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The MD effect of a moving UAV's rotor

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Abstract: Explosive growth of private drones pose great threat to privacy and safety. Accurately capturing is necessary for regulations. The micro-Doppler (MD) effect is commonly used to identify small unmanned aerial vehicles (UAVs), especially hovering UAVs. This study analyzes the MD effect of UAV rotor blades. It extracts the time-frequency features during radar-based UAV detection using the Short-Time Fourier Transform (STFT). By comparing the MD characteristics of UAVs in hovering and moving states within the same distance unit, as well as the signal difference when the distance unit changes or remains unchanged during the translation process, this paper analyzes in depth the MD characteristics of UAVs in various motion states. The results show that proper tracking of the range unit is necessary to extract the correct MD of a moving target.

1. Introduction

With the rapid development of UAV technology, the application of UAVs in civil and military fields is becoming extensive [1]. However, the widespread use of UAVs has also brought a series of safety and privacy issues, making effective control of UAVs particularly important [2]. Radar, as a remote detection means, is widely used in the detection and monitoring of UAVs due to its ability to penetrate obstacles and work stably in complex environments [3]. However, the radar echo signals of small UAVs are similar to those of natural objects such as birds, which poses a challenge to the accurate identification of UAVs [4]. The MD effect, as an important phenomenon in radar signal processing, can provide additional information about the motion state of the target, which helps distinguish UAVs from other similar objects. MD features have already been applied to the identification of UAVs [5] and the distinguishment between UAVs and birds [6].

Present research mainly focuses on the extraction of MD of hovering UAVs [7-8]. As range migration will occur, it is important to study the MD effect of moving UAVs. This paper aims to study the MD effect of UAVs in hovering and leveling states and compare the MD characteristics of these two states. By analyzing the MD signals of UAVs, it is possible to more accurately identify and classify UAVs, thereby improving the accuracy and reliability of radar detection systems. The research first reviews the basic principles of the MD effect and the key technologies in UAV detection. Then, through experiments, radar echo data of UAVs in different states were collected, and MD features were extracted using signal processing techniques. Finally, by comparing the MD characteristics of UAVs in hovering and leveling states at the same or different distance units, differences in frequency shift and signal modulation between the two were found, providing a theoretical basis for an in-depth understanding of the MD effect in radar-based UAV detection systems.

This research not only provides further theoretical basis and technical methods for radar detection of UAVs but also has important significance for improving the efficiency and safety of UAV control. The research results are expected to be applied to the design and optimization of UAV monitoring systems, providing technical support for the safe management of UAVs.

2. The basic fundamental

2.1 MD Effect

The MD effect, as referenced in [9], is a phenomenon where the rotation of a target alters the radar wave's frequency, resulting in a noticeable MD (MD) shift. To extract this MD effect, time-frequency analysis techniques are typically employed. These techniques examine the signal in both the temporal and spectral domains to detect the frequency variations induced by minor target movements.

One of the prevalent methods for time-frequency analysis is the Short-Time Fourier Transform (STFT), as mentioned in [10]. The STFT localizes signal characteristics in time and frequency by segmenting the signal into several brief time frames and then applying a Fourier transform to each segment. Here's a rephrased description of the STFT process:

1). The received radar signal is divided into several discrete time segments.

2). A Fourier transform is conducted on the signal within each segment to calculate the corresponding frequency spectrum.

3). The individual frequency spectra are aggregated to create a comprehensive time-frequency representation, known as a spectrogram.

2.2 Reflected radar signal of point target model

LFM signals are frequently utilized in radar technology because they offer the advantage of high-resolution range detection within a narrow bandwidth. This is possible due to the signal's strong interference rejection and the ease with which it can be implemented, as highlighted in the reference [11]. The formula for the LFM signal is shown in equation (1):

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

$\mathrm{f_c}$ stands for the carrier frequency, which is the central frequency of the radar signal. *t* represents the fast time, which is the rapid temporal dimension of the signal. T_p denotes the pulse duration, defining the temporal length of the radar signal. *t0* is the time delay caused by the distance between the target and the radar. K_r is the frequency modulation rate, describing the rate at which the signal's frequency changes over time, described as follows in equation (2).

