Study and Simulation of Radar Targets' Micro-Doppler Signature

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***Abstract*—Micro-Doppler signature of any radar target is induced due to back-scattering from rotational parts of engine compressor, exposed blades, turbine etc. The study of micro-Doppler signature aids in feature extraction based target recognition. To devise coarse target recognition scheme, it is necessary to study and model different types of aerial targets for micro-Doppler signature. In this paper, JET Engine Modulation(JEM), Helicopter Rotor Engine Modulation(HERM), propeller modulation is simulated for surveillance band radar using standard existing models. The simulated I/Q data is validated with some degree of closeness against real radar data. Doppler energy received for different types of targets varies with aspect,range and RCS. This energy is quantified at coarser level target recognition into different classes. Since the normal radar waveform for search and track function is used for this quantification, the radar computational resources are saved. The radar tracker kinematics, aspect angle and RCS is also used in conjunction with Doppler information to increase confidence of classification . Thereafter, specially designed NCTR waveform for feature extraction can be played for track with high confidence.**

***Index Terms*—MicroDoppler Signature, JEM, HERM, propeller modulation, target recognition**

I. Introduction

Micro-Doppler signature of any radar target refers to Doppler induced due to rotational motion of any part of the target exposed to radar which can backscatter the incident radar energy. Different radar targets such as helicopter, turbo-prop and turbo-jet aircraft have rotating parts like rotor blades and helicopter rotor hub. The difference lies in plane of rotation, rotation speed, blade RCS, aspect and wavelength dependency. This aids in broad classification of targets based on micro-Doppler signature. Literature survey [1] - [11] is done for different micro-Doppler radar signature models and target recognition techniques. Jet Engine Modulation (JEM) [1], [5] occurs when radar observes a jet airplane at an aspect angle that allows electromagnetic radiation to be backscattered from moving parts of the compressor and blade assembly of the jet engine. The reflections are characterized by both positive and negative Doppler sidebands corresponding to the blades moving toward and away from the radar respectively. JEM increases when radar is orthogonal to the axis of blade rotation. Consequently, for a fully exposed blade as in a turbo-prop aircraft or helicopter, JEM increases with angle off the bore sight axis of the propeller and observed for almost all aspects. The JEM spectral content is dependent upon PRF of the radar, the maximum speed of the engine and the number of blades on the first few engine rotor stages. Helicopters have smaller number of rotor blades but bigger in RCS rotating at comparatively lower speed than aircraft. The rotor blade produces short spike like signal called rotor flashes due to which the rotor echo is distributed all over Doppler domain which is composed of many equivalent spaced impulses [2],produces equally spaced bands in Doppler domain. The rotating hub induces characteristic 'shelf' around fuselage Doppler which is peculiar to helicopter and is present even when helicopter is hovering. The turbo-prop aircraft have lesser number of blades and lesser rotational rate than turbojet aircraft which result in continuous spectrum at lower Doppler range. The difference between helicopter and turbo-prop aircraft lies with different plane of rotation due to which helicopter micro-Doppler spectrum is visible at all aspect whereas propeller spectrum varies with aspect. Since X-band radar provides better signature for target identification hence most of the literature is based on Non Cooperative Target Identification (NCTI) techniques for X-Band radar which estimates target parameters like blade rotation rate and number of blades for identification. However, in surveillance radar, the PRF is not high enough and micro-Doppler signature is ambiguous [7] and not fit for extraction of target parameters like number of rotor blades and rotation rate . However, different targets exhibit peculiar signature that can be distinguished from each other based on Doppler content. Hence target modeling aids in study of the difference of micro-Doppler content for different targets to be used for broad classification. This paper is organised as follows: Section II shows different mathematical models used for modeling different target signatures. In Section III , different target returns are simulated using mathematical models and data is analysed for micro-Doppler content and their uniqueness for feature extraction. The simulation is compared with real data for degree of correctness in target modeling. Spectral content is calculated in Section IV for different targets to distinguish each other for target recognition. In Section V, results of spectral content estimation for differentiating different target types is discussed. Lastly, conclusion is drawn in Section VI to devise a feedback method with radar data processor and signal processor in a loop to perform target recognition with less burden on radar resources.

