Aircraft classification using micro-Doppler analysis

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Abstract

The analysis of micro-Doppler effects has gained its importance in the field of target recognition in radars. The propulsion systems which are the rotary parts of the targets viz. helicopter blades, propeller blades, jet engine blades induce micro-Doppler effects. Time frequency analysis methods are used to represent these micro-Doppler features. In this paper, a classification method is proposed to categorize aircraft as fixed wing, propeller or jet engine using micro-Doppler analysis. Time frequency analysis is performed using Short time Fourier transform. Periodicity of the blade flashes is extracted from the spectrogram. The number of blades are categorized as odd or even for helicopter and propeller aircraft. The proposed method of extracting blade flash frequency and the odd or even number of blades forms predominant feature for non-cooperative aircraft recognition in radars.

Keywords: micro-Doppler, time-frequency analysis, aircraft classification, inverse Radon transform

I Introduction

Automatic (non-cooperative) target recognition is becoming increasingly important in modern radar systems, apart from target detection, plot extraction and tracking. Distinguishing targets automatically is a challenge and steady progress has been made over the past couple of decades. Most military, civil fixed-wing aircraft and helicopters have features associated with their propulsion systems, which are good candidates for target recognition. Typically, Doppler spectrum is used to identify moving targets and used to broadly classify the targets based on its velocity. In addition to the bulk translation of the target, the target or its structural components exhibit micro-motions such as vibration, rotation, coning motions etc. These micro-motions induce micro-Doppler effect which is a frequency modulation on the returned signal that generates sidebands about the target's Doppler frequency shift [1] [2]. The rotating parts' radial velocity with respect to a static radar, changes over time and consequently there is a change in micro-Doppler frequency. The frequency domain method (Fourier transform) which is used for extracting Doppler frequency does not capture the time varying information of micro-Doppler. Hence time – frequency transforms are used to analyze the micro-Doppler frequencies. Linear and bi-linear transforms such as short-time Fourier transform, Wigner Ville distribution and Adaptive S methods are analyzed for aircraft recognition [3]. The Wigner-Ville distribution not only possesses many useful properties, but also has better resolution than the STFT spectrogram. One main deficiency of the Wigner-Ville distribution is the cross-term artifacts, in presence of multi-component signals.

Different feature extraction techniques were used to represent micro-Doppler effects and then used for classification. Wavelet and time-frequency analysis are used in [4] to extract the m-D features of radar target returns. Features such as rotation rate and period of oscillation, has been obtained for classifying helicopter and human data. Eigen pairs extracted from the correlation matrix of the signature are used as informative features for classification [5]. Target velocity, spectrum periodicity, spectrum width extracted from SVD of spectrograms and used to classify UAVs [6]. Hough transform is used to extract parameters of m-D features from spectrogram [7].

In our work, mathematical modeling of returned time domain signal from rotating parts of helicopter, propeller and jet aircraft were simulated. Time frequency transform is performed to capture time-varying micro-Doppler frequencies. The blade flash frequency is extracted from spectrogram using the peak energy locator. Odd or even number of blades are identified based on the positive or negative Doppler frequency at the blade flash locations.

II Proposed Methodology

The returns from rotary parts of aircraft such as helicopter blades, propeller blades and turbo-jet blades are modelled mathematically as described in [8] and [9] and simulated. Short time frequency transform is performed on the time domain signals to obtain time-frequency response. The magnitude spectrum along the frequency is summed up for every time sample to get the energy. Local maxima are detected from the time-energy plot to get the blade flash locations. The time difference between adjacent blade flashes is calculated to give the chopping frequency or blade flash frequency. The number of blades are categorized as odd or even based on the positive or negative Doppler frequency energy at the adjacent blade flashes. The overall block diagram is shown in Figure 1.

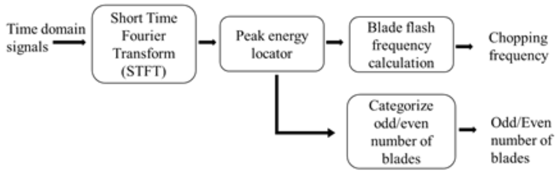


Figure 1 Proposed methodology – block diagram

III Mathematical model

The geometry of rotating blades of propeller and jet with respect to radar is modelled as shown in Figure 2.

