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ON A COMPARISON OF RADAR SYSTEM PERFORMANCE BETWEEN RANDOM AND LINEAR FREQUENCY MODULATION CONSIDERING SIDELOBE SUPPRESSION TECHNIQUES

B. POMPEO, L. PRALON, G. BELTRAO, H. CIOQUETA, B.COSENZA AND J.R. MOREIRA

In order to improve sidelobe suppression, to increase processing gain and range resolution at the receiver filter's output, many techniques based on transmit waveform and receiver's filter design have already been proposed. This paper addresses a comparison on the performance of pulse compression radar systems that apply random frequency modulated transmitted signals, commonly used in noise radars, and linear frequency modulated transmitted signals. For the latter, it will also be analyzed pulse compression's sidelobes reduction techniques, more precisely, it is investigated window functions techniques and mismatched receiver filter design using the Lp- norms minimization techniques. Peak to sidelobe ratio, range resolution, compression gain and signal to noise ratio will be evaluated for all cases by means of mathematical analyses and simulations.

Keywords: noise radar, LFM, sidelobes.

I. INTRODUCTION

Many techniques related to transmit waveform design [3] and receiver filter design [2] emerged in order to increase the detection performance, to improve sidelobe suppression, to increase processing gain and range resolution in pulse compression radar systems. Pulse compression is a signal processing technique widely used in modern radar systems. A pulse compression radar involves the transmission of a long coded (modulated) pulse and the processing of the received echo to obtain a relatively narrow pulse. The increased detection capability of a long-pulse radar system is achieved while retaining the range resolution capability of a narrow- pulse system [1].

Studies to improve radar performance when this technique is employed have been a research subject since it's inception in mid 1950s[2]. However, the pursuit to achieve all the previously reported goals simultaneously is a never-ending challenge, because almost in every proposed scheme a requirement has to be relaxed in order to satisfy another.

A well known waveform generation procedure is based on linear frequency modulation. Transmitted signals of this nature have been more employed than any other coded waveform in radar systems due to it's great popularity, easy generation and it's insensibility to Doppler shifts [1]. Traditionally, matched filtering is then applied in the receiver's signal processing chain when pulse compression technique is employed, maximizing signal to noise ratio, for AWGN, at the filter's output [4]. This technique, however, introduces high levels of sidelobes, which can significantly increase the false alarm rate.

In order to eliminate the previously mentioned drawback, sidelobe suppression techniques can be applied. In the present paper, windowing function along with matched filtering and mismatched filtering are taken into consideration in order to improve the proposed comparison. The former reduces sidelobes to an acceptable level, but do not make use of any optimization algorithm. The latter has gain notoriety in radar society due to recent presented research results. It is a method based on a minimization of Lp norms of the sidelobes seeks to achieve not only low sidelobe levels but also a constant value over all non-zero time shifts [2].

A more widespread approach to solve high levels of sidelobes at pulse compression output relays on waveform design. Nonlinear frequency modulation, phase coded pulses generation, which range from analytical techniques [5] to exhaustive searches and random waveforms are examples of such approach. However, the first two methods mentioned are limited in use and development due to computational complexity and time computing [1,2].

Random waveforms present some advantages when used as transmitted waveform: low probability of interception [10], suppression of range ambiguity and low range sidelobe levels [6]. However, until a few years ago, such transmitted signals could be left aside due to generation complexity. Nowadays, with the advances made in hardware as well as the rise of software defined noise radar concept [7] many works have been published in this area referred to: system modelling [8], waveform generation [9] and optimal detectors design [10].

In the present work, random waveforms are taken into consideration on a comparison between linear frequency modulation waveforms, the latter with and without the usage of the sidelobes suppression techniques previously mentioned. Lukin [11] and Axelson [6] published recent works describing the phase/frequency randomly modulated signal's power spectral density and autocorrelation function for employment as transmitted signal in noise radar systems which will be directly used in the discussion.

This paper is organized in 6 more Sections. In Section II, a brief discussion about radar coherent reception is performed, highlighting the importance of pulse compression. The Section III describes the linear frequency modulated signal's characteristics. Section IV presents two distinct methods widely disseminated in radar systems to reduce pulse compression output's sidelobe level. In Section V, the specific features of Noise Radar coherent reception are taken into consideration and randomly frequency modulated signal's properties are presented when a Gaussian, unit power and with rectangular power spectral density modulating signal is used. In Section VI, the results of software simulations are showed and finally Section VII presents the conclusion about the results obtained.

II. PULSE COMPRESSION

Pulse compression is a signal processing technique applied in radar systems that enables the transmission of a long pulse, achieving higher energy without jeopardizing range resolution. Furthermore, it is also possible to extract the exact position of the target based on the delay of the returning signal when this method is employed.