II. Target Mathematical Models

The signal backscattered from rotor blades is modeled as [3]:

$$u_b\left(t\right) = \sum_{n=0}^{N_b-1} \left(L-l\right) A_n B_n \tag{1}$$

where

$$A_n = \alpha.sinc\left(\frac{\left(L-l\right)}{\pi} \cdot b_t\right) \tag{2}$$

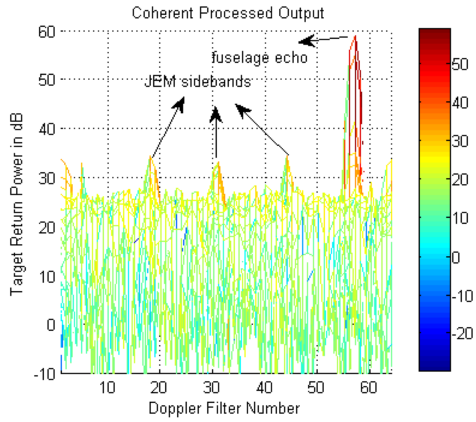

Fig. 1. JEM signature for aircraft (Simulated)

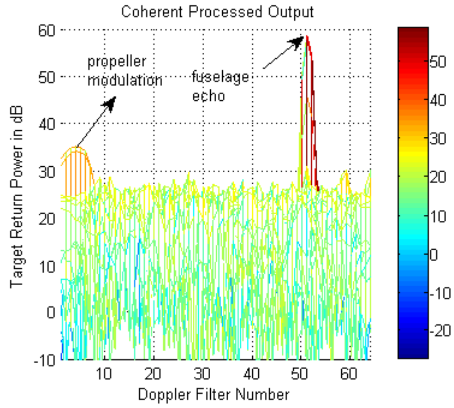

Fig. 2. Propeller aircraft signature (Simulated)

$$B_n = \cos\left(2\pi f_c t - \frac{4\pi}{\lambda}(R - vt) + \pi \cdot (L + l) \cdot b_t\right) \quad (3)$$

$$b_t = \beta sin\left(2\pi f_r t + \theta_0 + \frac{(n-1)\cdot 2\pi}{N_b}\right) \quad (4)$$

where $\beta = 2\pi\cos(\phi/\lambda)$, α is the intensity of the echo, f_c is the carrier frequency of the transmitted signal, λ is the wavelength of radar, f_r is the rotor rate, N_b is the number of blades in the rotor, L is the blade radius, l is the radius of rotor axis, θ_0 is the angle of blade normal line relative to the radar beam, R is the range of the phase center of radar to the rotating center of rotor axis, v is the radial velocity of helicopter, and ϕ is the angle of rotor plane relative to the radar beam.

The signal backscattered from rotor blades of airliners resulting in JEM is modeled as [4]:

$$S_i(t) = Ae^{j\left[2\pi f_d t - \frac{2\pi f_0 D}{c}\right]} \times \left[1 + V_\theta K" \sum_{n=0}^{N-1} S_{ni}(t)\right]$$

$$S_{ni}(t) = \left[\alpha + \beta\cos\left(\omega_r t + \frac{2\pi n}{N}\right)\right]$$

$$\times sinc\left[\frac{4\pi f_0}{c}.\frac{L_2 - L_1}{2}\cos(\theta)\sin\left(\omega_r t + \frac{2\pi n}{N}\right)\right] \quad (5)$$

$$\times e^{-j\frac{2\pi}{\lambda}\frac{L_1+L_2}{2}\cos(\theta)\sin\left(\omega_r t + \frac{2\pi n}{N}\right)}$$

$$\alpha = \sin(|\theta + \phi_p|) + \sin(|\theta - \phi_p|)$$

$$\beta = -sign(\theta)\left[\sin(|\theta + \phi_p|) + \sin(|\theta - \phi_p|)\right]$$

where, S_{ni} is return for each blade n, L_1 is radius of engines nozzle, L_2 is radius of engines main rotor, N is number of blades, θ is the angle of blade normal line relative to the radar beam, D is the range of the phase center of radar to the rotating center of rotor axis, v is the radial velocity of aircraft, λ is wavelength of the transmitted signal, ω_c is radian frequency of the transmitted signal, ω_r is rotation speed, f_0 is radar frequency, c is speed of light, ϕ_p is engines blades pitch angle, V_θ is fan visibility function, K" is amplitude of return signal due to engines and due to the body ratio. The fan visibility function is defined in much simpler manner to simulate the dependency of aspect angle on engine obscuring the blade from backscattering incident energy.

