Micro-Doppler signature based helicopter identification and classification through Machine learning

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Abstract—This paper focuses on identification of helicopter by exploiting the concept of micro-Doppler effect which is prominent in targets containing rotating, oscillating or vibrating parts in it. Radar received signal is analyzed by Short Time Fourier Transform (STFT) to extract the micro Doppler (mD) signature. From the mD signature, the helicopter parameters are estimated. In a multiple helicopters scenario, estimated parameters will be a mixure, pertaining to the multiple helicopters. These parameters are classified further using a machine learning algorithm, namely k-means clustering to classify the helicopters. Simulated results for the synthesized received signal shows the betted estimates of the helicopter parameter through mD signature. Dataset containing basic parameters like number of blades, blade length and rotational rates of the UN-1N helicopter (rotor with 2 blades), the SH-3H helicopter (rotor with 5 blades) and the CH-54B helicopter (rotor with 6 blades) are considered for the classification. Results show a good classification. When analysed with different SNR level in dataset, at lower SNR, observed some ovelapping in the classification.

Keywords— k-means clustering, Micro-Doppler effect, Micro-Doppler signature, Short Time Fourier Transform.

I. INTRODUCTION

The micro-Doppler signatures extracted from the target's backscattered signal contain a lot of information about the target which can be extensively used in target detection and identification. Target detection and tracking dates way back in time. It's just the methodologies that keep advancing day by day. Initially detection of a target was based on its Radar Cross Section (RCS). This indicates how much a target is detectable by a radar based on the property of the object's reflectivity. This RCS is dependent on so many features of the target such as the material of the target, shape of the target, the angle at which the transmitted signal hits the target (i.e., incident angle), the angle at which the received signal is reflected from the target (i.e., reflected angle), etc. When the target has a high RCS then it is considered to be easily detectable. RCS is the earlier method used for aircraft detection over various ranges. But in recent times the concept of micro-Doppler (mD) effect is used to identify the target.

Micro-Doppler effect is caused due to the micro-motions in the target, when there are rotating, oscillating or vibrating parts in it. The extraction of these micro-Doppler signatures from the received signal of the target contains phase modulations. These phase modulations are extracted using time-frequency analysis techniques. There exist wide varieties of time-frequency analysing techniques such as Short Time Fourier Transform (STFT), Wigner Ville distribution (WVD), wavelet transform and so on. The pioneer of Micro Doppler effect in Radar is Victor C Chen. His book [1] contains research in extraction of micro-Doppler signatures from helicopters, human body, pendulum, bird, etc.

The micro-Doppler (mD) features in the time-frequency domain has also been studied in [2]. Further the received signal from the targets with micro-motions are analysed in both rigid and non-rigid bodies. These signals contain modulations that provide the information about the target. When special sensors are used to detect the living things at many instances wrong detections are made such as identifying other *mammals* as human beings. In [3] the author has overcome these confusions by introducing micro Doppler signatures for detection. Due to this the false alarm rate is reduced significantly. The blade length as well as rotation rate of the blades in a drone is calculated by extracting its micro-Doppler signatures using W-Band Micro-Doppler Radar [4, 5]. Identification for 1, 2 and 4 rotors are verified through simulation. In [6], Using mD, ballistic targets are classified based on the precession, nutation and wobble which are further used for categorizing them into warheads and decoy. They have achieved this by considering the occlusion effect as well as the point scatter model in the micro Doppler. Multi-static passive radars are used in [7] to extract the mD signature of the helicopter. Here the target appears to be at different angles for each receiver, giving rise to different micro-Doppler signatures, used as an additional information about the target to be identified. The concept of wavelet transform [8] and Inverse Radom transform (IRT) [9] along with the time frequency analysis is also used for feature extraction of helicopters and human models. The results of the main and the tail rotor blades appears as flashes. Other information like speed of the rotor and the number of blades in each rotor are used for the target categorizing [10]. Wavelet coefficients are extracted, and further examination has also been proposed in [11] to detect and classify the wind turbines and aerial targets in clutter environment. These classification results are obtained from employing Bayesian and Probabilistic Neural Networks classifiers. Since mD signature varies with the shapes of the blades, the received signal for each type of blade tips has been analysed in the time-frequency domain and this information is used for further classification in [12]. In [13], an algorithm for recognition of pedestrians in highways and parking lots has been developed through exploiting the micro-Doppler signatures of the target. Analysis of various micro-dynamics namely rotation, tumbling, vibration through time-frequency distribution images has also been proposed in [13]. Feature extraction is also performed using different classifiers. In [14] suspicious targets are identified and classified by using fractional Fourier transform, Wigner Ville distribution and tomographic imaging principle. In [15, 16] RCS time frequency spectrum is used for finding the length, rotation rate and number of blades in the rotors in modern warfare weapons containing rotating structures.

