Research on Radar Micro-Doppler Feature Parameter Estimation of Propeller Aircraft

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Abstract. The micro-motion modulation effect of the rotated propellers to radar echo can be a steady feature for aircraft target recognition. Thus, micro-Doppler feature parameter estimation is a key to accurate target recognition. In this paper, the radar echo of rotated propellers is modelled and simulated. Based on which, the distribution characteristics of the micro-motion modulation energy in time, frequency and time-frequency domain are analyzed. The micro-motion modulation energy produced by the scattering points of rotating propellers is accumulated using the Inverse-Radon (I-Radon) transform, which can be used to accomplish the estimation of micro-modulation parameter. Finally, it is proved that the proposed parameter estimation method is effective with measured data. The micro-motion parameters of aircraft can be used as the features of radar target recognition.

1. Introduction
Radar is an important tool for un-cooperated air targets recognition, based on which military schemes can be made, such as the judgment of military motives, the establishment of the battle scheme, and the fire control [1] etc. Air targets mainly consist of jet plane, propeller aircraft and helicopter. Among them, the propeller aircraft has the advantages in low velocity and taking off-landing properties, which make it an important role in air transportation, reconnaissance and surveillance, logistics etc. In general, air targets include obvious powerful rotating components, such as the compressor blades of engine in jet planes, the propeller in propeller aircrafts, the rotor and empennage in helicopters. These rotating components work periodically, which induce a frequency modulation on the returned radar echo, namely micro-Doppler effect. Therefore, the air target recognition can be realized by estimating the micro-Doppler parameters of powerful components from the radar echo of air targets. For example, the number and length of blades, the rotating velocity can be deducted from the estimated micro-Doppler parameters. Resultantly, the target recognition can be realized.

Most available references have studied the micro-Doppler effect and parameter estimation of rotating components in air targets deeply. The mathematical model of main rotor in helicopters has been given by Chen, in [2] and [3]. The radar echo of rotor is modelled as sinc-function behaved periodical pulse in time domain, while extends in frequency domain. By analyzing the parameters of available helicopter rotors from different countries, C. E. Rotander realizes that the ratio of length to number of blades can be used as a critical feature to identify different kinds of helicopters in [4]. Fortunately, the ratio of length to number of blades can be obtained via the Doppler spectrum of rotors. However, the type of available helicopter is too much to identify the exact type by using the ratio of length to number of blades, which limits its application in reality. In [5], by applying the time-to-frequency transform to the radar echo of helicopters, the number and length of rotor blades have
been estimated via inverse-Radon (I-Radon) transform by A. Cilliers. However, the estimation method of the blade length cannot be extended to other scenarios, due to the neglect of the incident angle between radar echo and the rotate plane [6].

Different from the micro-Doppler feature of rotors in helicopter, the blades of propeller aircrafts have such properties as short length, high rotating speed, large rotate angle, the low energy from the wingtip [7] etc. Most available researches focus on the micro-Doppler feature of rotors in helicopter. While, there are few researches on the micro-Doppler feature of propeller aircrafts. In this paper, the model of the radar echo of propeller aircrafts has been built based on both simulated experiments and real measured data. Through the analysis of micro-Doppler feature and spatial transformation, the parameters of micro-motion can be deducted. Finally, a method for parameter estimation of propeller aircrafts rotating components is proposed, which is helpful for air target classification and recognition.

2. Parametric model of radar echo of propeller aircrafts
Due to the rotation of propeller in propeller aircrafts, their echo behaves differently from normal radar echoes. In time domain, the echo from propeller is behaved as sinc-function pulse. While in frequency domain, its spectrum extends. All these features can be used to model the echo of propellers blades. First, the echo of a single propeller blade is modelled by assuming the blade as an ideal line source with same length and velocity of real one.

Under the assumption of far field and long wavelength working condition, a blade of propeller can be equally set as a line source with length, which rotates around the cicatricle center with constant speed. Let the range from the cicatricle center of propeller blade to radar be \( R \), as show in Figure. 1.

![Figure.1 The geometric relationship between cicatricle center and radar echo](image)

As shown in Figure.1, \( \varphi \) is defined as the angle between the radar incident beam and the propeller plane, \( \theta \) is defined as the angle between the normal of propeller blade and the projection of radar beam into the propeller plane, \( r \) is the length from cicatricle center to front of blade, \( l \) is the length from the end of blade to the cicatricle center.

