Gabor-Wigner Transform for Micro-Doppler Analysis

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Abstract:

Micro-Doppler signatures provide unique information about properties of the target. These micro-Doppler features can be used for real time target recognition in military applications and surveillance operations. In this paper, we present Gabor-Wigner transform for extracting micro-Doppler features from the radar returns. The effectiveness of the Gabor-Wigner transform in extracting micro-Doppler features has been compared with short-time Fourier transform, Wigner Distribution. The efficiency of the Gabor-Wigner transform in micro-Doppler feature extraction is demonstrated by applying it to different experimental data sets.

***Keywords:** Time-Frequency analysis, micro-Doppler effect, Short-Time Fourier Transform, Wigner Distribution, Gabor-Wigner Transform.*

I INTRODUCTION

In many cases, a target or structure on a target may have rotations or vibrations. These micro-motions of the target may induce frequency modulation on the radar returned signal. This may lead to generation of side bands about the center of the Doppler shifted carrier frequency. The frequency modulation due to target's rotating or vibrating motion is called micro-Doppler (m-D) effect [1]. Joint time-frequency methods can be used to extract m-D features [2]-[14]. The short-time Fourier transform (STFT) is the most widely used time-frequency representation. In STFT, the time and frequency resolution depends on the size of the window function used in calculating STFT. In order to improve time-frequency concentration, various quadratic time-frequency methods have been proposed. Wigner distribution (WD) is a well-known time-frequency method among the quadratic time-frequency methods, however it suffers from cross-term interferences. Recently, a new approach based on Gabor-Wigner transform is proposed, which efficiently suppresses the cross-terms in the output of WD function [3]. In this paper, we use Gabor-Wigner transform for the extraction of m-D features.

II. GABOR-WIGNER TRANSFORM

STFT is the simplest time-frequency representation introduced for time localization of the frequency contents of a signal by using a suitable window. Basic principle behind STFT is segmenting the signal into narrow time intervals using a window function and taking Fourier transform of each segment.

$$STFT(t,\omega)=\int_{-\infty}^{\infty} x(\tau)\gamma(t-\tau)\exp(-j\omega\tau)d\tau \quad (1)$$

Where $x(t)$ is the signal to be analyzed and $\gamma(t\text{-}\tau)$ is a windowing function centered at $t = \tau$. STFT has limited time-frequency resolution which is determined by the size of the window used. The STFT with Gaussian window is called a Gabor transform [3]. Mathematically Gabor transform (GT) of $x(t)$ is defined as:

$$GT(t,\omega)=\sqrt{\frac{1}{2\pi}}\int_{-\infty}^{\infty} e^{-\frac{(\tau-t)^2}{2}} e^{-j\omega(\tau-\frac{t}{2})} x(\tau)d\tau \quad (2)$$

The WD was originally developed in the area of quantum mechanics by Wigner [4] and then introduced for signal analysis by Ville [5]. It is defined as:

$$WD(t,\omega)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x(t+\frac{\tau}{2})x^*(t+\frac{\tau}{2})e^{-j\omega\tau}d\tau \quad (3)$$

Compared to STFT, WD has much better time and frequency resolution. But the main drawback of the WD is the cross-term interference. This interference phenomenon shows frequency components that do not exist in reality and considerably affect the interpretation of the time-frequency plane. Cross-terms are oscillatory in nature and are located midway between the two components [6]. Presence of cross-terms severely limits the practical applications of WD. Pei and Ding proposed Gabor-Wigner (GW) transform that is defined as a multiplication of STFT with WD, which can significantly remove the cross-terms without affecting the quality of auto-terms [3]. Since cross-terms do not appear in GT, the time-frequency distribution of the GT can be used as a filter, to filter out the cross-terms in the output of the WD.

There are many different combinations to define the GW transform. Here four different definitions are given [3].

$$GW(t,\omega) = GT(t,\omega)WD(t,\omega) \quad (4)$$

$$GW(t,\omega) = min\{\,|GT(t,\omega)|^2, |WD(t,\omega)|\} \quad (5)$$

$$GW(t,\omega) = WD(t,\omega)\{\,|GT(t,\omega)| > 0.25\} \quad (6)$$

$$GW(t, \omega) = GT^{2.6}(t, \omega) WD^{0.6}(t, \omega) \quad (7)$$

GW transform combines the advantages of GT and WD by eliminating cross-terms while maintaining the clarity as good as WD. However GW transform fails to provide useful results once the cross terms are superimposed on the auto components of WD in a multi component signal [7].