Even though mD signatures along with multi-static scenarios are considered to classify the targets, problem arises when the features are closely related. Recent machine learning algorithms prove better classification in many applications. In [17], there are studies on how K-means clustering is used for classifying leukocyte images based on their geometrical features. These images were used for extraction of the features. These features were considered as the input dataset over which K-means clustering was applied. K-means clustering is simple but works better and provides greater prediction accuracy when the normalised data is used for classification. Sometimes some of the data points remain unclustered, for which one needs to provide the number of clusters. This is one of the drawbacks in K-means clustering. This disadvantage has been overcome by characterizing the number of clusters. This technique increases accuracy and clustering quality by performing more number of iterations and also the time taken for clustering is significantly reduced [18]. In this paper, we have initially focused on extracting the mD signatures of the helicopter blades from the synthesised reflected signals which are assumed to be received from the helicopter. Later, when the set of features are extracted from the mD signatures pertaining to the multiple helicopters, one of the machine learning classification algorithm namely K-means clustering algorithm is used to classify these helicopters.

II. METHODOLOGY

A. *Micro-Doppler Effect*

Mechanical rotations or vibrations of an object or any part of the target may cause additional frequency modulations on the radar backscattered signal. This leads to the generation of sidebands about the target's Doppler frequency. This phenomenon is called the micro-Doppler effect. The extraction of micro-Doppler signatures from the received signal provides additional information of the target which in turn helps in its identification.

The translational motion of the target may result in a frequency shift in the backscattered or received signal. Sometime the target may consist of certain motions apart from translation which include rotations, vibrations or oscillations. These come under the category of “micro motions”. Not all the parts of the target which might be in motion cause frequency shifts in the received signal. Instead, they produce the phase shift and get modulated with the received signal. The phase modulations found in the backscattered signal are due to the presence of micro motions in the target and this is known as the micro-Doppler effect.

B. *Radar signal model for micro Doppler shift*

Consider a RADAR with space fixed coordinates as (X, Y, Z). The target of interest is available at a range, R from the RADAR with the body fixed coordinates (x, y, z). Here it is assumed that the target is a helicopter and the position of its rotor blade is assumed to be at (x, y, z) where the values of x,y and z are 0.

Consider that the target’s reference frame coordinates are (X′, Y′, Z′). This reference frame is located at the same origin as the body fixed coordinates and it is the translated version of the space fixed coordinates. These coordinates are clearly depicted in Fig.1. The blades in the rotor rotate along the z-axis with a certain angular rotation rate, *Ω*, which is measured in rev/s. These are the initial set of parameters to be taken into consideration.