The hub spectrum width [8] for helicopter is given by

$$\triangle f_{hub} = 2\omega_r D/\lambda \quad (6)$$

where $\triangle f_{hub}$ is hub spectrum width for helicopter,ω_r is hub rotation speed, D is hub diameter.

III. Study and Simulation of Target Micro - Doppler

Targets are simulated using parameters as listed in Table I for different types of targets using models given in SectionII. The target model equation is integrated in Radar I/Q simulator at baseband level to study the micro-Doppler characteristic of these targets. Model for jet engine aircraft rely on basic principle of Physical Optics(PO) where the energy is incident at critical angle , it gets backscattered from jet engine compressor blades. For Surveillance band radar, the radar energy is backscattered strongly from first stage of engine/blades as long wavelength does not penetrate engine blades beyond single stage. Whereas , for helicopter and propeller blades, the backscattering is observed at most of the aspect angles and centimeter and decimeter wavelengths. The helicopter's complex time domain return signal is simulated by adding fuselage echo, blade flash, hub echo signal and noise. Tail rotor echo is not simulated as it is not visible at all aspect and has smaller diameter so contribution in Doppler spectra is not so significant. The main rotor blade model [3] generates returns based on physical and dynamic properties of the main rotor blades of the aircraft which includes blade length, number of blades and rotation rate of the rotor. The hub echo [8] is simulated in frequency domain as band noise spread around the Doppler frequency of the helicopter fuselage for width given by equation(6). The propeller is simulated by adding fuselage echo , blade modulation and noise.Jet engine modulation [4] is incorporated in the I/Q simulator by adding fuselage echo , blade modulation and noise. Since turbo-prop airliners use gas turbine engine for thrust in addition to propeller blades, the energy that enters through air intake is backscattered as

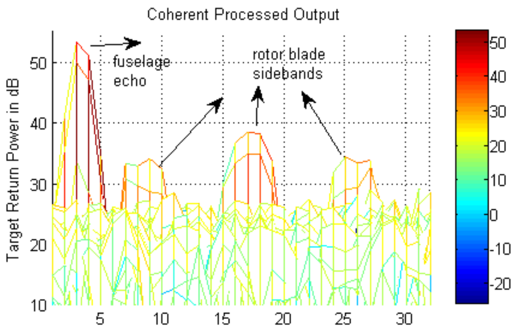

Fig. 3. Helicopter rotor engine modulation (Simulated)

TABLE I
SIMULATION PARAMETERS FOR DIFFERENT TARGETS

	L_1 (in m)	L_2 (in m)	N	N_r(RPM)	θ	ϕ
Helicopter [3]	0	5	4	300	$\pi/2$	0
Propeller [2]	0.5	1.5	6	2400	0	$\pi/2$
Jet airliner [4]	0.13	0.54	36	7200	0	0

JEM sidebands from blades. Hence, the Doppler spectrum consists of both JEM and propeller modulation. For this target model, the complex return signal consists of summation of contribution from number of propellers and number of gas turbine engine based on target physical parameters with difference in rotor blade speed for multi-engine and multi-propeller speed. However, this phenomena is aspect dependent and more dominant at head on aspect. Simulated target returns for different target types with peculiar Doppler spectrum is shown below in Fig.1 - Fig.4. The Doppler filters of real data for target is also plotted for verifying the simulation results.

1) Simulated JEM modulation for large turbojet engine

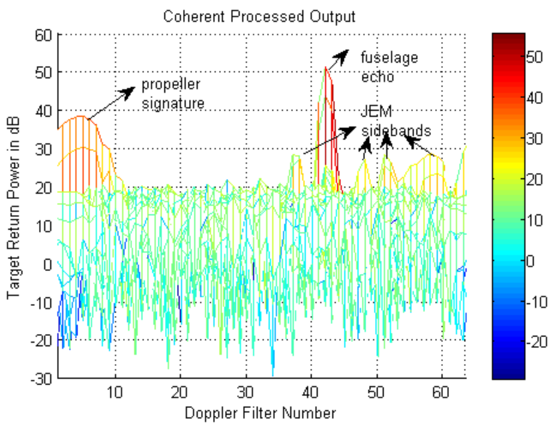

Fig. 4. JEM signature with propeller (Simulated)

