Feature Extraction Method of Helicopter Target Based on Flicker Phenomenon Combined with Phase Compensation

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ABSTRACT For the typical multi-component periodic micro-Doppler signal parameter estimation, a helicopter rotor feature extraction method based on flicker phenomenon and phase compensation is proposed in this paper. The method firstly analyzes the formation mechanism of helicopter rotor flicker phenomenon in time domain and time-frequency domain through the integral model. Then the demodulation operator of the micro-Doppler signal is constructed for the phase compensation of the echoes with respect to the time-frequency flicker characteristics and the phase information of the slow time dimension of the target echoes. The parameter combination of the possible number of blades and rotational speed is predicted using the time domain flicker interval, and the phase compensation process is evaluated and optimized to significantly reduce the amount of computation. Finally, the parameter estimation of rotor blade number, blade length and rotational speed is acquired by calculating whether the center frequency of each flicker after phase compensation is periodically focused to zero frequency. The simulation results show that the method can effectively estimate the main parameters of helicopter rotor blades, and the processing results of the measured data show that the proposed method has more stable performance compared with OMP algorithm and Hough transform, which provides a new technical way for helicopter rotor blade feature extraction.

INDEX TERMS Helicopter Target; Micro-Doppler Effect; Flicker Phenomenon; Phase Compensation.

I. INTRODUCTION

Apart from the center-of-mass transitional motion of the aerial vehicles, some micro-motion, such as vibration or rotation of components, also can be detected, which will result in periodic modulation of the phase of radar echoes and further generate an additional frequency modulation band near the target transitional Doppler shift. This additional modulation band is called the micro-Doppler signal, and the modulation phenomenon caused by micro-motion is called the Micro-Doppler effect (MDE) [1-2]. The MDE can reflect the geometric composition and motion characteristics of the target, which can be used to determine the properties of the target and innovate means to target identification [3]. Nowadays, the application of the MDE for target identification has been a research hotspot. There are three main types of aircraft in the modern battlefield: rotor helicopters, propeller aircraft and jet aircraft. Among them, helicopters are typical "low, slow and small" targets with features such as flexibility and maneuverability, which has posed a great threat to air defense security. In order to enhance the situational awareness of the battlefield, it is imperative to extract and analyse the features of helicopter target to achieve automatic target identification. Currently, scholars have conducted in-depth research on the modeling and feature extraction methods of helicopter. There are three main modeling methods: (1) RCS model [4-5], which obtains echoes by calculating the target backward scattering field and can fully consider the scattering characteristics of the target, and the model is the most accurate, but the calculation is too complicated; (2) Scattering point model [6-7], which is the most traditional and applied modeling method, analyzes the target by equating it into a number of scattering points. This method can be applied into complex scenes with non-uniform
distribution and different scattering intensity, but the amount of computation increases with the increase of the number of scattering points; (3) Integral model [8-11], which equates the target as a rigid, uniform line, with simple mathematical calculation, can reflect the structural differences of the target as a whole. It should be noticed that the scattering point model can be equated to the integral model when the scattering points in the scattering point model are uniformly distributed and spaced less than half of the radar wavelength. Based on the MDE in the echo, the feature extraction of helicopter rotor blade can be transformed into a parameter estimation of multicomponent periodic micro-Doppler signals.

In general, the most common practice is to estimate the target parameters by using the flicker period and the maximum instantaneous micro-Doppler frequency, where the flicker period is determined by the number of blades and rotational speed, and the maximum instantaneous micro-Doppler frequency is determined by the blade length and rotational speed. Obviously, this is an underdetermined equation. Therefore, more effective information from the target echo is needed to avoid the problem of solving the underdetermined equation.

The solutions to the parameter estimation of multicomponent periodic micro-Doppler signals can be classified into four main categories [12]: (1) Methods based on signal decomposition. These methods can decompose multicomponent signals into single component signals, such as separating micro-Doppler components from echoes by chirplet transform [13], variational mode decomposition (VMD) [14] and empirical mode decomposition (EMD) [15], but due to the serious overlap of each micro-Doppler component in echoes, it is difficult to perform effective separation and micro-motion parameter extraction when the frequencies of two components are close to each other; (2) Transform domain-based method. The micro-Doppler signals caused by target vibration and rotation are in the form of Sinusoidal Frequency Modulation (SFM) signals, so the micro-Doppler spectrum of the echoes can be obtained by constructing a matching calculation to establish a sinusoidal frequency modulation signal domain with a unique operational definition and decomposing the echoes in an orthogonal triangular function basis [16]. This method has better estimation accuracy and anti-noise performance, but the cross terms are serious when there are more than three signal components, and it is difficult to extract micro-motion features based on the micro-Doppler spectrum; (3) Image domain-based methods. This type of method is widely used. Firstly, the time-frequency image is obtained by time-frequency analysis through short time Fourier transform (STFT) or short time fractional order Fourier transformation (STFRST) [17]. Then the curve detection in the image space is transformed into the peak detection in the parameter space to extract the micro-motion features of the target by using Hough transform [18-19], iRadon transform [20] and other image processing methods. The advantage is that the extraction of target micro-motion features can be achieved as long as the curve equation of the target micro-motion in the time-frequency domain can be derived. However, such methods rely heavily on the performance of time-frequency analysis methods, and when there are multiple micro-motion signal components in the echo, the time-frequency aggregation is poor, and the computational complexity increases exponentially with the increase of the parameter space dimension; (4) Sparse reconstruction-based methods. Since the target echoes naturally have sparse characteristics, the micro-Doppler signal can be analyzed by sparse reconstruction methods. These methods based on the sinusoidal modulation property of the micro-Doppler signal, construct the corresponding sparse dictionary, and invert the micro-Doppler components by algorithms such as Orthogonal Matching Pursuit (OMP) [6,21], which obtains a good estimation under subsampling conditions but is not robust when the search grid mismatched.