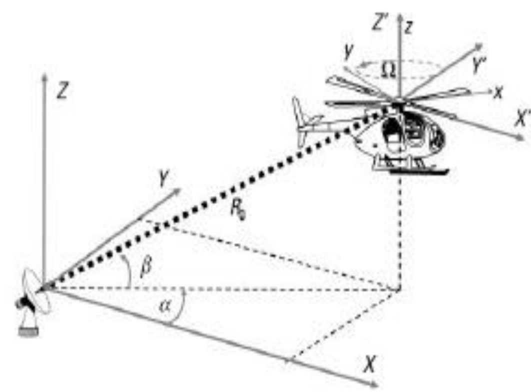


Fig.1. Geometry of RADAR (courtesy V. C. Chen [1])

Let the radar transmitted signal *T(t)* be assumed as

$$T(t) = exp(j2\pi ft) \quad .....(1)$$

In case of a non-stationary target, the received signal consists of a time delay (τ), and a modulated Doppler frequency (f_D). Then the received signal, *S(t)* is as follows:

$$S(t) = exp\{-j[2\pi ft + \tau]\} \quad .....(2)$$

$$\text{where } \tau = \frac{4\pi}{\lambda} R(t) \quad ......(3)$$

In the helicopter, there are rotatory motions of blades, which further cause phase modulations in the received signal. This is due to the micro-Doppler effect. In case of the micro Doppler this τ may be represented by

$$\phi(t) = \frac{4\pi}{\lambda} R(t) \quad ...... (4)$$

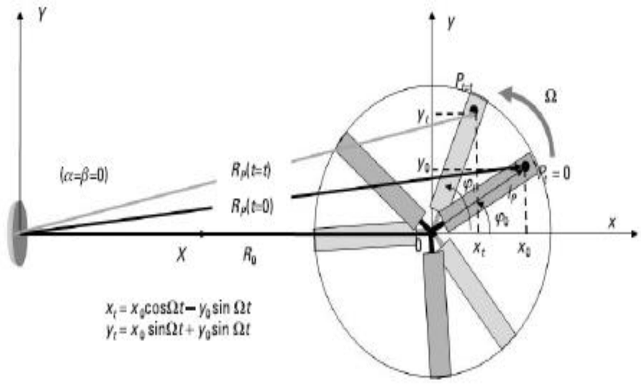


Fig.2. Rotation of rotor blades (courtesy V. C. Chen[1])

Here *Φ(t)* is the phase function of the point of scattering and *R(t)* is the varying distance between the scattering point on the rotating blade and the radar, with f as the transmitting frequency and λ as the wavelength of the radar as shown in Fig.2.

When the rotor height is z_0, with a blade length of L, then the phase function in equation (3) for the scattered point is modified as [1]:

$$\phi(t) = \frac{4\pi}{\lambda}[R_0 + \cos\beta(l\cos\phi_0\cos\Omega t + l\sin\phi_0\sin\Omega t) + z_0\sin\beta] \quad \text{........ (5)}$$

Thus, the received signal shown in equation (2) for the scattered point becomes,

$$S(t) = \exp\left\{-j\frac{4\pi}{\lambda}[R_0 + z_0\sin\beta]\right\}\exp\{-j2\pi ft - \frac{4\pi}{\lambda} l\cos\beta\cos(\Omega t + \phi_0) \quad \text{...... (6)}$$

where β is the elevation angle of the target from the radar and Ω is the angular rotation rate of the rotor. For a rotor with *N* blades, there are *N* different initial rotation angles which can be represented as:

$$\phi(k) = \phi_0 + \frac{2\pi k}{N} \quad \text{...... (7)}$$

Here k=0,1,2,3,…,N-1. The returns of each blade at an observed interval will appear as the backscattered signal. Then the radar cross section (RCS- σ) of the blade is given by

$$\sigma = \frac{4\pi a^2 b^2}{\lambda^2}\left(\cos\theta \times \frac{\sin x_k}{x_k} \times \frac{\cos y_k}{y_k}\right)^2 \quad \text{....... (8)}$$

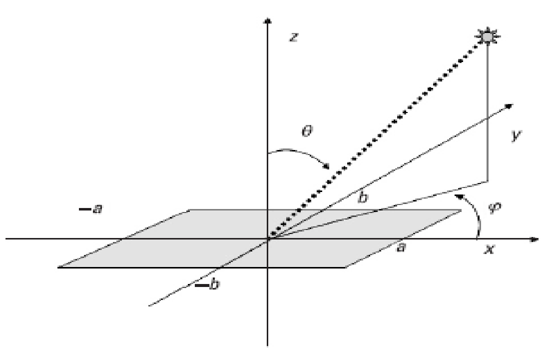


Fig.3. Rectangular flat plate modelled as the rotor blade (courtesy V. C. Chen [1])