Let the incident radar echo be

\[
u(t) = \exp(j2\pi f_o t)\]

in which, \( f_o \) stands for the frequency of the incident beam. Thus, the radar echo of a point in the blade at time \( t \) can be expressed as

\[
u(t) = \exp(j2\pi f_o (t - \tau(t)))\]

in which, \( \tau(t) = 2(R - Vt - x \sin(\theta_0 + 2\pi F_{rot} t) \cos(\varphi))/c \) denotes the delay time, \( V \) is the velocity of plane, \( x \) means the distance from the point to cicatricle center, \( \theta_0 \) is the initial angle of the blade at time \( t = 0 \), \( F_{rot} \) is denoted by the rotate frequency of such propeller blade. Thus, the radar echo of such blade can be regarded as the sum of the echo of all the points in that blade as
\[ v_n = \int_0^l v(t) \, dt = \int_0^l \exp(j2\pi f_n(t - \frac{2(R - Vt - \frac{x \sin(\theta_n + 2\pi F_{rot}, t) \cos(\phi))}{c})) \, dx \]

\[ = (l - r) \sin c(\frac{2(l - r) \sin(\theta_n + 2\pi F_{rot}, t) \cos(\phi)}{\lambda}) \times \exp(j2\pi f_n t - \frac{2(R - Vt)}{\lambda} + \frac{(l + r) \sin(\theta_n + 2\pi F_{rot}, t) \cos(\phi)}{\lambda}) \]  \tag{3}

in which, \(\lambda\) is denoted by the wavelength of the radar echo. As can be seen from (3), the ideal maximum amplitude of propeller blade is decided by its length. The shape of the amplitude depends on such parameters as propeller blades length, rotating frequency, the angle between radar beam and propeller plane, and wavelength. Meanwhile, the carried frequency of echo from propeller relies on the frequency of incident beam. The Doppler shift is introduced by both the vertical motion of blade and the rotation of blade around the cicatrice center.

Let the propeller is consisted of \(N\) blades, the radar echo can be represented by

\[ v_n = (l - r) \sum_{n=1}^{N} A_n B_n \] \tag{4}

in which,

\[ A_n = \exp(j2\pi f_n t - \frac{2(R - Vt)}{\lambda} + \frac{(l + r) \sin(\theta_n + 2\pi F_{rot}, t) \cos(\phi)}{\lambda}) \] \tag{5}

\[ B_n = \sin c(\frac{2(l - r) \sin(\theta_n + 2\pi F_{rot}, t) \cos(\phi)}{\lambda}) \] \tag{6}

\[ \theta_n = \theta_0 + \frac{(n - 1)2\pi}{N} \] \tag{7}

in which, \(\theta_0\) means the initial angle of the nth blade. Since the blade distributes equally in propeller plane, the initial angle of other blades can be deducted from that of certain blade.

Based on above analysis, the echo of propeller aircraft is affected by the structure, motion, working conditions of the aircraft, and the relative geometric position to aircraft propeller etc.

From (4) to (7), the term \(A_n\) determines the phase of propeller echo, while \(B_n\) affects its amplitude. Therefore, under the assumption that long illuminated time is promised by radar, the receiver obtains sinc-function modulated pulses cluster. When the direction of radar beam is consistent with the normal direction of blade, the amplitude maximizes. When the direction of radar beam departs the normal direction of blade, the amplitude attenuates. In that way, the radar echo of propeller behaves specifically in time-to-frequency domain, which is concerned with the certain rotation of the propeller blade. Generally, it behaves as sine modulated function, which can be utilized to estimate the micro-Doppler parameter of propeller blade.

3. Micro-Doppler parameter estimation of propeller

According to the domain, available researches on radar echo analysis of micro-motion components can be classified into three types, namely analysis based on time domain, Doppler spectrum domain and time-frequency domain. For time domain, the radar echo of micro-motion components behave as shining pulses, which the energy of radar echo concerns mainly in a short time but with high level of clutter power. For Doppler spectrum, the energy of clutter concerns around 0, while the energy of airframe concerns on a short spectrum around the peak frequency. Resultantly, the energy of clutter remain in micro-Doppler units is rather low. However, the micro-Doppler of rotation components extends in spectrum, leading to low energy of certain micro-Doppler units yet. For time-frequency domain, the variation of Doppler modulation with time caused by the rotation of micro-motion components can be clearly represented by the means of short time Fourier transforms (STFT), Wigner-Ville transforms and so on. In reality, the radar echo is consisted of noise, clutter and interference etc.

Due to the fact that the cross term after second order time-to-frequency transform is too obvious to
pollute the micro-Doppler units with low energy, STFT is adopted in this paper to estimate the micro-Doppler parameters.

