Recognition of Radar Signal Modulation Based on Fractional Fourier Transform

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***Abstract*—Considering the issue that the recognition of LFM signal, NLFM signal, FSK signal and PSK signal, a recognition method based on fractional Fourier transform (FRFT) is presented. This method is divided into two steps. Firstly, according to the envelope curve of fractional order domain, by judging if the curve peak corresponding fractional order is 1, we can divide these signals into two categories. Secondly, notice that the sharp and flat degree of the curve is different, so in this paper, the kurtosis of curve and the difference of peak are used to demonstrate the sharp and flat degree, by setting the kurtosis threshold and the difference of peak threshold to obtain the final recognition result. The simulation results show that the new method has better recognition ability under low signal-to-noise ratio.**

***Index Terms*—modulated radar signal, recognition of modulation, FRFT, feature extraction, sharp and flat degree**

I. Introduction

Modern electromagnetic environment become more and more complicated and electromagnetic signal density has reached millions. Along with pulse compression radar [1] is widely used in electronic warfare, the traditional five parameters [2] are unable to meet the needs of the electronic reconnaissance for intercepting the enemy's radar signal correctly. In addition to the traditional parameters, it also needs to recognize the modulation of radar signals.

LFM signal, NLFM signal, FSK signal and PSK signal have been widely used as typical pulse compression radar signals. In the field of signal modulation recognition, literature [3] proposed a method based on Short-Time Fourier Transform (STFT) and Wigner Ville Distribution (WVD). Literature [4] proposed the wavelet transform method. However, the STFT is difficult to choose a appropriate window function, WVD is been influenced by cross-terms, and the wavelet transform method has a large amount of computation. This paper puts forward a new coarse to fine recognition method based on FRFT. According to FRFT envelope curve peak corresponding order is 1 or not to extract FM signal. By extracting sharp and flat degree of the normalized envelope curve, FM signal will be identified as LFM signal and NLFM signal, other signals' fine recognition result are FSK signal and PSK signal. Simulation results show that the proposed method has better ability of signal recognition in low SNR.

This paper is organized as follows. Section II mainly introduces the basic principle, including brief introduction of FRFT. Section III presents detailed recognition process and the simulation results. Algorithm performance analysis is also given in Section III. Section IV concludes the paper.

II. Basic Principle

FRFT is a generalized form of the Fourier transform. As a kind of time frequency analysis tool, it has been widely used in the field of signal processing. Compared with the traditional Fourier transform, the FRFT transform is more flexible and can deal with non-stationary signals. The FRFT of the signal $x(t)$ is defined as follows:

$$X_\alpha(u) = \int_{-\infty}^{\infty} x(t) K_\alpha(t,u)\, dt \tag{1}$$

where α is the rotation angle. Here $\alpha = p\pi/2$ and p is the fractional order of FRFT. $K_\alpha(t,u)$ is the transformation kernel function and is defined as follows:

$$K_\alpha(t,u) = \begin{cases} A\exp(j(0.5t^2 \cot\alpha + 0.5u^2 \cot\alpha - ut\csc\alpha)), \alpha \neq n\pi \\ \delta(t-u), \alpha = 2n\pi \\ \delta(t+u), \alpha = 2n\pi \pm \pi \end{cases} \tag{2}$$

where $A = \sqrt{\frac{1 - j\cot\alpha}{2\pi}}$, n is integer, $\delta(\bullet)$ is impulse function.

In practical engineering applications, the discrete calculation of FRFT (DFRFT) is required. There exist several kinds of different DFRFT fast algorithm [5], [6]. Literature [5] proposed a decomposition type of discrete fast algorithm by H. M. Ozaktas in 1996, whose computing speed and complexity are equal to FFT. Furthermore, its calculating result is relatively close to the continuous FRFT. Therefore, this paper adopts the decomposition of discrete fast algorithm to achieve the DFRFT.

III. Recognition Process and Simulation

A. Typical Radar Signal

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Modern radar signal modulation is complex and flexible which mainly concentrates in the modulation of frequency and phase. Here are some typical radar signals.

The analytic form of LFM signal is

$$s(t) = A\exp\{j2\pi[f_0 t + 1/2kt^2 + \phi_0]\} \tag{3}$$

where A is the signal amplitude, f_0 is the initial frequency, k is the frequency modulation slope, ϕ_0 is the initial phase. For instantaneous frequency,

$$f_i = f_0 + kt \tag{4}$$

here mainly study the NLFM signal of three order polynomial phase.

$$s(t) = A\exp\{j2\pi[f_0 t + 1/2at^2 + 1/3bt^3 + \phi_0]\} \tag{5}$$

where A is the amplitude, f_0 is the initial frequency, a, b are the phase polynomial coefficients. ϕ_0 is the initial phase.

