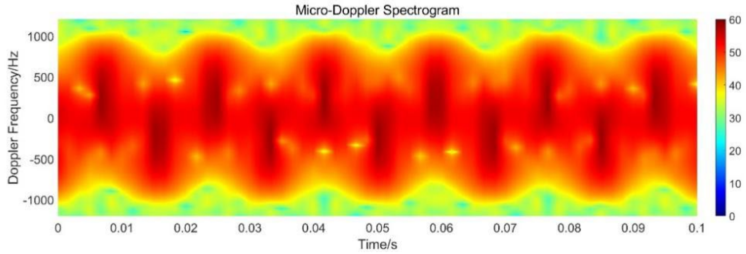
$$STFT\{s(t)\}(t,f) = \int_{-\infty}^{\infty} s(\tau) \cdot \omega(t-\tau) \cdot e^{-j2\pi f\tau}\, d\tau \tag{6}$$

where $s(t)$ is the transmitter signal, $\omega(t-\tau)$ is the window function to extract the time slice of the signal. In this paper, STFT is realized by the spectrogram function in MATLAB. The signal is first segmented into short time segments, and then a fast Fourier transform is performed on each of them to obtain spectral information. The number of points in the Fourier transform determines the frequency resolution. Finally, the spectrograms of the time segments are stitched together.

4. Results

4.1 Effect of bandwidth on Micro-Doppler characteristics

Bandwidth is an important parameter that affects the resolution of a radar system. We simulated the spectrograms at bandwidths of 250 MHz, 500 MHz, and 1 GHz with 3 blades, a velocity of 20 rad/s, and a blade length 10.



(a) Bandwidth = 250MHz

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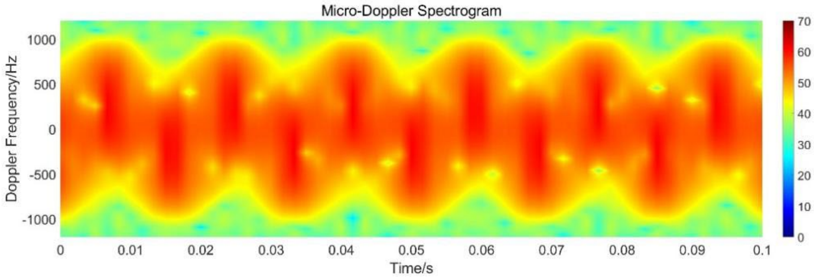
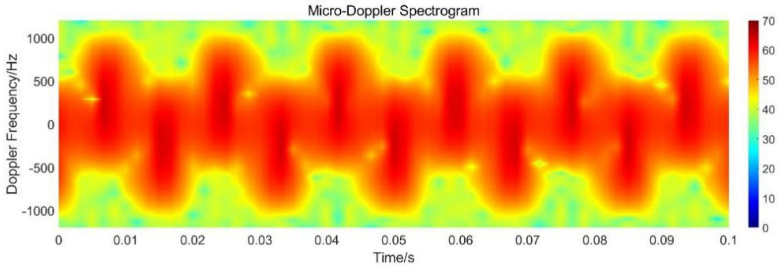


(b) Bandwidth = 500MHz



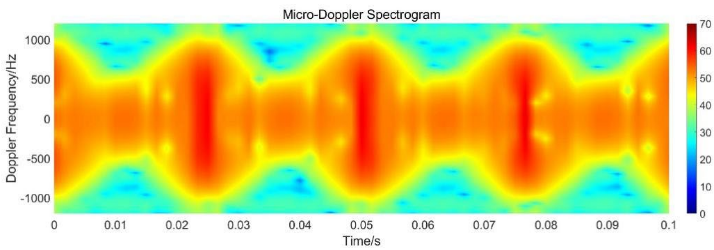
(c) Bandwidth = 1 GHz

Figure 1: Spectrogram with different bandwidth

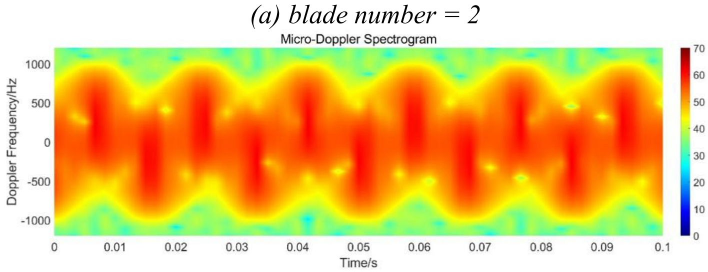
As shown in Figure 1, the resolution in the MD spectrograms increases significantly when the bandwidth increases. When the bandwidth is 250 MHz, the frequency components in the spectrogram are fuzzy, while when the bandwidth is increased to 1 GHz, the resolution of the spectrogram is improved, and the distance between the frequency components is more prominent, which allows the blade's rotational motion features to be shown more clearly.