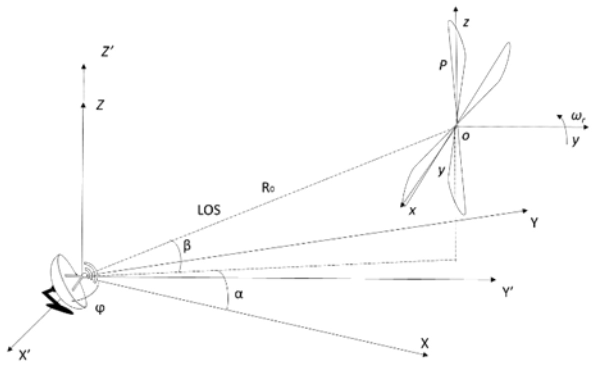


Figure 2 Model of propeller/jet blades with respect to radar

The mathematical model for the returns of signal from rotor blades in a prop aircraft and turbojet [5] is given in Eqn. 1

$$S_n(t) = (L_2 - L_1) * \sum_{k=0}^{N-1} sinc\left[\frac{2\pi}{\lambda}(L_2 - L_1)\, cos\left(sin^{-1}(sin(\alpha + \varphi)\cos\beta)\right)\cos(\theta_k + \omega_r t - \cot^{-1}(\cos(\alpha+\varphi)\cot\beta))\right] * \exp[-j\frac{4\pi}{\lambda}(R_0 + \frac{L_1+L_2}{2}\cos(\sin^{-1}(\sin(\alpha+\varphi)\cos\beta))\cos(\theta_k + \omega_r t - \cot^{-1}(\cos(\alpha+\varphi)\cot\beta)))] \quad (1)$$

where,

L_1 = Distance between the blade roots and center of the rotation,

L_2 = Distance between the blade tips and the center of the rotation,

N = Number of blades,

α = Azimuth angle of the rotor to the radar line-of-sight (LOS),

β = Elevation angle of the rotor to the radar LOS,

ϕ = the angle between the reference coordinates (X', Y', Z') and radar coordinates (X, Y, Z),

R_0 = Initial distance between the blade center with radar,

ω_r = Rotation radian frequency,

$\theta_k = \theta_0 + 2\pi k / N$, (k=0,1,...,N-1) denotes the initial rotation angle of the (k-1)th blade,

$\lambda = c / f_0$, f_0 = radar carrier frequency and λ = wavelength of radar transmitted signal.

Simulations were done with carrier frequency of 3GHz. Figure 3 shows the time domain signal for propeller with the following parameters, N = 4, f_r = 1900 rpm, L_1 =0.36, L_2 = 1.2, β = 5^0, ϕ =20^0, $\theta_0 = \pi/8$, PRF=6.685kHz, α = 45^0. The required PRF is calculated as 2* f_d where f_d is the maximum Doppler frequency given by $f_d = \frac{2*v}{\lambda}$ where v is the tip velocity given by $2\pi f_r(L_2 - L_1)$.

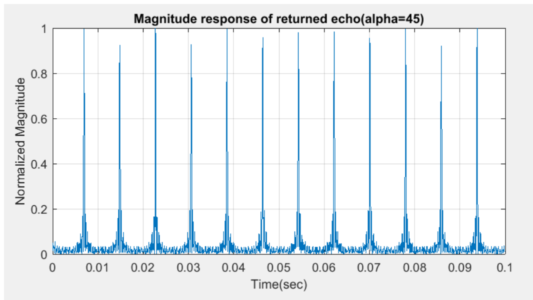


Figure 3 Time domain signal for propeller

Figure 4 shows the time domain signal for Turbo-jet with the parameters : N = 38, f_r = 3520 rpm, L_1 =0.38, L_2 = 1.1, β = 5^0, ϕ =20^0, $\theta_0 = \pi/8$, PRF=10.61kHz and α = 45^0

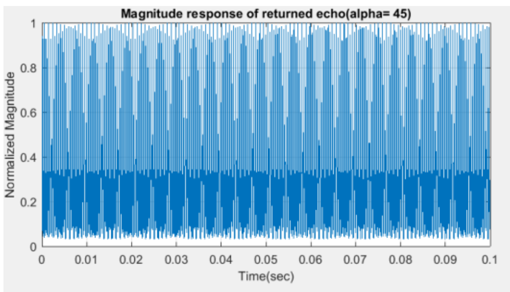


Figure 4 Time domain signal for turbo-jet

The rotating blades of helicopter with respect to radar is modeled as shown in Figure 5