For FSK signal,

$$s(t) = \sum_{k=1}^{N} A\exp\{j[2\pi(f_0 + (k-1)\Delta f)t + \phi_0]\} \tag{6}$$

where A is the signal amplitude, f_0 is the initial frequency, Δf is the frequency interval, ϕ_0 is the initial phase.

For PSK signal,

$$s(t) = A\exp\{j(2\pi f_0 t + \pi C_d(k) + \varphi_0)\} \tag{7}$$

where A is the signal amplitude, f_0 is the carrier frequency, φ_0 is the initial phase. $C_d(k)$ is the phase coded function.

B. *Signal Extraction*

By (1) we know that $X_\alpha(u)$ can be regarded as $x(t)$ spread in function space based on the transformation kernel $K_\alpha(t,u)$, and the kernel is a set of orthogonal chirp-base in fractional domain.

FM signal will represent as an impulse function in an appropriate fractional domain, namely FM signal has a very good energy gathered characteristic in one fractional domain. Other signals will also gather in one appropriate fractional domain. By different fractional domains we can extract FM signal.

The simulation parameters set as: for LFM signal, the initial frequency is 10MHz, sampling frequency is 100MHz, frequency modulation slope is 1.4×10^{12} Hz/s. For NLFM signal, the initial frequency and sampling frequency are the same as LFM signal. a, b is $a = 1.4\times10^{12}$ Hz/s, $b = 1\times10^{16}$ Hz/s^2. FSK signal carrier frequency is 10MHz, with a sampling frequency of 100MHz, the frequency interval is 2MHz, with four jumping frequencies. PSK signal adopts Frank codes [1, 1, 1, 1, 1, 2, 3, 4, 1, 3, 1, 3, 1, 4, 3, 2], the carrier frequency is 10MHz, with a sampling frequency of 100MHz, code width is 0.64us. All signals' amplitude is 1V and the SNR is 0dB. As the range of FRFT amplitude is different for different signals, to simplify the data processing, here we map the FRFT result into (0, 1), which is defined as normalized procedure. We call the normalized result as normalized envelope. Do FRFT when $p \in (0,2)$ under searching interval is 0.05. Then FRFT normalized envelope curves of above signals are shown in Fig. 1.

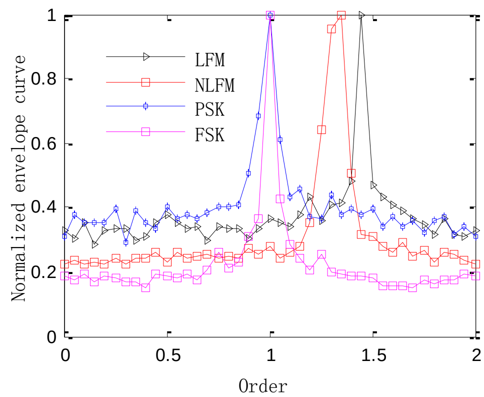

Figure 1. Typical radar signal normalized envelope curve

Fig. 1 shows that the abscissa of curve peak is different for different signals. This is because the frequency of LFM signal and NLFM signal is changing which is controlled by frequency modulation slope, while PSK has a constant frequency and FSK has a constant frequency in a certain period of time. If the signal frequency modulation slope k and rotation angle α correspond the relation $k = -\cot\alpha$, the normalized envelope curve will appear a peak at that fractional order, if not, the peak will not exist. Therefore, for FSK signal and PSK signal, the peak will appear at p=1, for LFM signal and NLFM signal, the peak will not appear at p=1. So by judging the curve peak corresponding fractional order, we can extract FM signal from other signals when the fractional order is not equal to 1.

C. *Recognition of Radar Signal*

In probability and statistics, kurtosis is the index to reflect the sharp and flat degree of distribution curve top. Sometime two sets of data have same arithmetic mean, standard deviation, but their sharp and flat degree of distribution curve top is different. Statistics use fourth central moment to calculate kurtosis [7]. Literature [7] extracted the kurtosis of normalized envelope curve to distinguish LFM signal and NLFM signal. The kurtosis is defined as [1]:

$$\varepsilon = \frac{u_4}{\sigma^4} - 3 \tag{8}$$

where u_4 is the fourth central moment, σ is the standard deviation.

We did Monte-Carlo experiment 100 times in SNR for -10dB~0dB, and drawn the kurtosis distribution of LFM signal and NLFM signal as shown in Fig. 2. From Fig. 2 we can know that there is a large range overlap in SNR for-10dB~-6dB in kurtosis distribution. So literature [7] recognized LFM signal and LFM signal by setting kurtosis threshold which had a poor recognition result under low SNR.