From Fig.3., we observe that,

$$x_k = ka\sin\theta\sin\Phi \quad \text{........ (9)}$$

$$y_k = kb\sin\theta\cos\Phi \quad \text{........ (10)}$$

$$\text{Where } k = \frac{2\pi}{\lambda} \quad \text{........ (11)}$$

Equation (8) gives the amplitude of the received signal.

III. THE PROPOSED METHOD

Methodology to classify the Helicopters from the radar received signal is shown in Fig 4. Mathematical model of the phase function in the reflected signal from the point scattered helicopter is given in the equation (5). Similarly, the expected received signal magnitude based on the radar range *R* is given in the equation (8).

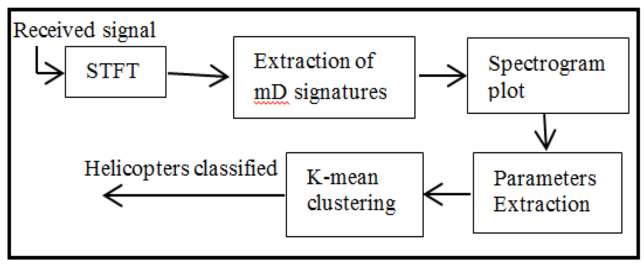


Fig.4. Block diagram representation of mD extraction and helicopter classification process

The mD signature from the radar received signal, when it is reflected by a helicopter with 2 blades in its rotor is shown in Fig.5. This is the spectrogram plot of the change in frequency of the signal with respect to time. Next section explains the method using which the parameters are extracted from the spectrogram.

A. Micro-Doppler signature extraction

When the radar returns from the helicopter is viewed in the frequency domain, its mD shifts can be seen from the central frequency. But phase change cannot be identified through simple frequency analysis i.e., FFT. Hence the concept of time frequency analysis is preferred. To analyse the time-varying frequency characteristics of the micro Doppler modulated received signal, basic Short Time Fourier Transform (STFT) is used.

B. Short Time Fourier Transform (STFT):

It is a sequence of Fourier transforms performed on windowed signal which provides the time-localized frequency information. It is usually implemented on signals whose frequency components vary over time. This reveals the Fourier spectrum on each shorter segment. Then the changing spectra is plotted as a function of time. This plot is called the Spectrogram which clearly provides the information needed for the purpose of target identification and further classification.

From the spectrogram one can estimate the following parameters as shown in Fig. 5:

- Number of blades (N)
- Rotation rate $\left(\Omega = \frac{1}{T_c}\right)$
- Length of the blade (L)

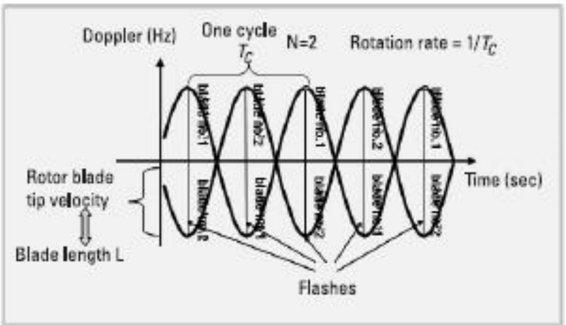


Fig.5. Micro-Doppler signature of a rotor with 2 blades (courtesy V. C. Chen [1])