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

Where B is the bandwidth of the radar signal.

2.3 Range Migration

The range migration is formed by the change in the relative distance of a target in the radar beam direction over time, due to the movement of the radar platform (such as an aircraft or satellite) or the targets during the illuminating period. This change in distance causes a phase variation in the echo signal, which is related to the target's motion relative to the radar. The tracking of the range cell is achieved with the help of range migration curve.

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;

3.2 Rotary blade modeling

The trajectory of the blade is defined by its location at a given point in time t.The center of the blade's rotational motion is positioned at coordinates $\mathrm{rot_center} = (\mathrm{x_{center}}, \mathrm{y_{center}})$, and the blades have a radius of R. The axis of rotation is located at the coordinates (0,1000), while the radar is situated at (0,0). The blade's position at moment t is as in equations (3) and (4).

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

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

V_x is the velocity of the UAV's motion on the x-axis and V_y is the velocity of the UAV's motion on the y-axis.The speed at which the blade spins is indicated by ω , the angular velocity. The starting orientation of the blade is set by φ_0, the initial phase angle, which defines where the blade is positioned when we begin to track its motion.

3.3 Pulse Compression

The radar signal received must be subjected to pulse compression to improve its resolution. The process includes the following steps:

1). Fast Fourier Transform (FFT): The time-domain echo signal received is converted to the frequency domain using the Fast Fourier Transform.

2). Matched Filtering: The conjugate of the transmitted signal is determined and multiplied by the frequency-domain representation of the echo signal. This step is essentially a matched filter, designed to maximize the correlation between the signal and the reference signal [12].

3). Inverse Fourier Transform (IFFT): The frequency-domain signal that has undergone matched filtering is transformed back into the time domain via the Inverse Fast Fourier Transform.

4). Pulse Compression Outcome: By following these steps, we achieve the signal after pulse compression. The mathematical formula for pulse compression is expressed in Equation (5).

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

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 Short-Time Fourier Transform (STFT) is capable of presenting the time-frequency characteristics of non-stationary signals in a graphical form. Particularly for the MD effect induced by rotating blades, the STFT can distinctly expose the dynamic features like the angular velocity and the rotation cycle of the blades. The mathematical expression for STFT is depicted in Equation (6).

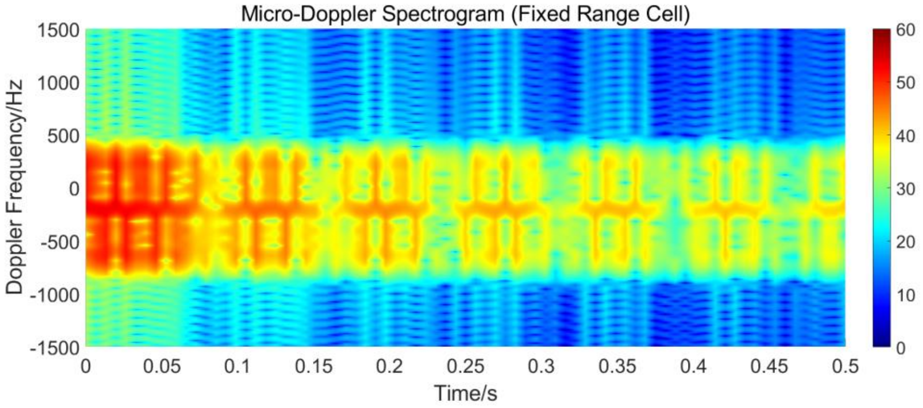
$$STFT\{s(t)\}(t,f) = \int_{-\infty}^{\infty} s(\tau) \cdot \omega(t-\tau) \cdot e^{-j2\pi f\tau}\, d\tau \tag{6}$$

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, the Short-Time Fourier Transform (STFT) is implemented using MATLAB's spectrogram function. The approach starts by dividing the signal into segments, followed by applying the Fast Fourier Transform (FFT) to each segment to acquire spectral data. These data are then combined to create a time-frequency spectrogram that vividly demonstrates the MD effect. This procedure not only shows how the signal's frequency changes with time but also captures the motion characteristics of moving targets, such as rotating blades.