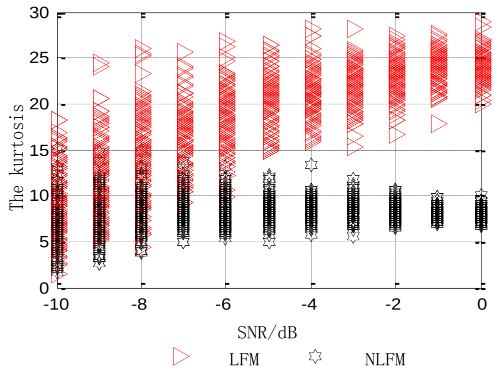

Figure 2. The kurtosis distribution of FM signal normalized envelope curve in different SNR

To solve the poor recognition performance under low SNR, notice that the difference of curve's first maximum and second maximum which is referred to simply as the difference of peak hereinafter can also reflect the sharp and flat degree of the curve. Here we extract this local feature. We did Monte-Carlo experiment 100 times in SNR for-10 dB~0 dB as well, the difference of peak distribution of LFM signal and NLFM signal as shown in Fig. 3.

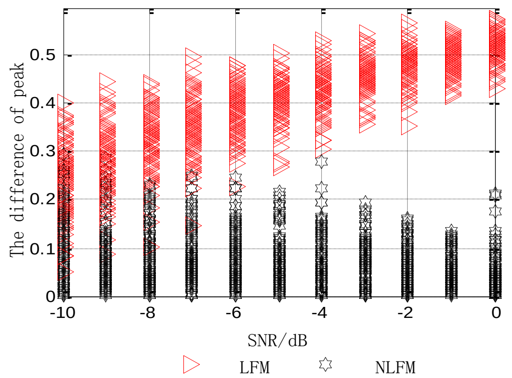

Figure 3. The difference of peak distribution of FM signal normalized envelope curve in different SNR

Fig. 3 shows that the difference of peak distribution has a better boundary compared to kurtosis distribution especially under low SNR. So we can set an appropriate threshold of the difference of peak to recognize LFM signal and LFM signal, which will improve the recognition performance under low SNR.

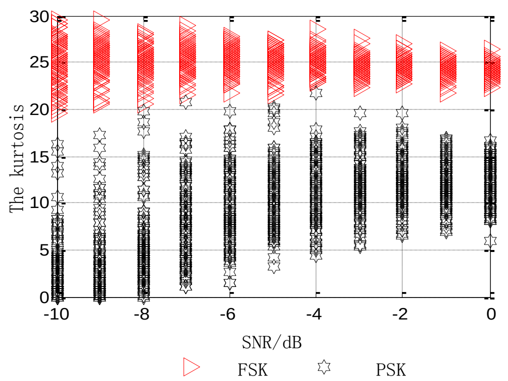

Figure 4. The kurtosis distribution of FSK and PSK signal normalized envelope curve in different SNR

Considering the issue that the recognition of FSK signal and PSK signal, we did Monte-Carlo experiment 100 times in SNR for-10 dB~0 dB as well to obtain the kurtosis distribution as shown in Fig. 4. From Fig. 4, we can see there is an obvious boundary between FSK signal and PSK signal. So we can set an appropriate threshold of the kurtosis to realize the recognition of FSK signal and PSK signal.

D. Algorithm Performance Analysis

In order to validate the effectiveness of the extraction algorithm, we did Monte-Carlo experiment 100 times in SNR for −10 dB~0 dB, and drawn the extraction rate curve, as shown in Fig. 5. From the curve, we can see the extraction rate of FM signal and FSK signal is 100%, the extraction rate of PSK signal reaches 86% when SNR is -9 dB.

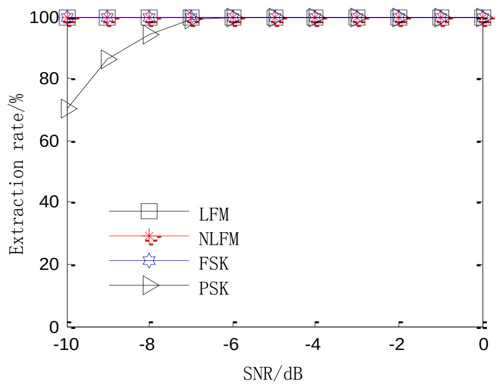

Figure 5. Signal extraction rate in different SNR

After FM signal is correctly extracted, it will be recognized as LFM signal and NLFM signal. To validate the effectiveness of the new algorithm, we did Monte-Carlo experiment 100 times in SNR for -10 dB~0 dB, and drawn the recognition rate curve, as shown in Fig. 6. From the curve, in SNR for -10dB~-6dB, we can see the new method has a better recognition performance of LFM signal and NLFM signal than the kurtosis method. When SNR is -7dB, the recognition rate of LFM signal and NLFM signal is above 90%. In general, this new method can provide a higher recognition rate in SNR for -10dB~ -6dB.