Let us consider a radar emitting a time limited signal $s(t)$. Furthermore, we shall assume that a single point scatterer is located at the range r_0. According to this assumption, the received signal, $r(t)$ can be written as $r(t) = A(t)s(t-T_0)+\nu(t)$ where v(t) is associated to external interferences; $A(t)$ denotes the fading function of the signal; $T_0 = \frac{2r_0}{c}$ is the time spent by the echo signal to return to the radar and c is the vacuum light speed. Usually radar systems perform signal processing digitally using signal's complex envelope. Therefore, the mathematical analysis was performed under this perspective. The delayed reference signal's complex envelope is correlated with the actual target echo's complex envelope. The peak position value of the correlation output indicates the round-trip delay of the electromagnetic wave, resulting in a measure of distance. The output of the coherent receptor that has an equivalent impulse response $\tilde{h}(t), \tilde{y}(t)$, is given by

$$\tilde{y}(t) = \int_0^{T_{\text{int}}} \tilde{r}(\tau)\tilde{h}(t-\tau)d\tau\,, \tag{1}$$

where T_{ind} denotes the integration time and $\tilde{r}(t)$ denotes the received signal's complex envelope.

Matched filtering has simple implementation and maximizes signal to noise ratio associated to the pulse compression output, increasing the system's probability of detection. Hence it is preferred by most radar designers. Matched filter's impulse response is given by $\tilde{h}(t) = \tilde{s}^*(-t)$, where $\tilde{s}^*(t)$ is the complex conjugate of the transmitted signal's complex envelope. In the next sections it is analyzed the behaviour of two different frequency modulated transmit waveforms when employed in pulse compression systems.

III. LINEAR FREQUENCY MODULATION

Frequency modulated waveforms complex envelope are given by

$$\tilde{s}(t) = \sqrt{2P}\, e^{K_p \int_{-\infty}^{t} a(\alpha)d\alpha}\,, \tag{2}$$

where P is signal's mean power, K_p is the modulation constant and $a(t)$ is the modulating signal.

When the modulating signal is given by a linear function, the transmitted signal is said to be linear modulated and it's complex envelope is given by

$$\tilde{s}(t) = \sqrt{2P}\, e^{\left[\frac{K_p t^2}{2} - \frac{K_p \tau_s t}{2}\right]}\,, \tag{3}$$

where ts is the pulse duration.

When matched filtering is applied and when $A(t) = A$, pulse compression's output can be showed to be given by

$$\tilde{y}(t) = 2AP\tau_s sinc\left(\frac{K_p \tau_s \tau}{2}\right) e^{j\left[-\frac{K_p t^2}{2} - \frac{K_p \tau_s t}{2}\right]} e^{j\frac{K_p \tau_s \tau}{2}}\,. \tag{4}$$

Range resolution of such systems are associated with the 3dB width of the pulse compression's output and the signal to noise ratio associated to the pulse compression output is given by the relation between it's peak instantaneous power and the noise power. For linear frequency modulated waveforms along with matched filtering the range resolution is given by [12]

$$\Delta\tau_{3dB} = \frac{0.9}{B_s}\,, \tag{5}$$

where B_s is signal's bandwidth. The instantaneous power of the pulse compression's output peak is given by $P(T_0) = |\tilde{y}(T_0)|^2 = 4A^2P^2\tau_s^2$

It can be observed from (4) that the absolute value of the pulse compression output, when linear frequency modulated signals are employed as transmit waveforms and matched filtering is performed at the receptor chain, has high levels of sidelobes. They are spaced in time by $\tau = \frac{1}{B}$ and the sidelobe with higher intensity is just $13.2\,dB$ below the pulse compression peak [1].

A. Sidelobe Suppression Techniques

Sidelobes can severely deteriorate radar performance since it can induce a false alarm or, if any sidelobe suppression technique is employed it can mask nearby targets. Many methods for sidelobe suppression have been proposed in the scientific community. Next we take into consideration a widespread windowing approach and a mismatched filtering approach.

1) Windowing: Windowing technique consists in multiplying the reference signal for a window function prior to the pulse compression. Some windows function are represented in Table I where the column PSLR stands for peak to side lobe ration achieved and G stands for the peak value gain.

TABLE I

Window functions properties

window	PSLR(dB)	G
Uniform	-13	1.00
Hamming(0.54)	-43	0.54
Gaussian(a=3.0)	-55	0.43
Blackman	-58	0.42
Dolph-Chebyshev(a=4.0)	-80	0.42

In the present work it is used the Hamming(0.54) window [1], which is the most popular in radar systems. It's digital implementation is given by

$$\omega(t) = 0.54 - 0.46\cos\left(\frac{2\pi t}{N-1}\right), \tag{6}$$

where *N* stands for the size of the window in samples.