3.1. Micro-Doppler Spectrum Analysis Based on I-Radon Transform

Suppose \( f(x, y) \) is a two-dimensional function in time-frequency plane \((x, y)\). The radon transform is used to project a single line \( u = x \cos \theta + y \sin \theta \) in the plane \((x, y)\) into another plane defined by \((u, \theta)\). It can be expressed mathematically as

\[
g(u, \theta) = \int_{-\infty}^{+\infty} f(x, y) \delta(u - x \cos \theta - y \sin \theta) \, dx \, dy
\]

(8)

According to the image reconstruction theory, the projection of a sine behaved curve into parameters domain can be realized by the I-Radon transform. Here, suppose there is a point \((x_0, y_0)\) in the time-frequency plane \((x, y)\), a line across this point with \( u = x \cos \theta + y \sin \theta \) can be transformed by triangle transform such as

\[
u = B \sin(\theta + \varphi_0)
\]

(9)

in which, \( B = \sqrt{x_0^2 + y_0^2} \); \( \sin \varphi_0 = x_0 / \sqrt{x_0^2 + y_0^2} \); \( \cos \varphi_0 = y_0 / \sqrt{x_0^2 + y_0^2} \).

As can be illustrated, after applying the radon transform with different \( \theta \), \( u \) varies as a sine modulated function in plane \((u, \theta)\). Therefore, a sine behaved curve in the plane \((u, \theta)\) can be projected as a single point \((u_0, y_0)\) in the plane \((x, y)\). Fortunately, the point \((x_0, y_0)\) can be obtained by I-Radon transform. Namely, the I-Radon transform can realize the projection of a sine behaved curve into parameter space.

The projection angle can be decided by the rotation velocity of the propeller blade. For example, an I-Radon transform image of the radar micro-Doppler spectrum is illustrated as Figure 2(a). The real measured data is recorded, in which the propeller is composed of 4 blades. As can be seen from the image, the energy of each blade is accumulated, from which the rotation velocity, the number of blades, the radius of cicatrice and the length of blade can be estimated.

3.2. Micro-Doppler parameter estimation of propeller

Since different types of propeller aircrafts are composed of different propellers and powerful engines, air target classification can be realized by estimating the micro-Doppler parameters of propellers. The feature extraction method is accomplished by following steps.

The time-frequency distribution image of target can be achieved by applying the STFT to the signal of target in time domain.

- According to the range of the rotation velocity, I-radon transform is applied with different rotation velocity during this range. The rotation velocity is estimated which focuses the time-frequency distribution image best.
- By applying image segmentation to the best focused image, the image of the propeller can be obtained to estimate the rotational velocity of blades in the propeller.
- Let the I-Radon transform center be the center of a circle, a circle with radius \( R \) (here let \( R=1m \)) is plotted to estimate the number of the blades. The number of the blades is equal to the number of intersections of the circle and the image of the propeller.
- Let the I-Radon transform center be the benchmark. The projected radius of the cicatrice is estimated by the length from the intersection of a line equally between two blades to the benchmark. According to the given velocity from tracking progress, the incident angle can be obtained, thus the real radius of the cicatrice can be deducted.
- Let the I-Radon transform center be the benchmark as well. The projected length of the blades can be estimated by applying detection progress to the energy of the blades. Since the incident angle can be easily got, the real length of the blade can be deducted. It should be noticed that
the estimated length may be shorter than real ones due to the low energy of the blade end by I-Radon accumulation.

4. Experimental results and analysis based on real measured data
The real measured radar echo of a certain kind of propeller aircraft is utilized in this section. The carried frequency is 10GHz. The number of blades is 4 with length 1.7m and rotation velocity around 1300r/min. After applying STFT to the radar echo, figure 2 (b) can be obtained, in which micro-Doppler modulation is obvious in certain time with sine distribution. The average energy reaches its maximum when the velocity is 1250r/min. I-Radon transform is applied with the velocity to obtain such image as Figure. 2 (d). The segmented image can be obtained by the proposed method in the above section, as shown in Figure. 2 (c). In Figure.2 (d), the top and end of blade are marked, in which there are 4 blades as known. The extracted length is 1.08m, which is smaller than real values. This is due to the fact that the energy of blade ends can hardly be accumulated by I-Radon transform. Although there is relatively high error of blade length estimation, the micro-Doppler parameters extracted can still be utilized to realize air target recognition.

![Real image of propeller](image1.png) ![Time-frequency distribution of propeller](image2.png) ![Segment image after I-Radon](image3.png) ![Parameter extraction on I-Radon images](image4.png)

Figure 2 The parameter extraction of real measured radar echo of propeller aircraft

5. Conclusion
In this paper, the micro-Doppler features of propeller aircraft are analyzed by real measured data. The parameters of propeller blades can be estimated by accumulating the energy of each blade with time-frequency transform and I-Radon Transform. The proposed micro-Doppler parameter estimation method is illustrated in this paper. Real measured data experimental results validate the effectiveness of the proposal. The micro-motion parameters of aircraft can be used as the features of radar target recognition.

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