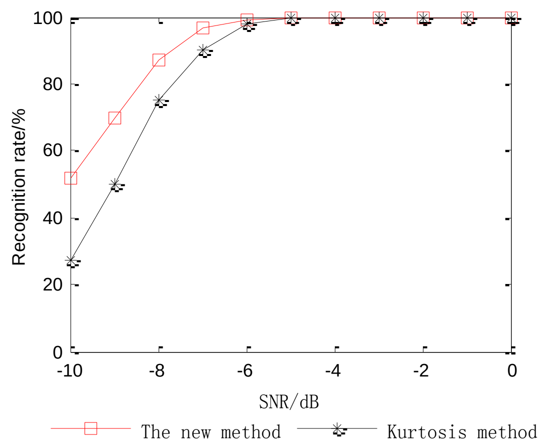

Figure 6. FM signal recognition rate in different SNR by two different methods

By setting a suitable threshold of kurtosis, we can recognize FSK signal and PSK signal. To validate the effectiveness, we did Monte-Carlo experiment 100 times in SNR for -10dB~0dB, and drawn the recognition rate curve, as shown in Fig. 7. Fig. 7 shows that even the SNR is -10 dB, the recognition rate of FSK signal and PSK signal is nearly 100%. In general, this method can provide a high recognition rate in SNR for -10 dB~-0 dB.

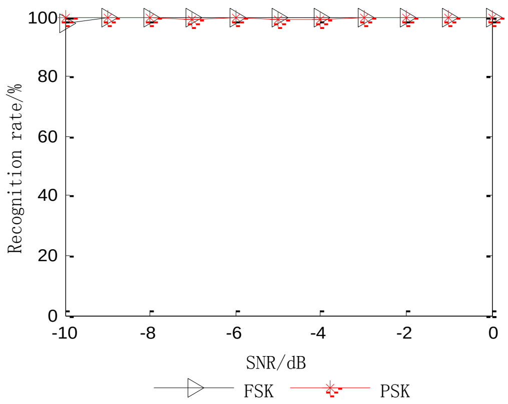

Figure 7. FSK signal and PSK signal recognition rate in different SNR

E. Flow-Process Diagram

The flow-process diagram is shown as Fig. 8

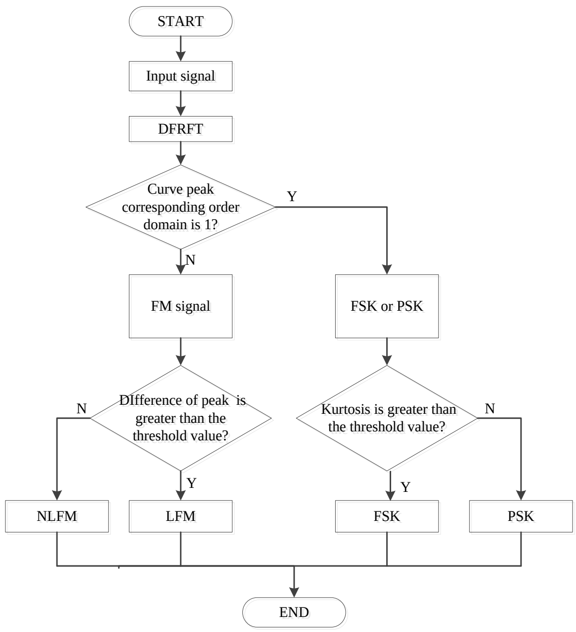

Figure 8. Flow-process diagram

As shown in Fig. 8, that is a from coarse to fine recognition procedure. Namely, detailed recognition steps are as flow:

- Do DFRFT firstly, by judging the curve peak corresponding fractional order to extract FM signal from FSK signal and PSK signal.
- For fine recognition of FM signal, according to the above analysis, we adopt the new method. Namely, we can set an appropriate threshold of the difference of peak to realize the recognition of LFM signal and NLFM signal.
- For fine recognition of FSK signal and PSK signal, we can set an appropriate threshold of the kurtosis to realize the recognition of FSK signal and PSK signal.

IV. Conclusions

Parameter estimation of radar signals is based on the recognition of modulation, so recognition algorithm is crucial. This paper puts forward a new recognition method based on FRFT, the simulation and flow-process diagram of signal recognition are also given. The simulation results show that the new method has higher recognition rate in low SNR. It has a certain engineering application value for the subsequent signal processing of wideband digital receiver. And the recognition of other signals will be the next research direction for us.

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