For the helicopter rotor blade feature extraction in narrowband radar, this paper proposes a helicopter rotor blade feature extraction method based on flicker phenomenon and phase compensation, which optimizes the extraction process and greatly reduces the amount of computation. The specific work are as follows: (1) Use the integral model of helicopter rotor to obtain the echo under the flicker condition; (2) Predict the possible target blade number and rotational speed parameter combinations through the time-domain flicker interval to reduce the parameter search space dimension; (3) Analyze the mechanism of the generation of echo time domain flicker and time-frequency domain flicker; (4) The feasibility of phase compensation is demonstrated. Also the number of blades, the rotational speed and blade length of the target are estimated based on the periodicity of time-frequency flicker after phase compensation. The greatest advantage of the proposed method is that it can obtain the specific number of target rotor blades directly from the time-frequency diagram of the phase compensation result. The simulation results show that this method can effectively estimate the main parameters of helicopter rotor, and the measured data processing results show that compared with OMP algorithm and Hough transform, its performance is more stable, which means a new technical way for helicopter rotor feature extraction.

II. ROTOR BLADE MICRO-MOTION MODEL

The relative position of the rotor target and the radar is shown in Fig. 1, the distance between the radar and the rotor center is \( R_0 \), the radar beam elevation angle is \( \beta \), and the wavelength is \( \lambda \). Let the rotor blade rotation speed be \( f_r \), and the corresponding rotation angular velocity be \( \omega \).
According to [2], the slow time dimensional echo signal of rotor under the integral model can be expressed after matched filtering, clutter suppression and translational motion compensation as

$$S(t) = \sum_{n=0}^{N-1} L \sin\left(\frac{2L}{\lambda} \cos \beta \cos(\omega t + \theta_n)\right) \cdot \exp\left(-j\frac{2\pi L}{\lambda} \cos \beta \cos(\omega t + \theta_n)\right)$$

(1)

where $j$ is an imaginary unit, $N$ is the number of rotor blades, $L$ is the blade length, $\theta_n$ is the initial phase of the nth blade, and $n=1,2,...,N-1$.

Then, the micro-Doppler frequency caused by the rotational motion of the nth blade is

$$f^\omega_{\text{rot}} = \frac{1}{2\pi} \frac{d\phi(t)}{dt} = \frac{wL}{\lambda} \cos \beta \sin(\omega t + \theta_n)$$

(2)

Equation (2) shows that the micro-Doppler frequency of target echo is modulated by the sinusoidal function $\sin(\omega t + \theta_n)$, which means that the micro-Doppler frequency is time-varying and nonlinear. In addition, (2) shows that the maximum value of the micro-Doppler frequency is determined by the length of the target rotor, the rotational speed, the wavelength, and the position of the target. When $\phi=\omega t + \theta_n$ satisfies (3), the instantaneous micro-Doppler frequency of this rotor target takes the maximum value, as shown in (4). In addition, combining the characteristics of (3) and sinc function, the extreme value of the sinc function appears at this time, that is, the flicker phenomenon occurs. The physical essence of the flicker phenomenon is that when a blade on the target rotor is rotated to be perpendicular to the radar LOS direction, the echo intensity is maximum, and when deviating from that position the echo intensity drops steeply, resulting in periodic peaks in the time domain echoes [11].

$$\phi=\omega t + \theta_n = \frac{\pi}{2} + k\pi \Rightarrow t = \frac{k}{2f_i} + \frac{\theta_n}{2\pi f_i} + \frac{1}{4f_i}$$

(3)

$$f^\omega_{\text{max}} = \frac{wL}{\lambda} \cos \beta$$

(4)

Considering the physical structure of the rotor blade, when the number of blades is even, the flicker phenomenon caused by the relative symmetry of the blades is simultaneous, then the phase difference between two adjacent flickers appears as $2\pi/N$, but when the number of blades is odd, the phase difference between two adjacent flickers appears as only $\pi/N$ [22]. Combined with (3), it can be seen that the time interval between two adjacent flickers satisfies

$$\Delta t = \begin{cases} \frac{1}{Nf_i}, & \text{if } N \text{ is Even} \\ \frac{1}{2Nf_i}, & \text{if } N \text{ is Odd} \end{cases}$$

(5)

Equation (5) proves that the time domain flicker interval is inversely proportional to the true rotational speed of the target and is related to the parity of the number of blades.

III. FEATURE EXTRACTION

A. TIME-FREQUENCY FLICKER MECHANISM

Examining (1) carefully and neglecting the effect of echo amplitude, the echo of a single blade is mainly the product of the sinc function (profile) and the exponential function (phase). Without loss of generality, the echo of the first blade can be abbreviated as

$$S_{11}(t) = \sin(\Lambda \cos(\omega t + \theta_1)) \cdot \exp(-j\pi \Lambda \cos(\omega t + \theta_1))$$

(6)

where $\Lambda = 2L \cos \beta / \lambda$. Under the condition that the wavelength and target properties are determined, this term can be considered as a constant value.

