Pedestrian Caused Doppler Signal Detection by Bispectrum Processing in Ku-Band Coherent CW Radar

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Abstract. The analyses of the signal using the power spectrum and autocorrelation function are insufficient. We do not have complete information about such signals, because of the loss of the phase information in the power spectrum and autocorrelation function. In that case, it is very important using higher order statistics (HOS). We are using higher order statistics to differ moving object from noise. Besides, finding coherent components in spectrum gives a great opportunity in identification tasks. Experiments were done with IQ continue wave (CW) radar.

Keywords: HOS, bispectral estimating, cumulants, micro-Doppler, phase coupling, pedestrian detection, IQ CW radar

1. Introduction.

Availability of radars gives huge opportunities in different areas. One of these areas is detection. Radars could be used for observation of huge areas for unwanted moving objects detection. The main detection methods are based on received signal energy spectrum estimating. As it is known, second order statistics, such as autocorrelation function and power spectrum provide only information amplitude information, but that information is not enough for pedestrian detection. For more information about moving human, such as pedestrian, we need more deeply analysis of received signal.

The reflected signal from narrative moving object with constant velocity estimation shows that in power spectrum there is only one useful frequency. That frequency is Doppler shift frequency. In case, when the object is moving with acceleration, there is spectrum correlation. The picks are appearing. It becomes more difficult to separate useful picks from noise. For example, separate useful picks, which are belong to moving pedestrian, from noise. Therefore, it is very important to estimate phase information. In this case, it is very important to use more powerful tool such as higher order statistics [1-3].

As it is known, the second order statistics, i.e. autocorrelation, power spectrum and *etc* are phase blind [4]. That is why cumulants and their Fourier transforms, known as higher order statistics, become very important. The phase information can be provided by higher order statistics such as third-ordered autocorrelation function and third-ordered spectra known as bispectrum [5]. Using of higher order statistics gives opportunities to find not only amplitude information, but phase information in addition. We are using higher order statistics to disclose pedestrian micro-Doppler signature.

Receiving signals from moving objects, especially from pedestrian, are classified in special group. The pedestrian global motion consists of several micro-motions. He has center of gravity and his hands and legs are moving concerning that center. Pedestrian hands and legs are moving in opposite sides. The speed of pedestrian hands and legs are allocated between null and double of pedestrian body moving speed. So we have mathematical pendulums with opposite phases but with the same frequencies. This means that we have Doppler shift to different sides [6, 7]. In general, they are micro-Doppler shifts, because the pedestrian motion includes different body parts with different motion structure [8-11].

In this paper, we have received IQ signal using ground surveillance radar. That signal was received from moving target [12, 13]. At first sight in power spectrum, we have signal, which gives full description of pedestrian. However, deep analysis using HOS gives great opportunity to find phase coupled components in spectrum.

2. Method Description.

Received signal contains useful information. For disclosing that information, it is necessary to find available length of reflected signal spectrum. The discretization step number is N = 4000. Analyzing time will be $T_a = NT_d$, where T_a is the analyzing time and $T_d = 0.0001s$ is a discretization time.

As it is mentioned above, reflected signal from pedestrian is very difficult. It means we have signal, which includes frequencies, where i = 1, 2, ...

$$s(t) = \sum_{i=0}^{N} A \cos(2\pi f_i t), \qquad (1)$$

The Fourier transform of (1) signal will be

$$S(f) = \sum_{n=1}^{N} s(t) \exp(j2\pi \operatorname{fn} \mathbf{T}_{d}), \qquad (2)$$

where $j = \sqrt{-1}$.

 $R_x(n,l)$ triple autocorrelation function and $\dot{B}_x(p,q)$ bispectrum are functions of two variables. $R_x(n,l)$ triple autocorrelation function is set as

$$R_{x}(\mathbf{n},\mathbf{l}) = \left\langle \sum_{i=0}^{N-1} \left[x^{(m)}(\mathbf{i}) - \mathbf{E} \right] \left[x^{(m)}(\mathbf{i}+\mathbf{n}) - \mathbf{E} \right] \left[x^{(m)}(\mathbf{i}+\mathbf{l}) - \mathbf{E} \right] \right\rangle_{\infty}$$
(3)

where n = 0, ..., N - 1 and l = 0, ..., N - 1 are the independent shift indices, $\langle ... \rangle_{\infty}$ denotes ensemble averaging for infinite realization number; $E = \left\langle \frac{1}{N} \sum_{i=0}^{N-1} x^{(m)}(i) \right\rangle_{\infty}$ is the mean value. $\dot{B}_{x}(\mathbf{p}, \mathbf{q})$ bispectrum is complex-variable function of two independent frequencies p and q. It can be written as 2-D discrete Fourier transform of triple autocorrelation function:

