Radar Backscatter Analysis Using Fractional Fourier Transform

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Abstract– This paper focuses on analyzing radar backscatter returns using the fractional Fourier Transform. This study is motivated by two factors: first, to examine radar backscatter mechanism of standard small targets, and second, to extract pertinent scattering features that can be used in target recognition. Radar returns have been examined using time-frequency analysis techniques, particularly those targets with dispersive scattering behavior. The FrFT scattering analysis scheme is tested using real radar signatures of commercial aircraft recorded in the UHF range.

1. INTRODUCTION

Examining electromagnetic scattering of basic geometric metallic objects has long been the subject of extensive research the fields of microwave and propagation. The significance of this research lies in the interest in developing target detection, and identification systems. The Fractional Fourier Transform (FrFT) which has received significant renewed interest in the last few years offers a good compromise between the gathering of scattering information and insights that are attainable using time-frequency and time-scale techniques but without some of the limitations. This paper shows that FrFT can be used as a tool for analyzing scattering of specular and dispersive radar targets. The targets examined are theoretical in nature, and the examples are presented to justify the use of FrFT. The same approach is then applied to real radar returns recorded using stepped-frequency radar interrogating commercial aircraft models.

2. FRFT: DEFINITION AND PROPERTIES

The Fractional Fourier Transform of a signal f(t) is defined as

$$F^{\alpha}(u)=\int_{-\infty}^{\infty}f(t)K_{\alpha}(t,u)dt$$

where

$$K_{\alpha}(t,u)=\sqrt{\frac{1-j\cot(\alpha)}{2\pi}}$$

$$\exp\left(j((t^2+u^2)/2\cot(\alpha)-jtu\csc(\alpha)\right)$$

if α is not a multiple of 2π

Also $K_{\alpha}(t,u)=\delta(t-u)$ if α is a multiple of 2π

$K_{\alpha}(t,u)=\delta(t+u)$ if α - π is a multiple of 2π

where α represents the rotation angle of the transformed signal [5]. The inverse transform can be obtained using the kernel $K_{-\alpha}(t,u)$. The FrFT of an important signal in radar, the impulse $\delta(t-nt_0)$ is

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$$\sqrt{\frac{1+j\cot(\alpha)}{2\pi}}$$

$$\exp\left(-j((t^2+(nt_0)^2/2)\cot(\alpha)+j(nt_0)t\csc(\alpha))\right)$$

Furthermore, the FrFT of a delayed signal [1] $f(\tau)$ is

$$F^{\alpha}(u-\tau\cos(\alpha))$$

$$\exp\left(j\frac{\tau^2}{2}\sin(\alpha)\cos(\alpha)-ju\tau\sin(\alpha)\right)$$

The most significant feature of the FrFT spectrum is that it can be regarded as a rotation of the time-frequency axes by an angle α so that a chirp that is normally spread in the time-frequency plane is concentrated in the fractional domain. The motive here is that dispersive target scattering can be concentrated in the fractional domain assuming an appropriate α exists.

3.FRFT OF SYNTHETIC TARGETS

Electromagnetic plane waves are scattered from objects in a transient phenomenon that depends on the geometry of the object. Point scatterers (theoretical scatterers) have an impulsive response represented by an impulse with delay proportional to travel to and back from the target. Any scatterers that have more defined geometric shape such as a sphere, flat plate, dihedral, corner, curved edge, etc will have a response that is more dispersive in frequency and is often modeled as fractional integrals or derivatives of an impulse. The impulse response of a target composed of N scatterers is thus modeled as

$$h(t)=\sum_{k=1}^{N} Na_k\delta(t-t_k)$$

where a_k is the magnitude of the response of the kth scatterer and $\delta^{(n)}$ denotes the nth fractional derivative or integral of the impulse function. Previous studies have used the following models for specific scatterers [2]:

n=1 for a flat plate, dihedral; n=0.5 for a curved surface; n=0 for a point scatterer, straight edge, or a doubly curved surface; n=-0.5 for a curved edge diffraction, and n=-1 for a corner diffraction. The delay to and from the kth scatterer normalized with respect to a reference point on the target is denoted by t_k. The frequency response of the target is thus modeled as