As seen from (6), the echo of a single blade is presented as the form of multiplication of sinc function and exponential function, and the micro-Doppler frequency is time-varying, so the short time Fourier transform (STFT) is considered here to analyze the micro-Doppler frequency of the echo in the slow time dimension. From the properties of the Fourier transform, it is known that

$$S_{11}(f) = \text{FT}\left\{\sin(\Lambda \cos(\omega t + \theta_1))\right\} \otimes \text{FT}\left\{\exp(-j\pi \Lambda \cos(\omega t + \theta_1))\right\}$$

(7)

where $\text{FT}\{\ldots\}$ denotes the Fourier transform and $\otimes$ is the sign of the convolution operation. Given that $\text{sin}(t)$ and $\text{rect}(f)$ are a pair of Fourier transform pairs, then the Fourier transform of the time domain echo envelope is a rectangular strip function occupying a certain bandwidth, which is expressed as a flicker strip in the time-frequency diagram, as shown in Fig. 2(a). The Fourier transform of the exponential function is easy to solve as a sinusoidal function, as shown in Fig. 2(b).
From (7), the Fourier transform of the single blade echo is the convolution of the envelope Fourier transform and the phase Fourier transform, which leads to the time-frequency profile of the complete echo signal, as shown in Fig. 2(c). This is the mathematical formation mechanism of the rotor blade echo in the time-frequency domain showing the flicker phenomenon. Therefore, if the phase of the blade in the echo is compensated, the time-frequency diagram of the corresponding blade will return from Fig. 2(c) to Fig. 2(a). As a result, the completed phase compensated flicker can be identified and extracted from the multiple flickers. Given that the flicker focused to zero frequency must belong to the same blade, the number of blades of the whole rotor can be estimated according to the number of flickers between the two zero frequency flickers.

**B. ECHO PHASE COMPENSATION**

Since the rotational speed and length of each blade on the rotor are the same, and only different in the initial phase, which means obtaining one of the blade parameters can obtain the relevant parameters of the whole rotor, this paper considers using the phase compensation of a single blade to extract the feature of the whole rotor target. According to (6), the phase compensation operator is established to compensate the phase of the echo, and the rotor blade feature extraction can be converted into the optimal solution of parameter estimation.

\[
S_\alpha(t) = S(t) \exp(j \alpha \cos(\mu t + \chi)) \tag{8}
\]

where \( \alpha, \mu, \chi \) is the amplitude, angular velocity and initial phase factor, respectively. According to section 3.1, the time-frequency distribution of single blade echoes after phase compensation is a series of flickers with zero center frequency, and the feasibility of phase compensation is mathematically analyzed below.

When the target rotor contains an odd number of blades (asymmetrical structure), the time-frequency flicker alternates between positive and negative frequencies due to the asymmetry of the blades, and the time-frequency distribution is similar to Fig. 2(c). Given the relationship between the parameters \( \Lambda \) and \( f_{nd}^{max} \) of the echo phase \( \Lambda = 2 f_{nd}^{max}/w \), namely, the parameter \( \alpha \) associated with \( \mu \). At this time, the center frequency of the single blade time-frequency flicker is half of the flicker strip bandwidth, noted as \( f_{nd}^{od} \), that is, \( f_{nd}^{od} = f_{max}/2 \). Further derivation, the (8) can be rewritten as

\[
S_\alpha(t) = \text{sinc}(\Lambda \cos(wt + \theta_1)) \cdot \exp\left[j \pi \left(4 f_{nd}^{od} \cos(\mu t + \chi)/\mu - \Lambda \cos(wt + \theta_1)\right)\right] \tag{9}
\]

A further study of the phase term reveals that it is positively correlated with the difference of two sinusoidal functions, and the trend of the difference is related to the parameter \((\mu, \chi)\). This can be discussed in three specific cases as follows.

1) When \( w = \mu, \theta_1 = \chi \), the phase of this blade echo is fully compensated, and the phase term is annotated.

\[
S_\alpha(t) = \text{sinc}(\Lambda \cos(wt + \theta_1)) \tag{10}
\]

2) When \( w = \mu, \theta_1 \neq \chi \), the residual phase is the difference between two sinusoidal signals of the same frequency but with unequal initial phases, varying with the same trend as the sinusoidal signal.

\[
S_\alpha(t) = \text{sinc}(\Lambda \cos(wt + \theta_1)) \cdot \exp\left[j 2 \pi \text{Asin}\left(wt + \frac{\theta_1 + \chi}{2}\right)\sin\left(\frac{\theta_1 - \chi}{2}\right)\right] \tag{11}
\]

where \( \text{sin}((\theta_1 - \chi)/2) \) is a constant that does not vary with time.

3) When \( w \neq \mu, \theta_1 = \chi \), the residual phase is the difference between two cosine signals of different frequencies and different amplitudes, presented as an oscillation of both amplitude and frequency with time.

\[
S_\alpha(t) = \text{sinc}(\Lambda \cos(wt + \theta_1)) \cdot \exp\left[j \pi \left(4 f_{nd}^{od} \cos(\mu t + \chi)/\mu - \Lambda \cos(wt + \theta_1)\right)\right] \tag{12}
\]

Obviously \( w \neq \mu \Rightarrow \Lambda \neq 4 f_{nd}^{od}/\mu \), at this time, the amplitude of the two cosine signals are also different, so let \( a = 4 f_{nd}^{od}/\mu.b = \Lambda \), while the frequency is expressed in the following form \( \mu = w + \epsilon \), where \( \epsilon \) is the frequency difference between the two cosine signals, then its phase can be written as

\[
\phi = \cos\left((w + \epsilon)t + \theta_1\right) - \cos(wt + \theta_1) = (a \cos(\epsilon t) + b) \cos(wt + \theta_1) - a \sin(\epsilon t) \sin(wt + \theta_1) \tag{13}
\]

\[
= \sqrt{a^2 + b^2 + 2ab \cos(\epsilon t)} \sin(wt - f(\epsilon t) + \theta_1)
\]
where \( f(\epsilon t) = \arctan\left( \frac{a \sin(\epsilon t)}{b + acos(\epsilon t)} \right) \) is a time-varying quantity with a value range of \([-\arctan(a/b), \arctan(a/b)]\).