$$\dot{B}_{x}(\mathbf{p},\mathbf{q}) = \sum_{n=0}^{N-1} \sum_{l=0}^{N-1} R_{x}(\mathbf{n},\mathbf{l}) \exp\left[-j2\pi(\mathbf{n}\mathbf{p}+l\mathbf{q})\right]$$
(4)

or as

$$\dot{B}_{x}(\mathbf{p},\mathbf{q}) = \left\langle \dot{X}^{(m)}(\mathbf{p})\dot{X}^{(m)}(\mathbf{q})\dot{X}^{*(m)}(\mathbf{p}+\mathbf{q})\right\rangle_{\infty} = \left\langle \dot{X}^{(m)}(\mathbf{p})\dot{X}^{(m)}(\mathbf{q})\dot{X}^{(m)}(-\mathbf{p}-\mathbf{q})\right\rangle_{\infty}$$
(5)

Namely, for two f_1 and f_2 independent frequencies equation (5) will be written as

$$B(f_1, f_2) = S(f_1)S(f_2)S^*(f_1 + f_2)$$
(6)

If $f_3 \neq f_1 + f_2$ or $\varphi_3 \neq \varphi_1 + \varphi_2$, $B(f_1, f_2) = 0$. So, reflected signal from contains coherent components and those components can be found using HOS, i.e. by equation 6.

3. Moving Object Detection.

Reflected signal from pedestrian consists of several micro-motions. They are micro-Doppler shifts, because the pedestrian motion includes different body parts with different motion structure [6].In power spectrum the phase relations between micro-Doppler harmonics are lost. Therefore, it is impossible to recover phase-coupled frequencies by energy spectrum estimation. So to keep phase information is essential. Under those circumstances, using in-phase (I) and quadrature (Q) components is sufficient for keeping phase information to retain useful picks in bispectrum graph. Ground surveillance radar's block-scheme is illustrated in Fig. 1.



Fig. 1. Simplified block-diagram of Ku-band CW Radar.

Take in account that Doppler frequency of pedestrian in Ku-band is lying on 10 Hz to 100 Hz due to phase features distortion phase noises have the highest importance. For this reason in ground surveillance radar system VCO and LO are chosen ultra-low phase noise. Although, LO has high linearity. There is need to estimate whole spectrum because pedestrian can move away and toward the radar. In Fig. 2 are illustrated pedestrian moving away (a) and toward (b) the radar.



Fig. 2. The spectrum of moving pedestrian away (a) and toward (b) the radar.

As it is shown on Fig. 2 with coherent components, which we have received from moving object, we infuse two non-coherent components which picks are situated in f = 900Hz. Those non-coherent signals can be jammers, clutter, oscillator and etc. This was for show one of the main properties of bispectrum, i.e. phase coupling phenomenon [11]. In Fig. 3 are illustrated complex fast Fourier transform (FFT) and bispectrum estimation of received signal. There we have clutter and generated non-coherent signals.



Fig. 3. Complex FFT (a) and bispectrum (b) of the received signal.

As it is shown on Fig. 3 (a) from both sides on f = 900Hz we have non-coherent signal. Signal to noise ratio is SNR = 15dB, But on Fig. 3 (b) we have no such kind of picks because they are non-coherent signals, henceforth they aren't phase coupled.

Ground surveillance radar emitted signal is reflected from all oscillating parts of the moving object. The complex FFT and bispectrum estimation of moving object are shown on Fig. 4.



Fig. 4. The complex FFT (a) and bispectrum estimation (b) of moving object

As it is seen from Fig. 4 (b) non-coherent components on bispectrum graph are suppressed. There is only useful information, i.e. reflected signal from the moving target with its own coherent components. At the same time signal to clutter ratio for complex FFT is 25dB, meanwhile for bispectrum is 35dB.

Comparative analysis the result in Fig. 4 a) and b) allows to summarize that the benefits purchased by bispectrum-based approach is approximately 10dB.



Fig. 5. Bispectrum XOY cross section

The most important property of bispectrum is disclosing of target motion structure. As it is shown on Fig.5 the bright points are phase coupled components. They are (60*Hz*, 60*Hz*), (110 Hz, 30 Hz), (30 Hz, 110 Hz), (80 Hz, 70 Hz) and (70 Hz, 80 Hz). These all components belong to moving target.

4. Conclusions.

Thus, in this paper was shown one of the most important property of HOS i.e. phase-coupled frequencies finding. In particular, phase information finding using HOS has been examined. The most important points of HOS and bispectrum estimation are given and it has been shown that they could provide information, which is impossible at second order statistics. Besides, the *SNR* of bispectrum better, than FFT. Finally, moving target identification method was presented. It gives opportunity to detect and find phase coupled components i.e. the coherent signals. Certainly, the results are very promising.

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