C. K-Mean Clustering

This is one of the learning algorithms which we used for classifying our dataset. Clustering comes under the category of unsupervised classification wherein a dataset containing information which needs to be classified is grouped into clusters of its own class. It is a distance based classification. The method used for finding this distance is Euclidean. We need a central point of choice and the data around it gets clustered based on the distance matrix. The algorithm for K-means clustering includes a dataset of stacked points from which the central point is chosen. Euclidean distance of the stacked points from the central point is computed and then clustering takes place. This is one of the simplest algorithms that suits well for clustering type problems. Consider a dataset of interest. When k-means algorithm is applied to it, it classifies the existing dataset into k different clusters. The number of clusters are decided initially. A centroid or a cluster head is defined for every cluster. These centroids are placed as points and these represent the initial group of centroids. Then each sample data from the dataset is associated with the nearest k point centroid. This is realized by calculating the distance between the centroid and the sample data. Euclidean distance between the centroids and the sample data point is calculated and the sample is assigned to the closest centroid. Once all the data from the dataset has been assigned to a cluster head, the position of the new k centroids are calculated again. This goes on for many iterations until there is no change in position of the centroids.

IV. RESULTS, ANALYSIS AND DISCUSSIONS

To extract the helicopter parameter and to further classify them, the radar received signals with point reflected micro Doppler effects are synthesized using the equation (6). The magnitude of the signal is chosen based on RCS given in equation (8). Table 1 shows the basic parameters with their assumed initial values for synthesizing the received signal.

Table **1**. Initial values assigned to different parameters

PARAMETERS	INITIAL VALUE
Range resolution	0. 5 m
Time duration	1 s
Number of samples	10240
Transmission frequency	5 GHz
Psi	0
Phi	Rotation rate×time
Theta	0
Window size	512

A. Transmitted signal and received signal plot

To synthesize the transmitted and received signal in time domain using equation (1) and (6), following assumptions are made. The target considered here is a two-blade rotor helicopter whose blade length is of 6.5 m each with a rotation rate of Ω = 4 revs/s and the nutation angle of θ=45°. Here, C-band FMCW radar with the wavelength of λ=0.06 m is assumed for trans receiving the echo signal from the previously mentioned helicopter. Same waveforms are plotted as shown in Fig.6 for ideal scenario. In this plot, it is odd to identify the mD signature from the received signal.

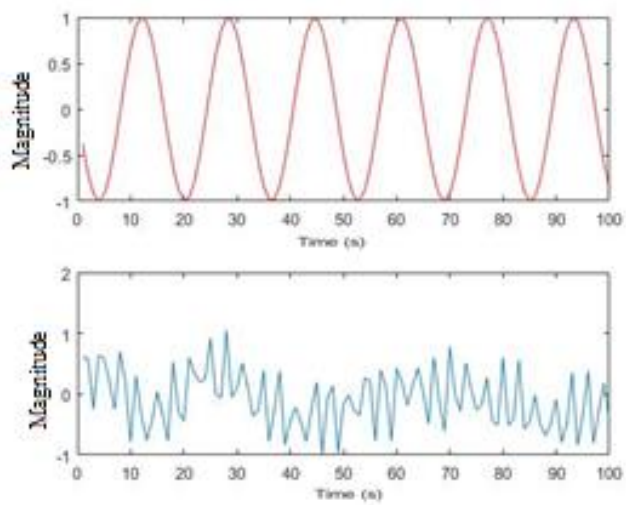


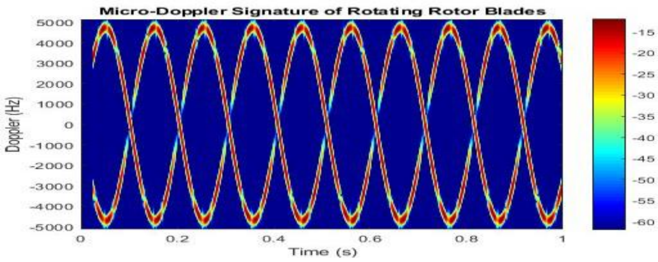
Fig.6. Plot of transmitted and received signal