III. RESULTS

In this section, we demonstrate the application and effectiveness of GW transform for extracting m-D features. Two different types of experimental radar data sets from different scenarios are used in this demonstration.

A. Rotating corner reflector

Experimental trials were conducted to investigate and determine the m-D radar signatures of targets using an X-band radar. The target used for this experimental trial was a spinning blade with corner reflectors attached that were designed to reflect electromagnetic radiation with minimal loss. These controlled experiments can simulate the rotating types of objects, generally found in an indoor environment such as a rotating fan and, in an outdoor environment such as a rotating antenna or rotors. Controlled experiments allow us to set the desired rotation rate and then permit us to cross check and assess the results.

A picture of the target is shown in Figure 1. The experiment was conducted with the radar operating at 9.2 GHz. The pulse repetition frequency (PRF) was 1 kHz. The target employed in this experiment was at a range of 300 m from the radar. The distance between the two reflectors is 38 inches. The corner length of the reflector is 10 inches and the side length of the reflector is 12 inches. The result in Figure 2 was obtained using one rotating corner reflector facing the radar. Details of the figure clearly shows the sinusoidal motion of the corner reflector. The second weaker oscillation represents the reflection from the counter weight that was used to stabilize the corner reflector during operation. Figure 2a illustrates the time-frequency signature using STFT and Figure 2b illustrates the time-frequency signature using WD. Figure 2c shows that result from the proposed GW transform. Clearly it produces concentrated time-frequency signatures compare to STFT and WD. From the time-frequency signature we can see that the m-D of the rotating corner reflector is a time-varying frequency spectrum. The rotation rate of the corner reflector is directly related to the time interval of the oscillations. From the additional time information, the rotation rate of the corner reflector is estimated at about 60 rpm. Figure 3 shows the result when the blade is rotating with two corner reflectors. In this case, the rotation rate of the corner reflector was 60 rpm. Rotation rates estimated by the time-frequency analysis agree with the actual values.

Figure 1: Picture of the target simulator experimental apparatus.

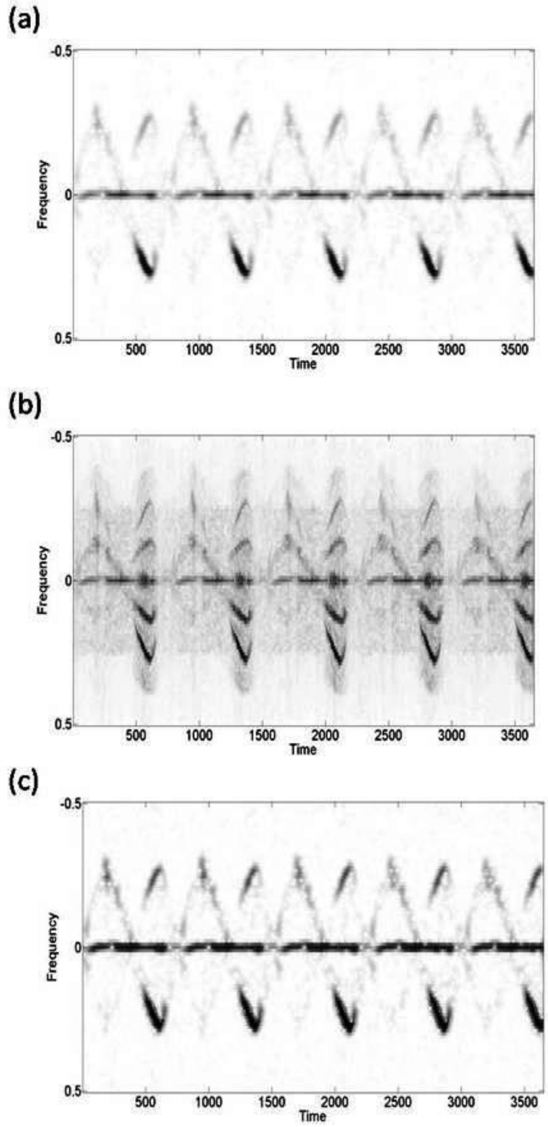

Figure 2: m-D effect from one rotating corner reflector facing the radar: a) GT b) WD c) GW.