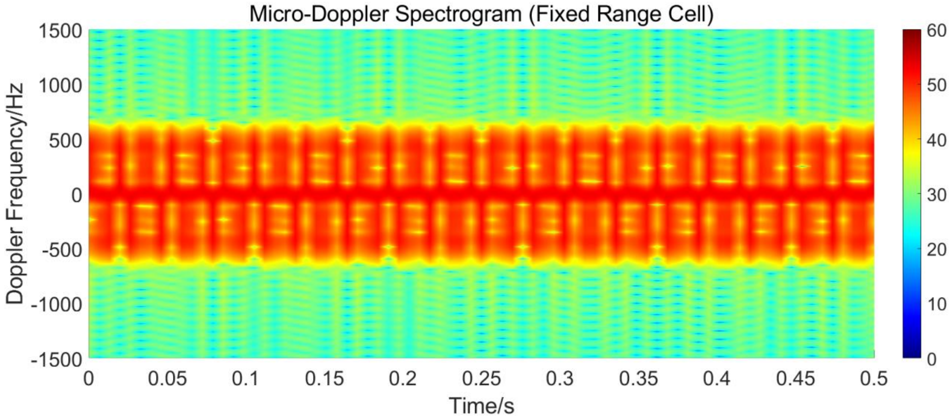
4. Results

4.1 Comparison of the MD Spectrogram of a UAV in Hovering State and Rapid Movement State (10 m/s)

In FIG1, we simulated the MD spectrograms of a UAV moving flat and hovering with the fixed range cell. FIG1 includes (a) and (b).Figure (a) shows the MD spectrogram of a high-speed moving UAV (with a speed of 10 m/s in the x-axis and y-axis, respectively) at a fixed distance cell. Figure (b) shows the MD spectrogram of the hovering UAV at a fixed distance cell.



(a) MD spectrogram of a UAV at x-axis speed and y-axis speed of 10 m/s with the fixed range cell



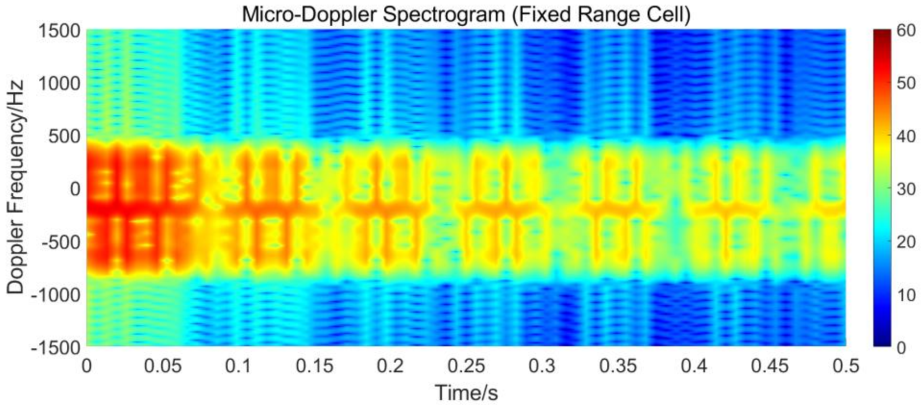
(b) MD spectrogram of a hovering UAV with the fixed range cell

Figure 1: The MD Spectrogram of a UAV in Hovering State and Rapid Movement State (10 m/s)