B. Micro-Doppler signatures from the helicopter blades

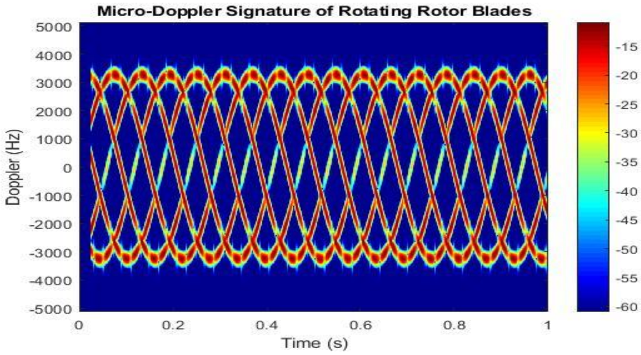
Fig.7 shows the spectrogram of the radar received signal. Using these spectrograms the three parameters namely number of blades, length of the blades and the rotation rate are calculated. Each blade rotation will be appearing as a sinusoidal wave form in the spectrogram. Thus the number of symmetric Doppler patterns in the spectrogram indicates the number of blades in the helicopter. Rotor's rotation rate (Ω) is calculated as Ω = 1/t_c; where t_c is the time period between two peaks of a sinusoidal waveform in the spectrum. Blade length(L) is calculated using the following equation [1]

$$V_{tip} = 2\pi L\, \Omega \quad \text{...... (12)}$$

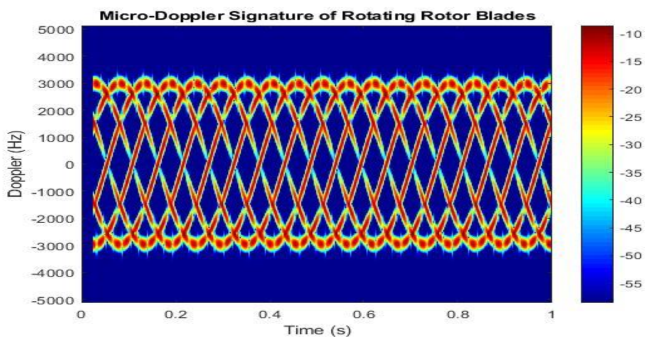
Where V_{tip} is obtain from $\{f_D\}_{max} = 2V_{tip}cos(\theta)/\lambda$.



(a)



(b)



(c)

Fig.7. Spectrograms of 3 different helicopters of interest. (a) Spectrogram of the helicopter UN-1N (rotor with 2 blades). (b) Spectrogram of the helicopter SH-3H (rotor with 5 blades). (c) Spectrogram of the helicopter CH-54B (rotor with 6 blades).

Table **2**. Calculated parameters for the UN-1N helicopter based on Fig.7(a)

Parameter	Actual Value	Obtained Value
No. Of Blades	2	2
Length Of Blade (m)	7.39	9.42
Rotation Rate (rev/s)	4.89	4.88

Table **3**. Calculated parameters for the SH-3H helicopter based on Fig.7(b)

Parameter	Actual Value	Obtained Value
No. Of Blades	5	5
Length Of Blade (m)	9.4488	9.59
Rotation Rate (rev/s)	3.39	3.38

Table 4. Calculated parameters for the CH-54B helicopter based on Fig.7(c)

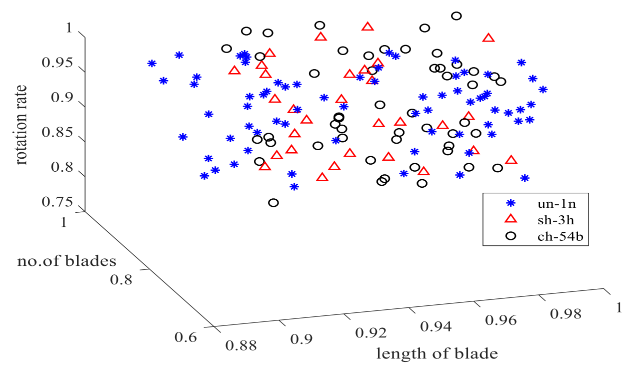
Parameter	Actual Value	Obtained Value
No. Of Blades	6	6
Length Of Blade (m)	10.9	9.78
Rotation Rate (rev/s)	3.081	3.074

Tables 2-4 shows the comparison between the actual parameters considered to synthesize the received signal and the calculated parameters which were obtained from the spectrogram.