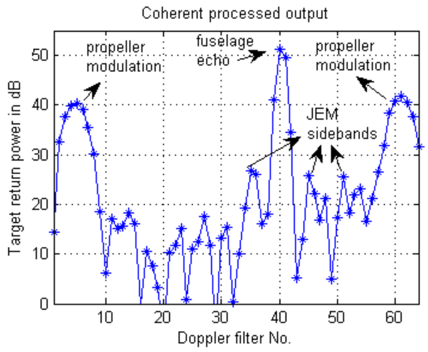

Fig. 5. JEM with propeller modulation in Doppler domain(Real data)

aircraft at head on aspect is shown in Fig.1. The Doppler sidebands are equidistant from fuselage echo.However, due to simple single engine model, it does not take into account the multiple-engine multiple-echo interaction. Practically, blades are pitched for aerodynamic reason which result in change in Doppler spectra. In this fig, blade pitch is assumed zero. The fan visibility function is modeled with much simpler function and enabled only for aspect angle within 60 deg around head on aspect. The JEM modulation increases with short air intake and large size engine exhaust and appears similar to propeller continuous denser spectrum for head on aspect at higher frequency.

2) Propeller Modulation is simulated for turbo-fan engine aircraft as shown in Fig.2. The propeller modulation increases with more number of propeller and propeller blades as the Doppler contribution from each gets added up. Due to lower propeller speed, it occupies lower spectrum region.The broadside aspect may partially obscure propeller blades. Due to aerodynamic reason, speed of different propellers are kept at same speed.
3) Helicopter engine modulation is simulated as shown in Fig.3. Since rotor blade flashes are spiky in time domain, it result in almost equal contribution in most of the Doppler filters. The widening of Doppler spectrum can be observed around fuselage echo due to rotor hub Doppler.
4) Jet engine modulation with propeller modulation is simulated for propeller aircraft with jet engine as shown in Fig.4. The smaller commercial aircraft as well as large turbo-prop propellers with multiple engine has increased micro-Doppler content due to contribution from multiple propeller and multiple-engine rotor blades.
5) Real data is plotted for jet engine modulation along with propeller modulation as shown in Fig.5. The upper sidebands [6]high energy content than lower sidebands is attributed to blade pitch of propeller at head on aspect
6) Helicopter engine modulation real data is plotted in Doppler domain as shown in Fig.6. The Rotor blades [10] shows contribution in large number of filters. The Tail rotor being faster in speed is seen in elevated

TABLE II
DOPPLER ENERGY SPREAD FOR DIFFERENT TARGETS

	Helicopter	Jet engine	Propeller	Turbo prop airliner	windmill
Doppler Filter energy(in percentage)	60-70	40-50	50-60	70-80	30-40
Amplitude width(in dB)	10-13	15-25	20-25	25-40	10-20
Aspect	all	head-on ,tail aspect	mostly all	mostly all	Head-on,tail-aspect

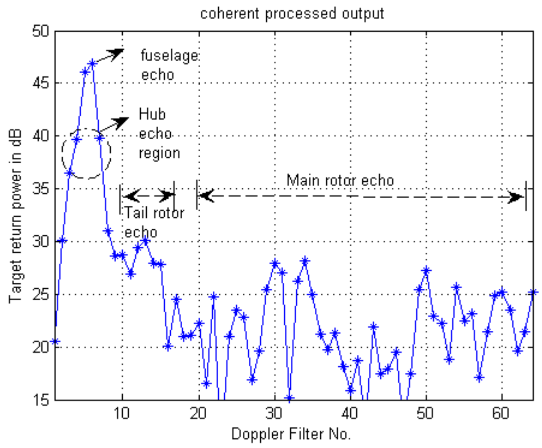

Fig. 6. Helicopter modulation in Doppler domain (Real data)

frequency domain. The Fuselage echo is widened by one more filter due to contribution from rotor hub.

IV. SPECTRAL CONTENT FOR COARSE TARGET RECOGNITION

The mathematical model eq.(1) to eq.(2) is incorporated in Radar I/Q data simulator for different targets like turbo-fan jet airliners, turbo-prop aircraft powered with jet engine and helicopters. The following parameters are programmable for I/Q simulator:

1) Radar waveform parameters: Carrier Frequency (Surveillance band) , PRF(MPRF), signal waveform (Chirp) and bandwidth (as per range resolution)
2) Radar range , target range, target velocity, Radar azimuth, elevation, target azimuth elevation,Time On Target(TOT), target SNR required
3) Tentative target physical parameters as given in Table I for different target type to be simulated.