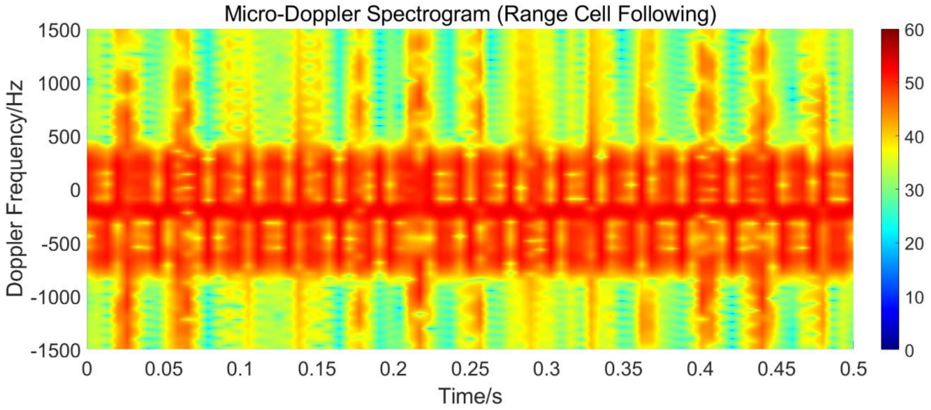
When observing a fixed range cell, the MD effect vanishes when the UAV is moving away. Although the MD effect of a hovering UAV can be extracted with a fixed range cell, it is not a suitable strategy for moving targets. Fixing range cell does not take into account the actual motion of the target, resulting in the phase change caused by the motion cannot be correctly compensated.

4.2 Comparison of the MD Spectrogram for a UAV in Fast Movement State(10m/s) with Fixed Range Cells and Range Cell Following

FIG2 compares the MD spectrograms of the fixed distance unit and the following distance unit under fast motion conditions. FIG2 includes (a) and (b).Figure (a) shows the MD spectrogram of a fast moving UAV (with a speed of 10 m/s in the X-axis and Y-axis, respectively) with the fixed range cell. Figure (b) shows the MD spectrogram of a fast moving UAV (with a speed of 10 m/s in the X-axis Y-axis) with range cell following.



(a) MD spectrogram of a leveling UAV at x-axis speed and y-axis speed of 10 m/s with the fixed range cell



(b) MD spectrograms of a leveling UAV at x-axis speed and y-axis speed of 10 m/s with range cell following

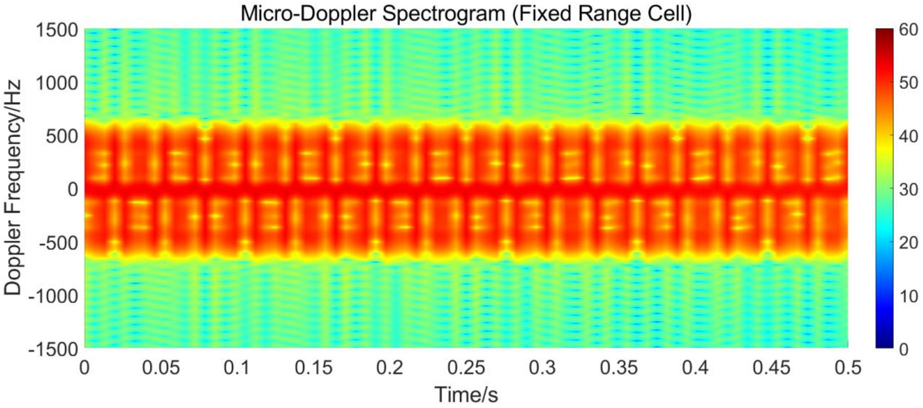
Figure 2: The MD Spectrogram for a UAV in Fast Movement State(10m/s) with Fixed Range Cells and Range Cell Following

Based on the aforementioned point of view, the spectrograms between fixed range cell and following range cell show the differences. By following the range cell, the moving UAV can be tracked during its movement, so the MD effect can be correctly extracted. It should be noted that the tracking is achieved by finding the maximum in the range migration curve.