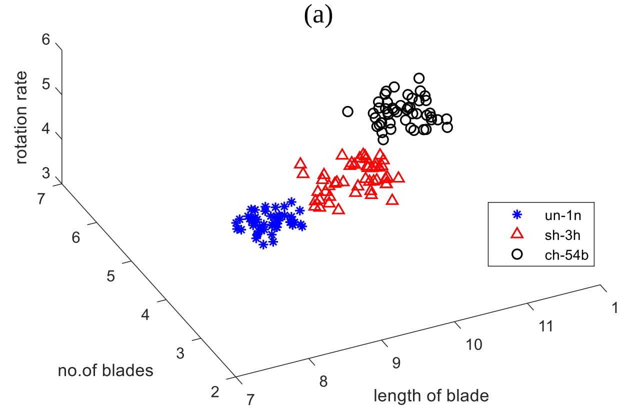
C. Classification Results

The parameters obtained from Tables 2-4 for the three helicopters UN-1N, SH-3H and CH-54B are duplicated using two different *randn()* function in MATLAB in order to create the dataset as shown in Fig.8(a) and Fig.8(c).

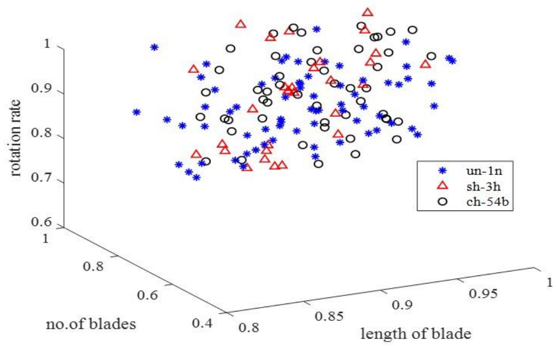
Each parameter has 150 samples. Fig.8(b) and Fig.8(d). represent the dataset after classification using k-means clustering algorithm. It is observed that the created samples in the dataset are assigned to one of the three categories giving rise to 3 clusters each corresponding to one of the three helicopters namely UN-1N, SH-3H and CH-54B.



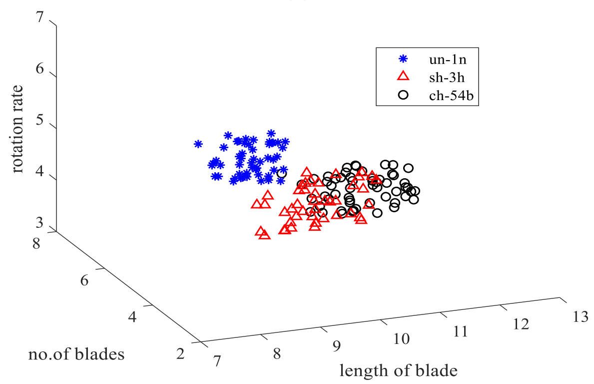
(a)



(b)



(c)



(d)

Fig.7. Classification using k-means clustering. (a) three dimensional representation of the dataset before classification. (b) the dataset after classification using k-means clustering algorithm. (c) dataset of the helicopter parameters with a slightly lower SNR value. (d) the classified dataset which has some ovelaping in the classification.

V. CONCLUSION

This paper used one of the existing algorithms for calculating the micro-Doppler signatures. With these extracted features, the concept of machine learning namely k-means clustering is used to classify the different targets. Being one of the simplest and at the same time the effective method for clustering, k-means clustering has provided the clustering of data belonging to three different helicopters with utmost precision. This classification methodology can be used to train the classifier with more dataset which may be collected in actual scenario and can be used for further testing.

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