Observe the amplitude of the above equation, when \( \cos(\epsilon t) = 1 \), the amplitude is taken to the maximum value of \( a + b \); when \( \cos(\epsilon t) = -1 \), the amplitude is taken to the minimum value of \(-|a - b|\). Then the amplitude of the sinusoidal function is expressed as a periodic change with the passage of time. For the phase of the sinusoidal function, at this time, its frequency component not only contains the fixed frequency component \( w \), but also is affected by the periodic time-varying component \( f(\epsilon t) \). Finally, it is expressed as a fixed frequency \( w \) as the reference, while the form of periodic change with \( f(\epsilon t) \) as the increment.

As mentioned above, the compensation operators of different frequencies or different phases cannot fully compensate the echo phase, and all the flickers of the same blade on the time-frequency spectrum cannot be focused to zero Doppler frequency. The single-blade echo phase can be fully compensated only at \( w = \mu, \theta_{i} = \chi \).

\[
S_{i}(t) = \text{sinc} \left( \Lambda \cos \left( wt + \theta_{i} \right) \right) - \text{exp} \left[ j\pi \left( 4f_{n}^{ev} \cos \left( \mu + \chi \right) \right) / \mu - \Lambda \cos \left( wt + \theta_{i} \right) \right] 
\]
\[
+ \text{sinc} \left( \Lambda \cos \left( wt + \theta_{i} + \pi \right) \right) - \text{exp} \left[ j\pi \left( 4f_{n}^{ev} \cos \left( \mu + \chi \right) \right) / \mu - \Lambda \cos \left( wt + \theta_{i} + \pi \right) \right] 
\]

When \( w = \mu \neq \theta_{j} = \chi \), the phase compensation case is as same as described in the previous part, so this part focuses on the optimal compensation case when \( w = \mu, \theta_{i} = \chi \). Equation (14) can be derived as follows

\[
S_{i}(t) = \text{sinc} \left( \Lambda \cos \left( wt + \theta_{i} \right) \right) 
\]
\[
+ \text{sinc} \left( \Lambda \cos \left( wt + \theta_{i} + \pi \right) \right) \text{exp} \left[ j2\pi \Lambda \cos \left( wt + \theta_{i} \right) \right] 
\]

From (15), it can be seen that at the time of flicker generation, the two symmetrical blades produce zero frequency flicker and non-zero frequency flicker, respectively. Specifically the Doppler frequency of the latter is \(-\Lambda \sin(\omega t + \theta_{i})\), showing a sinusoidal trend with amplitude \( \Lambda w \), namely, the center frequency of the non-zero frequency flicker undulates as a sinusoidal function. The scene is characterized by the phase of one of the blades being fully compensated, and the echo of this blade is left with a slow time domain envelope. The flicker in the time-frequency pattern is focused near the zero frequency, and the phase of the other blade becomes the original negative quadratic, with its center frequency focused near \( \pm f_{\text{max}}^{t} \). As with an odd number of blades, the flicker caused by a single blade in the blade pair can be focused to zero frequency by phase compensation.

Overall, a uniform description of phase compensation for echoes with different numbers of rotor blades can be obtained by choosing a suitable reference standard, and (8) is rewritten as

\[
S_{i}(t) = S(t) \exp \left[ j4\pi f_{5} \cos \left( \mu + \chi \right) / \mu \right] 
\]

In (16), \( f_{5} = f_{\text{max}}^{t} \) when the target has an odd number of blades; \( f_{5} = f_{\text{max}}^{ev} \) when the target has an even number of blades, so the parameter space dimension is transformed from three-dimensional \((\alpha, \mu, \chi)\) to two dimensional \((\mu, \chi)\). Combined with (5), because the number of blades usually ranges from 2 to 7, the rotational speed search node does not need to be set iteratively in fact, only a small number of special nodes are needed. By this way, the amount of search process calculations can be significantly reduced.

C. PARAMETER ESTIMATION

For the above analysis, the phase of a single blade in the echo can be determined by calculating whether the center frequency position of the flicker is shifted to the zero frequency position after phase compensation which means the phase of the echo is completely compensated. Since it is not known which flicker belongs to the same blade at the beginning of phase compensation, and there may be multiple phase compensation operators that can focus the center frequency of a flicker to zero frequency, but only when the phase of a blade is fully compensated, the center of the
flicker caused by the blade will all be focused to zero frequency, and there must be periodicity. The flicker center periodicity test can avoid the estimation error caused by the instability of a single flicker focusing effect, and here consider using all the flicker center frequency change during the echo time to optimize the parameter search. In order to determine whether the positive frequency flicker and negative frequency flicker are symmetrical, this paper obtains the time-frequency information of the original echo and accumulates the pixel values along the frequency axis for the positive and negative frequency parts of the time-frequency diagram respectively. In this part, the STFT without cross terms and with satisfactory resolution is selected as the time-frequency analysis method. The positive frequency accumulation result is recorded as $TFD_p$, and the negative frequency accumulation result is recorded as $TFD_N$. The cross-correlation processing of the accumulation results is

$$R_{pN}=TFD_p \otimes TFD_N$$  \hspace{1cm} (17)

The parity of the number of target blades can be determined by the time delay value of the cross correlation processing. If the time delay value is zero, then the target has an even number of blades, and if the time delay value is not zero, then the target has an odd number of blades.