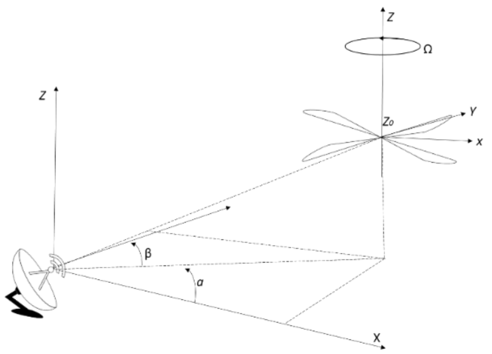


Figure 5 Model of helicopter blades with respect to radar

The mathematical model for the returns from rotor blades of a helicopter is:

$$s_N(t) = (L_2 - L_1)\sum_{k=0}^{N-1} sinc\left[\frac{2\pi}{\lambda}(L_2 - L_1)\cos(\beta)\cos(\theta_k + \omega_r t - \alpha)\right] exp\left[-j\frac{4\pi}{\lambda}\left(R_0 + \frac{L_1+L_2}{2}\cos(\beta)\cos(\theta_k + \omega_r t - \alpha)\right)\right] \quad (2)$$

The time domain signal for modeled helicopter with the following parameters is shown in Figure 6. N = 4, f_r = 395 rpm, L_1 =0, L_2 = 5.64, β = 5^0, ϕ =20^0, θ_0= $\pi/8$, PRF=6.685kHz and α = 45^0

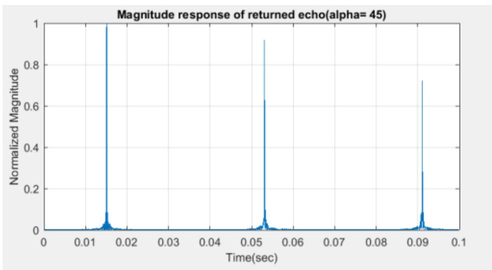
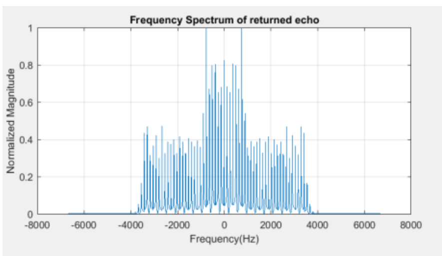


Figure 6 Time domain signal of helicopter

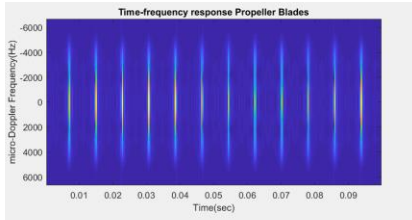
When the blades are orthogonal to the radar LOS, blade flashes occur. As the blade rotates, the micro-Doppler frequency changes over time which is discussed in next section.

IV Time frequency analysis

The micro-Doppler frequency changes over time and hence time frequency analysis is required to extract significant information. The frequency spectrum and spectrogram of returns from propeller is shown in Figure 3.



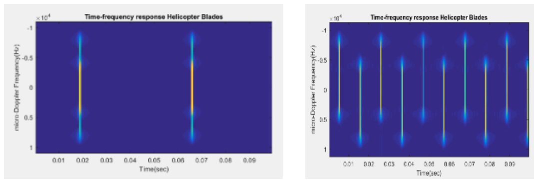
(a)



(b)

Figure 7 (a) Frequency spectrum of signal in Figure 3 (b) Spectrogram of signal in Figure 3

The time frequency plots have periodicity of micro-Doppler characteristics since the rotating parts repeat its cycle over time. The periodicity corresponds to the blade flash frequency which in turn is proportional to the spool rate and the number of blades. For odd number of blades (N), the chopping (Blade flash) frequency is given by Nf_r , where f_r is the spool rate. And for even number of blades (N), chopping frequency is given by 2Nf_r . The periodicity observed in time frequency transforms are found suitable for categorizing fixed wing, propeller and jet aircrafts. An example for odd and even number blade helicopters with different spool rates is given in Figure 8.



(a) (b)

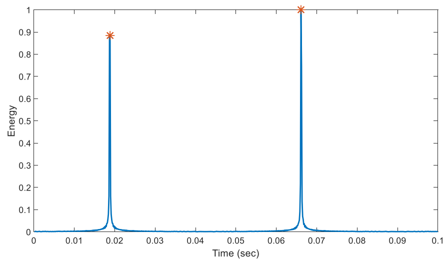
Figure 8 Spectrogram of (a) Four blade helicopter with spool rate 5.3 Hz (b) Five blade helicopter with spool rate 9.6 Hz