The simulated I/Q data is 2-D matrix of range cell$\times$pulses. The I/Q is processed by signal processing chain [11] of radar signal processor and coherent processed output matrix is used for Doppler spectrum analysis.The following steps are used for calculating spread in Doppler spectrum due to micro-Doppler signature of targets.

1) Each detection after CFAR processing is tested for extension in Doppler filter. If detection is reported in Doppler domain for more than three filter, Doppler filter spread is calculated. This is done to avoid processing of any clutter leaks,abnormal sample for system imperfection or noise sample.
2) The threshold is kept 30 dB below the peak filter strength for calculating the Doppler spread of target. This is due to the fact that JEM or blade modulations [1] are 30dB down for most of the cases.Although, for few near range targets with high SNR and at some aspects may even show sidebands as high as 5 dB below target fuselage echo strength. If the target SNR is low, The threshold is clamped at 3 dB higher than noise floor.
3) Doppler filter spread is calculated in percentage as ratio of number of filters with strength greater than threshold value to the total number of Doppler filters.
4) The amplitude bandwidth of the spread is calculated as difference between peak value of Doppler filter (after fuselage echo suppression in Doppler domain) and threshold value. This width varies with different Doppler types and can be used for coarse target recognition. Target fuselage echo along with two filters are not considered for calculating amplitude bandwidth. This parameter is significant for distinguishing helicopter with other targets as the rotor blade echo is spread uniformly in all the Doppler filters resulting in maximum energy content within narrow band. For other targets this may be wider as sidebands are concentrated only in few filters.

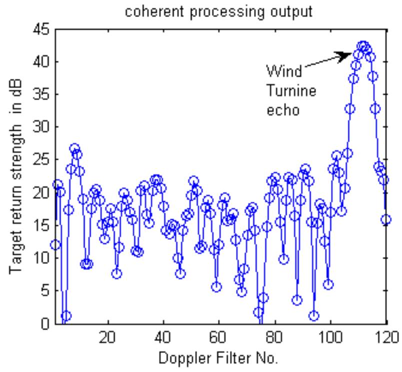

Fig. 7. Wind Turbine echo in Doppler domain(Real data)

V. MICRO-DOPPLER SPECTRUM ANALYSIS FOR DIFFERENT TARGETS

As seen from figure 1 to 7, the Doppler spectrum varies for different targets. This gives advantage of using the Doppler spread for distinguishing between targets. The Doppler spread calculation is done on real and simulated target data for more than 300 looks for different target types and result is tabulated in the Table II. As seen from the table the Doppler filter spread percentage, amplitude band varies for different target and can be used for coarse level target recognition. For few cases of turbo-prop aircraft with multiple engines and installed on different axis than propeller, the Doppler frequency content may be higher for head-on aspect than tabulated values with wide amplitude band.Such cases are differentiated in conjunction with target speed, RCS and height. The Doppler spectrum may get distorted in presence of internal or external interference. Hence, Micro Doppler spectrum is not calculated for data where interference is indicated in signal processor. In this paper, Wind Turbine echo returns from real radar data is also extracted for Doppler spectrum analysis. The wind turbine [12] also induces micro Doppler signature of the rotating blades and acts as interference to the radar. Since the helicopter rotor blades and Wind Turbine rotor blade-tip speeds are comparable [13], the folded returns in MPRF domain can give false indication of presence of slow moving target with micro-Doppler signature.

VI. Conclusion

In this paper, different targets with micro-Doppler signature is simulated for surveillance band using standard mathematical models. The peculiar spectral characteristic of each target is analysed. Since it does not perform target identification ,target physical parameter database is not maintained. The simulated as well as real data is processed in signal processor for calculating Doppler filter spread and amplitude width of this spread for coarse target recognition. This coarser level target recognition is done using radar search and track function with SNR along with M/N criterion to minimise false indication . Radar Data Processor(RDP) uses this information along with RCS, aspect and target kinematics to build the confidence level. RDP request beam scheduler for special waveform suitable for target recognition with atleast SNR greater than 25 dB. This is done only after high confidence level is built at RDP level. This approach put less demand to resource scheduler for target recognition. Future work may put the whole scheme with signal processor and RDP in loop for target recognition in S-Band.

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