In the phase compensation stage, when the number of rotor blades is odd, the blade number search range $[7, 5, 3]$ is set in reverse order. Since the time interval $\Delta t$ between two consecutive flickers is estimated in the time domain echo by its relationship with the number of blades $N$ and rotational speed $f_r$, the rotational speed search node $[1/4, 1/10, 1/6] \Delta t$ is determined at the same time. Considering the physical structure of the target rotor, when the rotor has $N$ blades, there must be a blade initial phase falling into $[0, 2\pi/N]$. For example, when the rotor has 5 blades, the initial phase search range is $[0, 2\pi/5]$, and so on. Similarly, when the rotor structure is symmetric, set blade number search range at $[6, 4, 2]$, rotational speed search range at $[1/6, 1/4, 1/2] \Delta t$, and the initial phase setting rules remain unchanged. The above parameter space nodes are used to construct the phase compensation operator to compensate the echo.

In the parameter estimation stage, the frequency difference between the center frequency of all flickers and the zero frequency is calculated. If a total of $K$ flickers occur in the echo and there are $M$ phase nodes, then the difference matrix is recorded as $[D_1, D_2, \ldots, D_M]$, $D_m=[d_{m1}, d_{m2}, \ldots, d_{mk}]$. When all flickers of the blade finish focusing during the observation time, and the flickers of other blades do not finish focusing, the initial phase node corresponding to the smallest value in the frequency difference matrix is the initial phase estimation of the blade, and the number of blades contained in the rotor target is determined under this initial phase node based on the period between zero frequency flickers, and the rotational speed node corresponding to the number of blades is the rotational speed estimation. According to (4), after estimating the rotational speed of the target, the length of the rotor blades can be estimated based on the reference frequency of the time-frequency flickers.

$$\tilde{L}_r = \frac{2\lambda f_b}{w \cos \beta}$$  \hspace{1cm} (18)

In summary, the flicker periodicity after phase compensation can achieve the extraction of the characteristic parameters of the helicopter rotor blade. The main steps of proposed algorithm are as follows:

1) Obtain the slow time echo of the distance unit where the target is located after pulse compression, clutter suppression, translational motion compensation, and calculate the flicker interval $\Delta t$.

2) Perform time-frequency analysis on the slow time echo. Accumulate pixel values on the time-frequency diagram and determine whether the blade structure is symmetrical by mutual correlation processing, and then calculate the flicker reference frequency $f_r$.

3) Set the blade number search node and the corresponding rotational speed search node. Divide the initial phase search range for different blade numbers, and construct the phase compensation operator to compensate the echoes according to the parameter matrix $\{\mu, \chi\}$.

4) Obtain the time-frequency spectrum of each compensation echo. Record the offset of the center frequency of all flickers from the reference frequency, and save the offset matrix.

5) Find the position of the minimum value of the offset in the difference matrix, and judge whether the zero frequency in each flicker appears periodically under the corresponding initial phase node. If yes, output the initial phase estimation $\hat{\Theta}$ and the number of blades estimation $\hat{N}$, and the loop ends; If not, update the range of blade number and return to step 3.

6) Based on the estimated value of the blade number $\hat{N}$ and the rotational speed $\hat{\omega}$, further estimate the blade length $\tilde{L}_r$.

IV. SIMULATION AND EXPERIMENTATION

A. SIMULATION ANALYSIS

This subsection based on the AH-64 helicopter gunship and Mi-28N helicopter gunship rotor models, simulates and analyzes them by using a conventional narrowband system whose radar parameters of carrier frequency is 1GHz, repetition frequency is 4000 Hz, and bandwidth is 2MHz. The target simulation parameters are shown in Table 1. To fully illustrate the feasibility and comprehensive advantages of the proposed parameter estimation method, this subsection also analyzes the estimation accuracy and computational of the proposed algorithm.

| TABLE I: THE PARAMETERS IN SIMULATION |
|---------------------------------------|
|                                       |
| **AH-64**                             |
| Number of blades | 4     |
| Blade length    | 7.3 m |
| Rotational speed | 4.8 r/s |
| Primary phase   | $\pi/12$ rad |
| **Mi-28N**                             |
| Number of blades | 5     |
| Blade length    | 8.6 m |
| Rotational speed | 4 r/s |
| Primary phase   | $\pi/12$ rad |
1) EVEN NUMBERED BLADE TARGET

The target in this part of the simulation is AH-64, and the target rotor contains four blades. Fig. 4 shows the echoes and time-frequency distribution of the rotor target, where Fig. 4(a) shows the slow time dimensional echoes of the distance bin where the target is located. It can be seen that because of the continuous rotation of the target blades, the slow time dimensional echoes are mainly composed of a series of identically spaced spectral peaks called flickers, and the average flicker interval can be estimated to be 0.05206s. Fig. 4(b) shows the results of the STFT of the slow time dimensional echoes, and it is obvious that both positive and negative frequency flickers occur simultaneously, and the center frequency of a single flicker can be estimated to be 633.32Hz. The asymmetry of the flicker in the time-frequency domain is mainly caused by the asymmetry of the rotor structure, which can be determined by accumulating the pixel values of the time-frequency diagram, and the accumulation results are shown in Fig. 4(c). Then the cross correlation process is performed, and the time delays of the two curves are judged to be 0 in Fig. 4(d), so it can be figured out that the target rotor contains an even number of blades.