4.2 Effect of blade number on Micro-Doppler characteristics

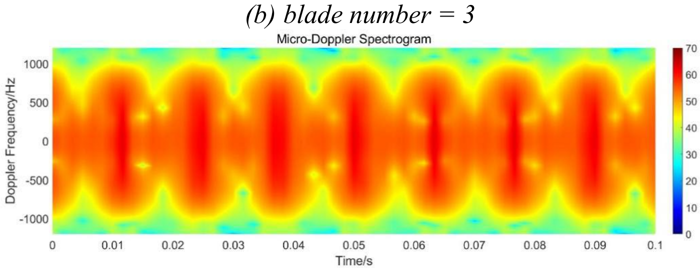
We simulated the micro-Doppler spectrograms at a bandwidth of 500 MHz, an angular velocity of 20 rad/s, and a blade length of 10 for the number of blades of 2, 3, and 4, respectively.



(a) blade number = 2



(b) blade number = 3



(c) blade number = 4

Figure 2: Spectrogram with different blade numbers

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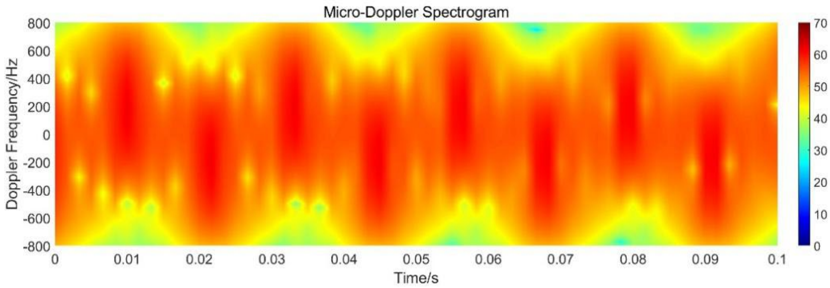
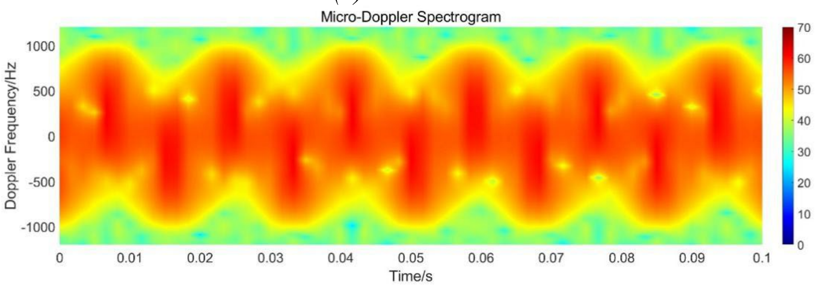
As Figure 2 shows, the frequency components in the spectrograms become more complex as the number of blades increases. The spectrograms of two blades are relatively simple with fewer frequency components; when the number of blades increases to four, the frequency components increase significantly and are more densely distributed. Thus, the MD features of the multi-blade system are more complex and informative.

4.3 Effect of angular velocity on Micro-Doppler characteristics

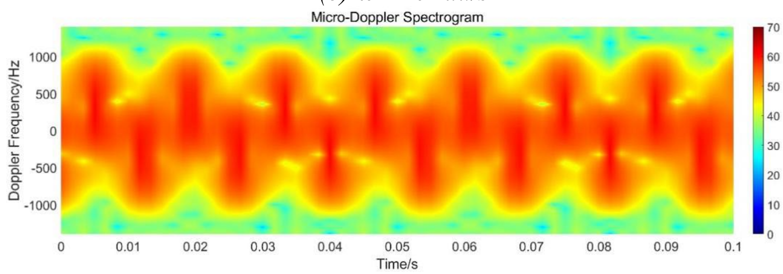
To verify the effect of rotational speed on the MD features, we set three different rotational speeds: 15 rad/s, 20 rad/s, and 25 rad/s with a bandwidth of 500 MHz, a blade number of 3 and a blade length of 10, to observe the changes in spectrograms under different rotational speeds.