$$H(\omega)=\sum_{k=1}^{N} Na_k(j\omega)^{n_k}\exp(j\omega t)$$

Figure 1 shows the FrFT for a point scatterer. Figure 2 shows the FrFT for a flat plate type scatterer, and Figure 3 shows the FrFT for a corner diffractor. It is clear from these figures that the FrFT signature of each scatterer type is distinct and can thus be used for identifying the scattering mechanisms of a specific target. Figure 4 shows the FrFT of a target with all three scatterers combined. Figure 4 shows that, while a corner reflector has dominant FrFT signatures, it is still possible to discern that of a flat plate. Point scatterers are better identified using the full Fourier Transform. The discrete Fractional Fourier Transform used in this study is due to the research reported in [3] and [4]. Figures 1-4 also show that while specific fractional transforms can be better suited to identify certain scatterers, it is the FrFT signature behavior over several angles of rotation α that provides a significant insight about certain scatterers. Therefore, these examples suggest two important benefits for FrFT-based feature extraction: first, identification of the geometrical nature of certain scatterers, and second, the potential for using these FrFT signatures in a target recognition scheme. The linearity and additivity of rotation of the FrFT makes it an attractive alternative to other nonlinear schemes particularly when the signatures of the target under examination are corrupted with additive noise.

4.FRACTIONAL FOURIER TRANSFORM OF REAL TARGETS

Real radar returns of model commercial aircraft recorded using a stepped-frequency radar in the 1-12 GHz frequency range were examined using FrFT. The motive is to use these signatures in a target recognition scheme that offers reliable classification results under practical signal-to-noise scenarios. The frequency range used to study the returns of model aircraft corresponds to UHF range when examining full scale targets. The UHF range is commonly known as the resonance scattering region, where the radar signature is presumably less sensitive to target azimuth. With careful examination of frft of commercial aircraft, it is possible to discern target portions that are dispersive, i.e., it is possible to determine whether a particular scatterer is a curved edge, a sharp edge, or a point scatterer. Algorithms that allow the decomposition of scatterers shown in Figure 5 are being developed to further assess the geometry of the target.

5.TARGET CLASSIFICATION

A feasibility study to investigate the potential of FrFT in target recognition was conducted. The error rate for classifying four commercial aircraft (Beoing 707, 727, 747, and DC10) versus the signal-to-noise ratio was plotted. The results indicate that the FrFT signatures can be used reliably for target recognition particularly in scenarios of relatively high noise levels. Classifiers based on signatures extracted via nonlinear methods behave much poorly in noisy environments. A drawback of the FrFT based classifiers, however, is that FrFT signatures are sensitive to target translation or shift. While shift in the target position produces a mere phase in the full Fourier Transform, it results in a shift and a phase term in the FrFT domain. This property renders FrFT classifiers sensitive to target position, particularly when the classifier depends on catalogue data that may be at a different relative position from that of the unknown target. Shift invariant FrFT-based alternatives would be more desirable for target recognition.

6. CONCLUSIONS

This study has investigated the use of the fractional Fourier Transform in examining the scattering mechanisms of radar targets. Features extracted using the FrFT can be a useful tool for target recognition. Results show that reliable target recognition can be obtained using FrFT signatures.

7. REFERENCES

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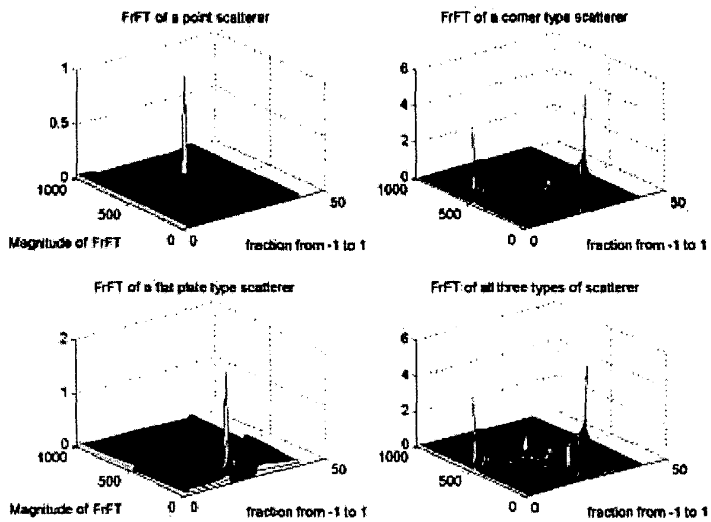

Figures 1 (top left): FRFT of a point target.
Figure 2 (bottom left): FRFT of a flat plate type scatterer
Figure 3: (top right) FRFT of a corner diffractor
Figure 4: (bottom right): FRFT of all three scatterers combined
The angle of rotation is varied from –1 to 1 with a step of 0.05 (41 different FRFT plots per graph).