To determine the number of blades contained in the target rotor, the target echoes are processed by phase compensation, and then time-frequency analysis is performed to record the magnitude of the deviation of the center frequency of all flickers from the reference frequency. Since the flicker interval of the target echo has been estimated in time domain and the target has an even number of blades. Combined with (5), the product of blade number and rotational speed shall be 19.21, then there are only three possible combinations of blade number and rotational speed, respectively [6,3.20], [4,4,80] and [2,9,60]. Set the initial phase search range for the above three groups of possible values as $[0,\pi/3]$, $[0,\pi/2]$ and $[0,\pi]$, and the initial phase search step is $\pi/180$. The algorithm gives priority to the combination of the least number of search nodes to compensate for the phase of the echo, that is to say, the first search process is under the six blades case. At this time, it can be seen that the minimum value of the offset matrix recording the deviation of all flicker center frequencies from the reference frequency is 39.52Hz and that after the phase compensation the time-frequency flicker is not focused to zero frequency. So it can be judged that this search process did not get the true value. Update the blade search parameters, and the search results under four blades case as shown in Fig. 5(a) and Fig. 5(b). It can be seen that during this phase search process, the center frequency of the 3rd flicker was focused to zero frequency at the 16th phase node, and at the same time the 1st, 5th, 7th and 9th flickers were focused to zero frequency, showing an obvious periodicity, and the period is 2. After optimal phase compensation, the time-frequency result is shown in Fig. 5(c).
For the time-frequency flicker with an even number of blades, the number of blades should be 2 times of time-frequency flicker period of the same blade, thus the estimated number of blades is 4 and the corresponding estimated rotational speed is 4.8r/s. The estimated initial phase value is $\pi/12$, and the estimated target blade length is 6.299m under the elevation angle by calculation. Most of the current narrowband radar systems have target ranging, angle and height measurement functions at the same time, and can easily obtain the elevation angle of the target. Combined with the prior information that the elevation angle of the target location is $\pi/6$, it can be estimated that the target blade length is 7.274m. Compared with the parameter settings in Table 1, it can be seen that the estimation of blade number and rotational speed is absolutely accurate, and the estimation error of blade length is only 0.36%.

2) ODD NUMBERED BLADE TARGET

The aforementioned validates the feature extraction effect of the symmetric structure rotor target. Since the flicker generated by the symmetric structure rotor differs from the asymmetric structure, this part verifies the feature extraction effect of the proposed method for the asymmetric structure rotor target, with Mi-28N as the simulation target, and its rotor contains 5 blades.

Fig. 6 shows the echo and time-frequency distribution of the rotor target. In Fig. 6(a) a total of 19 complete flickers occurred, and the average flicker interval can be estimated to be 0.0245s. In Fig. 6(b), it can be clearly observed that the positive and negative frequency flickers alternate with time, and the reference frequency of a single flicker can be estimated to be 622.31Hz. This value is very close to the reference frequency of the AH-64 in section 4.1.1, because it is related to the maximum instantaneous micro-Doppler frequency, which is only related to the product of the target rotational speed and blade length when the radar parameters are determined. Namely, it is only related to the linear velocity of the target rotor blades. But the linear velocities of the rotor blades of different helicopters are mostly designed to be in the range of 200-220m/s, so the maximum micro-Doppler frequencies caused by different helicopters under the same observation model are very close. The time-frequency diagram for pixel value accumulation results are shown in Fig. 6(c), and the time delay of the two curves can be judged as 0.025s in the cross correlation processing results in Fig. 6(d). Therefore, the accumulation results of positive frequency pixels and negative frequency pixels are not symmetrical. It can be determined that the target rotor contains odd number of blades.
In this simulation, since the flicker interval of the target echo has been estimated and the target has an odd number of blades. Combined with theoretical analysis, the product of blade number and rotational speed shall be 20.41, then the number of blades and the rotational speed of the possible combinations are \([7,2.86]\), \([5,4.02]\) and \([3,6.67]\). Set the initial phase search interval for the above three groups of possible values as \(\left[0,2\pi/7\right]\), \(\left[0,2\pi/5\right]\) and \(\left[0,2\pi/3\right]\), and the search step of initial phase remains the same. The search process under the five blades case can complete the phase compensation of the echo, and the initial phase node corresponding to the minimum difference between all flicker center frequencies and the reference frequency is the 16th, as shown in Fig. 7(a). The offset of each flicker is shown in Fig. 7(b), and it can be seen that the center frequency of the 8th flicker is focused to zero frequency under the 16th phase node, while the 3rd, 13th and 18th flickers are all focused to zero frequency at the same time, showing an obvious periodicity with a period of 5. After optimal phase compensation, the time-frequency result is shown in Fig. 7(c).

For the time-frequency flicker with an odd number of blades, the number of blades should be equal to the period of time-frequency flicker of the same blade, thus the estimated number of blades is 5, the corresponding rotational speed estimation is 4.02\(\text{r/s}\) and the initial phase estimate is \(12\pi\). Taking the target elevation angle into consideration, it can be estimated that the target blade length is 8.534m. Compared with the parameter settings in Table 1, it can be seen that the estimation of blade number is absolutely accurate, the estimation error of rotational speed and blade length are 0.5% and 0.77% respectively.

### B. ESTIMATION AND COMPUTATION ANALYSIS

The above section has verified the effectiveness of the proposed algorithm for feature extraction of targets with symmetric rotor structure and asymmetric rotor structure, and the following section further analyzes the parameter estimation accuracy of the proposed algorithm by taking Mi-28N as an example. In fact, for rotor target identification, the estimation of the initial phase of the blade does not gain due attention, and the main parameters of interest are the number of blades, rotational speed and blade length. In section 3, the conclusion has been drawn only when the initial phase and rotational speed are matched to complete the phase compensation, and the algorithm uses the flicker center frequency deviation in the time-frequency diagram and the periodicity of the minimum value to conduct parameter estimation, then the accuracy of the rotor blade number estimation directly determines the effectiveness of the algorithm, and the rotational speed is affected by the flicker interval and the number of blades. For blade length estimation, it is both affected by the flicker reference frequency estimation and the accuracy of rotational speed estimation.