(a) ω =15 rad/s



(b) ω =20 rad/s



(c) ω =25 rad/s

Figure 3: Spectrogram with three different angular velocity

The experimental results in Fig. 3 show that the range of frequency shifts in the spectrogram increases as the rotational speed increases. At a rotational speed of 15 rad/s, the frequency shift ranges from -800 Hz to 800 Hz; when the rotational speed is increased to 25 rad/s, the frequency component in the spectrogram extends from -1000 Hz to 1000 Hz. At the same time, with the increase of the rotational speed, the periodicity feature of the signal in the spectrogram is more prominent.

4.4 Effect of blade length on Micro-Doppler characteristics

In our experiments, we kept the bandwidth at 500 MHz, the rotation speed was set to 20 rad/s, and the number of blades was set to 3. We set three different blade lengths of 10, 12, and 15, respectively.

The experimental results are shown in Fig. 4, where the increase in blade length did not significantly affect the frequency distribution in the spectrogram. The range of frequency distribution is almost the same at three different blade lengths.

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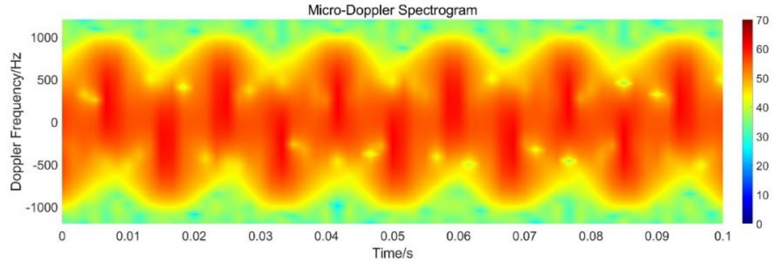
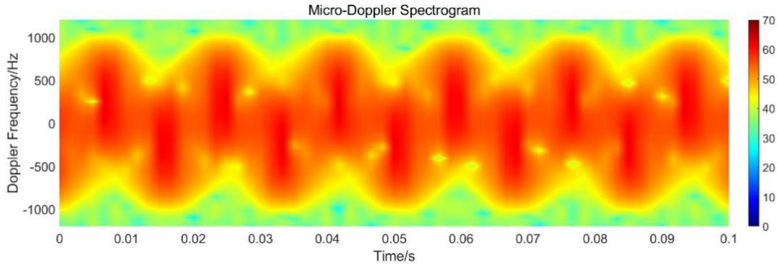
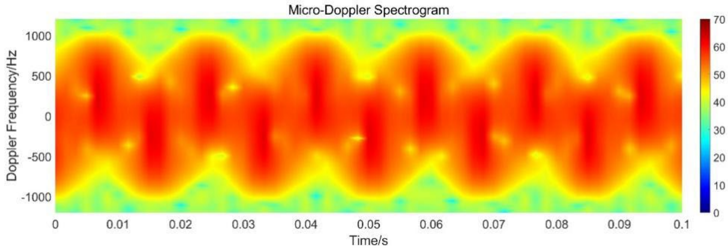


(a) blade length of 10



(b) blade length of 12



(c) blade length of 15

Figure 4: Spectrogram with three different blade lengths

5. Conclusion

Based on Matlab simulation, this paper systematically studies the effects of parameters such as bandwidth, blade number, blade length and rotational speed on the MD effect of rotating blades and discusses the role of these parameters in radar-based UAV detection. By discreting the blades into several units and extracting time-frequency features by short-time Fourier Transform (STFT), the experimental results show that the increase of bandwidth effectively improves the resolution of the target, while the increase of the number of blades makes the spectrum more complex, mainly due to the increase of information. With the increase in rotational speed, the frequency shift increases, and the periodicity in the spectrum becomes more apparent. In contrast, blade length has little influence on MD characteristics, and the simulation results of three different blade lengths have little difference. The research in this paper provides theoretical support for the parameter optimization of target recognition in radar-based UAV detection systems and provides a reference for further optimization of radar detection system design in the future.

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