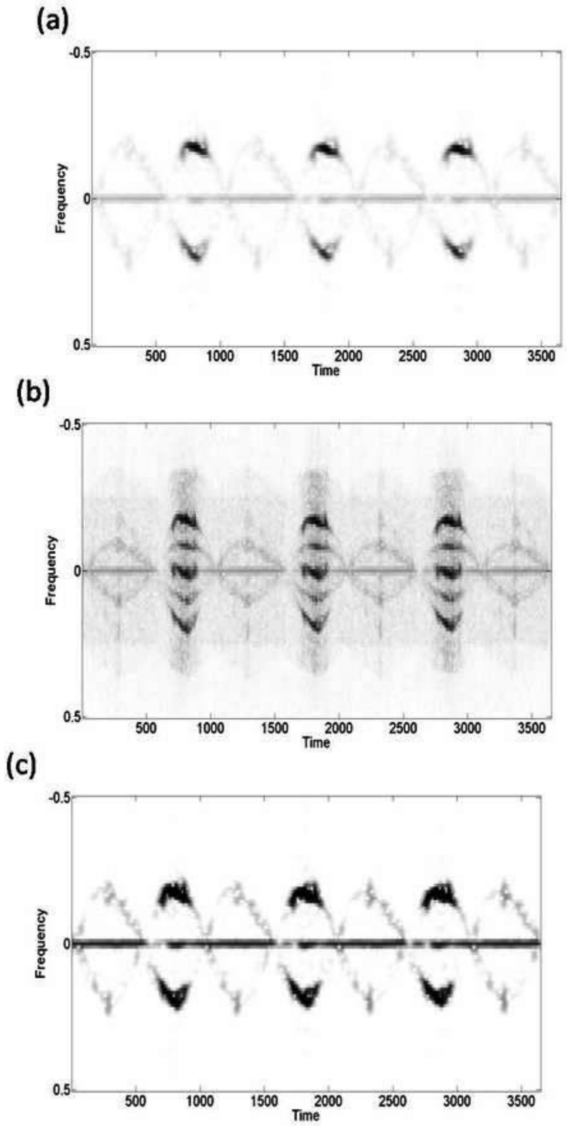

Figure 3: m-D effect from two rotating corner reflector facing the radar: a) GT b) WD c) GW.

B. Performance Analysis

The performance of the time-frequency representations (TFRs) can be compared based on their readability, resolution, cross-terms suppression and energy concentration. Cross-terms suppression and energy concentration of a time-frequency representation is evaluated by visual inspection or on the basis of quantitative measures like entropy measures and ratio of norms [13].

Renyi entropy [14] of time-frequency representation, φ (t, ω) is defined as:

$$Entropy_{Renyi} = \frac{1}{1-\alpha}\log_2\left(\sum_t\sum_\omega \phi^\alpha(t,\omega)\right) \qquad (8)$$

where α is the order of entropy. In the case of TFRs, low entropy stands for high concentration of auto-terms, where as high entropy means lower energy concentration of auto-terms. Ratio of norms (RN) is calculated by dividing fourth power norm of a TFR, φ(t, ω) by its second power norm [15]. Mathematically

$$RN = \frac{\sum_t\sum_\omega \left|\phi^\alpha(t,\omega)\right|^4}{\left(\sum_t\sum_\omega \left|\phi^\alpha(t,\omega)\right|^2\right)^2} \qquad (9)$$

Higher value of RN implies that signal auto-components are highly concentrated [15]. From Tables 1 and 2, it is evident that GW transform has minimum value of entropy and maximum value for RN. Therefore the proposed GW transform shows good energy concentration property compared to STFT and WD.

Performance measure based on Entropy			
Signal	STFT	WD	GW
One Corner Reflector	39.045	37.179	31.034
Two Corner Reflectors	35.690	34.386	24.523

Table 1. Comparison of GW transform with other time-frequency transforms based on Entropy.

Performance measure based on Ratio of Norms (x 10^{-3})			
Signal	STFT	WD	GW
One Corner Reflector	0.667	1.013	2.578
Two Corner Reflectors	1.019	1.234	5.021

Table 2. Comparison of GW transform with other time-frequency transforms based on Ratio of norms.

CONCLUSION

This paper presents Gabor-Wigner transform approach for the extraction of micro-Doppler features of radar returned signals from targets. The method combines the advantages of short-time Fourier transform and Wigner Distribution in order to extract the m-D features of radar target returns. By applying the proposed Gabor-Wigner transform to the experimental data, the effectiveness of this analysis technique is confirmed. From the extracted m-D signatures, information about the target's micro-motion dynamics, such as rotation rate and period of oscillation, can be obtained.

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