![FIGURE 6. The echoes of odd numbered blade target.](image-url)

![FIGURE 7. Estimation results of odd numbered blade target.](image-url)
estimation. So the estimation accuracy of rotor blade number and blade length is mainly discussed in this section.

Fig. 8(a) gives the successful estimation times of blade number after 100 Monte Carlo experiments under different signal-to-noise ratio (SNR) conditions. It can be seen that the algorithm in this paper fails when the SNR is less than 6dB after the pulse compression, because the time-frequency diagram is heavily contaminated by noise under the condition of low SNR, and the central frequency of each flicker cannot be estimated accurately. Fig. 8(b) shows the average estimation error of blade length for the premise that the number of blades can be successfully estimated (SNR>5dB), and it can be seen that as long as the number of blades can be successfully estimated, then the estimation error of blade length can also be kept at a low level, specifically, kept below 1.5%.

![Graph showing estimation results](image)

**FIGURE 8.** Estimation results of odd numbered blade target.

From the Monte Carlo experimental results, we can see that the estimation accuracy of this algorithm is very high under the conventional SNR condition. In addition, the algorithm also has a large advantage in terms of computational complexity. If we take the number of time-frequency analysis as the measure of the operation quantity, and the existing iterative search method of time-frequency analysis calculation number is \( kN_pN_0 \) (\( k \) is the number of iterations; \( N_p \) is the number of rotational speed search nodes; \( N_0 \) is the number of initial phase search nodes), usually the minimum number of iterations is 3. But the difference is the more the actual number of blades, the less the number of calculations in the proposed algorithm. Still take Mi-28N as an example, the number of calculations is only \( N_p^0 + N_0^0 \) (\( N_0^0 \) is the number of initial phase search nodes at seven blades case; \( N_0^0 \) is the number of initial phase search nodes at five blades case). It can be seen that the number of calculations of this algorithm is only about one percent of the existing algorithms under the same search grid resolution.

C. EXPERIMENT AND PERFORMANCE COMPARISON

In this section, the effectiveness of the algorithm is tested by a group of measured data of non-cooperative helicopters, and the performance is compared with the existing OMP algorithm and Hough transform method. These two methods for comparison are the commonly used micro-motion feature extraction methods at present. OMP algorithm is a classical sparse reconstruction algorithm, which inverts the micro-Doppler signal by constructing a sparse dictionary, and Hough transform is an image processing method which constructs a micro-motion feature by detecting the sinusoidal curve in the image. Iradon transform is another commonly used micro-motion feature extraction method, whose mechanism is similar to Hough transform. However, its performance has been proved to be weaker than Hough transform, so it will not be compared in this paper.

In the measured scene, the wavelength of the observation radar is 0.3093m; the repetition frequency is 3000Hz; the helicopter target flies back to the station; the elevation angle with the radar is about 0.024rad. And the ground clutter in the field environment is strong, clutter suppression and translational motion compensation is needed to carry out for the measured data. In this section, VMD [14,23] and principal component analysis (PCA) [24] are selected to complete this work. Fig. 9(a) shows the slow-time dimension echo after clutter suppression (900 pulses in total). As the radar adopts mechanical scanning, the strength of the echo will fluctuate with the rotation of the beam. At this time, the time-domain flicker with different amplitude can be observed in the echo. Among them, flicker with relatively strong amplitude occurs about 7 times, and the occurrence times are 0.06167s, 0.087s, 0.1133s, 0.1387s, 0.1647s, 0.1907s and 0.216s respectively. It is estimated that the average flicker interval is 0.0257s. The time domain echo is transformed to the time-frequency domain, as shown in Fig. 9(b). The maximum instantaneous micro-Doppler frequency is 1346.5Hz, and there is a modulation frequency band covering a wide range in the range of \([-550Hz, -300Hz] \) and \([370Hz, 550Hz] \), which is caused by the non-rigid motion of the fuselage and the rotation of the tail rotor. Its micro-Doppler frequency is low and there is no flicker occurred, therefore, it will not affect the feature extraction of helicopter by proposed method. The pixel value accumulation and cross correlation processing of Fig. 9(b) can easily determine that the number of target blades is odd, and it can be calculated that the product of the blade number and rotational speed is...
19.45 from the flicker interval. Therefore, it just need to set the following three groups of possible parameter combinations of blade number and rotational speed for phase compensation, which is \([7, 2.78], [5, 3.89] \) and \([3, 6.49] \). The initial phase search method is consistent with before.

![The process of measured data.](image)

The offset of the center frequencies of the flickers relative to the zero frequency after phase compensation is calculated, as shown in Fig. 10(a). At this time, it can be seen that the first flicker and the 6th flicker are focused near the zero frequency, with offsets of 8.343Hz and 3.991Hz respectively. Since the number of target rotor blades is odd, the estimated value of the algorithm for the number of blades is 5, which corresponds to an estimated speed of 3.89r/s. And from the experimental results in Fig. 10(a) and the simulation results in Fig. 8(b), we can see that the offset change pattern is highly similar. Fig. 10(b) shows the best phase compensation result, when the single blade initial phase is 6. Combined with the elevation relationship between radar and target, using (18) to estimate the blade length is 8.5193m.