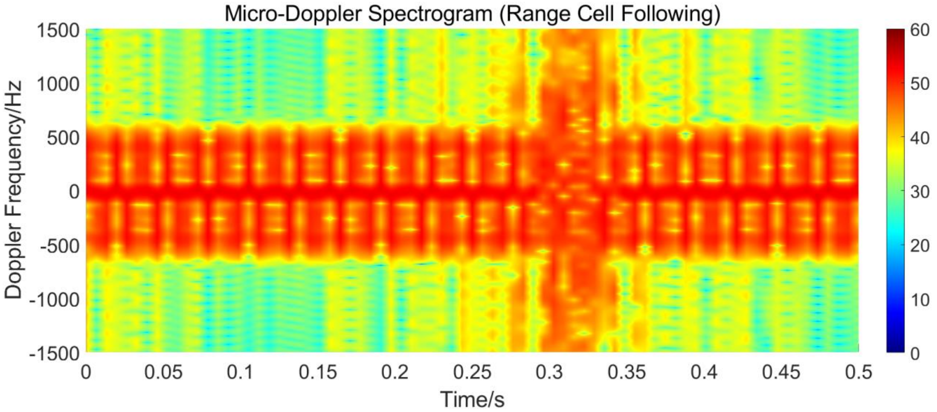
4.3 Comparison of the MD Spectrogram for a UAV in Slow Movement State (1 m/s) with Fixed Range Cells and Range Cell Following

In FIG3, the MD spectrograms for the low speed motion condition were simulated, considering both the fixed distance unit and the following distance unit scenarios.FIG3 includes (a) and (b). Figure

(a) shows the MD spectrogram of a low-speed moving UAV (with a speed of 1 m/s in the X-axis and Y-axis, respectively) with the fixed range cell. Figure (b) shows the MD spectrogram of a low-speed moving UAV (with a speed of 1 m/s in the X-axis Y-axis) with range cell following.



(a)MD spectrogram of a UAV at x-axis speed and y-axis speed of 1 m/s with the fixed range cell



(b)MD spectrogram of a UAV at x-axis speed and y-axis speed of 1 m/s with range cell following

Figure 3: The MD Spectrogram for a UAV in Slow Movement State (1 m/s) with Fixed Range Cells and Range Cell Following

It is worth mentioning that for slowly moving UAV, the effect of tracking range cell is not obviously better than fixed range cell. The reason is that the speed of UAV is not large enough to migrate multiple range cells during the observation period. In other words, it stays at two adjacent range cells during 0.5 second observation period. Although for fixed range cell strategy, the correct range cell is not captured, the magnitude of echo in the adjacent range cell is still strong enough to provide MD information. If the observation period is long enough, range cell migration will be more obvious.

5. Conclusion

This study discusses the MD characteristics of a small UAV under different motion states. Signal simulation is carried out by discretizing the rotor blades of the UAV into point targets and generating the echo signals of these targets. The MD characteristics were extracted with the help of STFT, and the MD differences between hovering, slow-moving, and fast-moving rotor blades were discussed. The results show that the MD effect of UAVs in hovering states is small, and the MD effect of flat-moving UAVs is more obvious. In fast motion, the tracking distance unit can compensate for the motion-induced phase changes, which reduces the aberrations due to distance changes, and this also indicates the need to track the ranging unit during fast UAV motion to capture the complete MD characteristics. However, in slow motion, periodic motions such as rotor rotation of the UAV show obvious periodic peaks in the MD spectrum easily captured by the fixed distance unit, thus less likely to cause aberrations and blurring. This paper provides the theoretical basis and technical method to study the tracking and following strategy to capture the MD effect of UAVs under different states.In future research, the strategy on tracking UAVs with various motions will be studied to achieve MD extraction of UAVs under multiple states.

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