V Feature Extraction

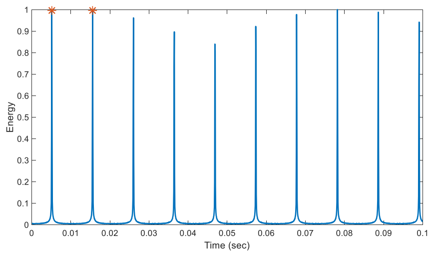
The time between two adjacent flashes (periodicity) is used to calculate the blade flash frequency. To find the time instant of blade flashes, time energy plot is obtained from the spectrogram as discussed below. The magnitude spectrum is summed for all frequencies to get the energy for each time sample in the spectrogram.

$$E(t) = \sum_{\omega=-\omega_{max}}^{\omega_{max}} S(t,\omega) \quad (3)$$

Where S is the spectrogram and ω_{max} is the maximum Doppler frequency. The energy is normalized and the peak energy is determined using local maxima with magnitude greater than threshold value. First two adjacent local maxima locations are chosen and the time differences between the two maxima gives the periodicity of blade flashes which is the chopping frequency.



(a)



(b)

Figure 9 Local maxima marked on time-energy plot for (a) Spectrogram in Figure 8a (b) Spectrogram in Figure 8b

Figure 9 shows the time energy plot with the first two local maxima marked for the spectrograms of even and odd numbered helicopters with different spool rates shown in Figure 8. The time difference between the two maxima gives the blade chopping frequency of aircraft.

In case of even number blade aircraft, two blades are orthogonal to the radar LOS at the same time instant. These blades which are approaching and receding the radar produces positive and negative micro-Doppler frequencies at the same time instant. While in case of odd number of blades, the blades which are approaching and receding the radar are alternatively orthogonal to the radar LOS. Hence positive and negative micro-Doppler frequencies occur at different time instances or at alternate blade flashes.

The energy in the positive Doppler frequency and negative Doppler frequency is used to determine whether the number of blades are odd or even. The positive and negative energy are calculated as follows at the determined first two local maxima positions.

$$E_{pos}(t) = \sum_{\omega=0}^{\omega_{max}} S(t,\omega) \quad (4)$$

$$E_{neg}(t) = \sum_{\omega=-\omega_{max}}^{0} S(t,\omega) \quad (5)$$

If E_{pos} is greater than E_{neg}, then the blade orthogonal to the radar is said to be approaching the radar and vice versa. If t_1 and t_2 are the time occurrences of blade flashes found by the peak energy locator,

$sign(E_{pos}(t_1) - E_{neg}(t_1)) = sign(E_{pos}(t_2) - E_{neg}(t_2))$ for even numbered blades, otherwise it is said to have odd number of blades.

VI Results and Discussion

Different types of aircraft under three classes: Turbo-jet, Propeller and Helicopter are modeled and simulated used for the experiments. Six different types under the three classes were used [10]. The odd or even categorization is not done for turbo jet as the number of blades and spool rate increases, it has seldom effects on the returned signal.

	Spool rate (Hz)	No. of blades	Actual Chopping Freq.	Calculated Chopping freq.	Odd/ Even
T_1	40	30	1200	1201.22	-
T_2	68.8	33	2270.4	2268.69	-
T_3	45	50	2250	2248.6	-
T_4	37	38	1406	1333.07	-
T_5	43.4	33	1432.2	3361.35	-
T_6	51	30	1530	1333.06	-
P_1	14.6	4	58.4	57.85	Even
P_2	21.9	3	131.4	131.58	Odd
P_3	25.5	3	153	152.5	Odd
P_4	31.5	2	63	62.97	Even
P_5	46.9	2	93.8	71.7	Even
P_6	31.5	3	189	187.35	Odd
H_1	5.9	2	11.8	11.85	Even
H_2	5.3	4	21.2	21.32	Even
H_3	9.6	5	96	95.65	Odd
H_4	5.4	4	21.6	21.7	Even
H_5	5.9	2	11.8	11.84	Even
H_6	5.8	4	23.2	23.32	Even

Table 1 Experimental results

As observed from Table 1, the calculated chopping frequency matched with the ground truth with greater accuracy. And the categorization of number of blades as even or odd was found to be 100% accurate for helicopter and propeller while this feature was not distinguishable for turbo-jet because of the increase in number of blades. Thus the chopping frequency extraction using the proposed method forms a predominant feature for aircraft recognition. The categorization of odd/even number of blades helps in categorization of propeller and helicopter.

Conclusion

This paper has proposed a novel method of feature extraction for aircraft recognition based on blade flashes and micro-Doppler frequencies. Blade flashes are determined from spectrogram and chopping frequency is extracted using blade flashes. Odd or even number of blades is determined from the micro-Doppler frequencies at the blade flashes. The extracted features have shown promising results for classification. Future scope of work includes extracting the number of blades using better time frequency distribution and test in actual radar scenario.

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Biodata

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