![Experiment results by proposed method.](image)

The same experimental environment is set up and three sets of possible parameter combinations are processed by using the OMP algorithm and the Hough transform. The Fig. 11 shows the processing result of OMP algorithm and the Fig. 12 shows the processing result of Hough transform, where X-axis indicates the initial phase estimation, Y-axis indicates the rotor length estimation, and Z-axis indicates the normalized magnitude. The number of peaks is the estimate number of blades. Fig. 11(a) shows the estimation results of the OMP algorithm for the seven blades case, corresponding to a rotational speed of 2.78r/s. However, since the 7 peaks are located at different blade lengths (5.1m, 5.5m, 7.6m, 7.9m, 8.3m, 8.5m, 9.3m), namely, the blade length estimation results are not consistent. Although the estimated value of blade length can be calculated by the mean value of all peaks, the mean value calculation result is not meaningful here because the initial phase corresponding to these peaks is not equally spaced distribution, so the target number of blades is not 7. It can be concluded that the OMP algorithm under this condition does not obtain the effective parameter estimation of the target. Similarly, as shown in Fig. 11(b) and Fig. 11(c), the OMP algorithm in both the 5 blades and 3 blades cases did not succeed in obtaining the target effective parameter estimations, and the algorithm failed. In the long-term experiments, it was found that the parameter search method based on the OMP algorithm tends to converge to the local extremes, but not stably to the global optimum, resulting in less reliable parameter estimation results. In addition, the degree of gridding of the parameter space can also seriously...
affect the validity of the parameter estimation results of the OMP algorithm.

![Fig. 11. Experiment results by OMP algorithm.](image)

Fig. 12 shows the sinusoid curve detection results of Hough transform under three different parameter combinations. However, the accumulated peaks cannot be observed in Fig. 12(a), thus it can be concluded that the Hough transform cannot obtain the target parameter estimation under seven blades case. The five blades case estimation results are shown in Fig. 12(b), where five peaks can be easily seen, that is, the estimated value of the number of blades by Hough transform under the condition of rotational speed of 3.89r/s is 5, and the initial phases of 5 blades are (1º, 73º, 149º, 226º, 289º), which basically show the law of equal interval distribution, and this group of parameters can be considered as the target parameter estimation value. The corresponding blade length estimations are (8.0m, 7.9m, 7.9m, 8.2m, 8.3m), and the average value is taken as the target rotor blade length estimation of 8.06m. It is found that the feature extraction method based on Hough transform may be invalid in the measured data processing, and it is very easy to confuse the above valid estimates. As shown in Fig. 12(c), the sinusoid curve is detected at the rotational speed of 6.49r/s. Theoretically, there should be no peak at this time, but three peaks with poor sharpening are accumulated at the positions of initial phase (65º, 187º, 302º) and corresponding blade lengths (8.7m, 8.4m, 8.2m). The reason for this is that the basis function constructed at 6.49r/s can partially fit the sinusoid curve of the target signal, thus forming the peaks, which is a very unfavorable coincidence. But thankfully, the peak in Fig. 12(b) is highly sharpened and no other peaks appear. On the contrary, there are not only the above three peaks in Fig. 12(c), but also many peaks with higher intensity near the blade length of 6.1m, which means the estimation is not valid. And the Hough transform as an image processing method is easily limited by the resolution of the time-frequency analysis tool, which further leads to a relatively low accuracy of the parameter estimation results.

![Fig. 12. Experiment results by Hough transform.](image)

The parameter estimation results of the three different methods are given in Table 2. It can be seen from the experimental results that the specific target type of the non-cooperative helicopter may be Mi-28N with high probability. To sum up, it can be seen that the parameter estimation based on the OMP algorithm fails in this experiment, while the Hough transform successfully estimates two sets of target parameters with the interference of invalid estimation, and further discrimination is needed to obtain the final best estimation. Compared with the Hough transform whose best estimation error of blade length is 6.28%, the parameter estimation error of blade length is 6.28%.

![Table II: Parameter Estimation Results](image)
estimation error of the proposed method in this paper is only 0.93%. In summary, the proposed method can accurately judge the parity of blade number by accumulating the pixel values of the positive and negative frequencies of the time-frequency diagram, and then combined with the flicker interval in the time domain, it can greatly reduce the parameter search range and the amount of computation. Specifically, it only needs to search for 3-4 groups of parameter combinations. Simulation and experimental results show that the proposed method can focus the center frequency of different flickers in the time-frequency diagram to the reference position through phase compensation, so as to determine which flickers are caused by the same blade, and judge the specific number of rotors through the periodicity between flickers. The experimental results show that the proposed algorithm can achieve more stable performance and more accurate parameter estimation than the OMP algorithm and the Hough transform, providing more ideas for further rotor target identification.

V. CONCLUSION

In this paper, we analyze the mathematical mechanism of flicker formation through the integral model of helicopter rotor blade, and propose a helicopter rotor feature extraction method based on flicker phenomenon and phase compensation by combining the time-frequency analysis and micro-motion signal characteristics. Firstly, the time-frequency analysis is used to obtain the time-frequency spectrum of the echoes, and then the phase compensation is applied to the echoes, and the blade number, blade length, rotational speed and initial phase of the target can be estimated according to the phase compensation results. During the execution of the algorithm, a small number of possible parameter combinations are firstly identified by the time domain flicker interval before the parameter estimation, which greatly reduces the amount of computations. In addition, by determining the periodicity of the flicker intervals that are all focused to zero frequency, the impact of individual flicker focus instability on the performance of the algorithm is effectively avoided. Simulation results show that the method can effectively estimate the main parameters of helicopter rotor, while the processing results of the measured data show that it has more stable performance compared with OMP algorithm and Hough transform, which provides a new technical way for helicopter rotor feature extraction.

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