Even though this technique reduces the sidelobe significantly, achieving nearly 40dB of peak to sidelobe ratio, the tradeoffs that it introduce are not always bearable. Pulse compression's output peak power is reduced, deteriorating the signal to noise ratio associated and the 3dB width is expanded decreasing range resolution.

2) Mismatched Filters: In the present work mismatched filter design was carried out by means of minimization of $L_{p\text{-}}$ norms of the sidelobes [2]. The signal to noise ratio associated to the pulse compression's output when any mismatched filter is always lower than the obtained when matched filter is employed and is usually called mismatch loss. Furthermore, the 3dB mainlobe width of the pulse compression output that employ mismatched filtering is slightly wider than for the corresponding matched filter [2]. Filter length is usually higher than transmitted pulse length thus filter coefficients calculation and mismatched filtering operation introduce a level of computational complexity that is not inherent to the corresponding matched filter operation.

IV. RANDOM FREQUENCY MODULATION

Random frequency modulated waveforms are generated from (2) using a modulating signal characterized by stochastic process. In the present work, the modulating signal, is here represented by a Gaussian wide sense random process with unit power and rectangular power spectral density. Hence, the transmitted signal is also represented by a stochastic process and therefore a better way to evaluate performance of this sort of signal is trough the analysis of the expected value of the output of coherent receptor, $\tilde{y}(t)$. When $A(t) = A$, and when the transmitted signal and thermal noise are considered independent processes, it is given as [9]

$$E[y(t)] = T_{\text{int}} A R_{ss}(t - T_0) \qquad (7)$$

where $R_{ss}(t)$ is the autocorrelation function of the transmitted signal and T_{int} is the total integration time. It can be seen that the transmitted signal's autocorrelation function plays an important row in radar systems that use random signals, since the target detection is directly obtained from the maximum of this function.

If $K_p \gg B_a$, the modulation is said to be wideband and approximations lead to an autocorrelation function given by

$$R_{\tilde{s}}(\tau) = 2Pe^{-\left[\frac{K_p^2\tau^2}{2B_a}B_a\right]} = 2Pe^{-\left[\frac{\tau^2}{2\frac{1}{K_p^2}}\right]} \qquad (8)$$

The instantaneous power of the pulse compression's output peak is given by

$$P(T_0) = E\left[\left|\tilde{y}(T_0)\right|^2\right] = 4A^2P^2\tau_s^2 .$$

The same as the one obtained when linear frequency modulation is employed along with matched filtering. It can also be showed that the signal to noise ratio associated to the pulse compression's output is the same as the one obtained when linear frequency modulation is employed along with matched filtering.

The $3dB$ width of the pulse compression's output from which it's derived system's range resolution can be showed to be given by

$$\Delta\tau_{3dB} = \frac{0.869}{B_s} \qquad (9)$$

It can be noticed from (9) that the range resolution of system's that employ random frequency modulated signals as transmit waveforms is slightly narrower than the one obtained when linear frequency modulated signals are chosen as transmit waveforms.

Since the transmitted signal is here characterized by a wide sense stationary random process, each sample of the pulse compression output will be a random variable. Therefore, even though the expected value of the pulse compression output (7) does not predict sidelobes, Axelsson [6] reported that this sidelobes are related to the variance of each random variable and is given by T_pB_sN where T_p is the pulse duration, B_s is the signal's bandwidth and N is the number of pulses coherently integrated. Thus, the radars designers ought to increase the number of pulses integrated in order to achieve less sidelobe levels.

V. SIMULATION

In this section, a numerical example is presented. Two distinct 2MHz transmitted signal were generated: (i) a linear frequency modulated signal; (ii) a random frequency modulated signal. Pulse compression was performed on both signals. For case (i), matched filter with and without windowing and mismatched filtering were performed. For case (ii) only matched filtering was applied however it was considered two distinct scenarios: only one pulse compression's output and an average of 1000 pulse compression's output.

At first, a comparison of pulse compression's output using linear frequency modulated signal was realized. This simulation is illustrated on Figure 1. It can be seen that windowing technique causes an increase of the 3dB width and a decrease of the peak value. Eventhough PSLR increases, the achieved sidelobe levels are higher than when mismatched filtering is applied. Thus, it was concluded that mismatched filtering has a better performance regarding sidelobe levels when compared to simple matched filtering and matched filtering along with windowing technique.

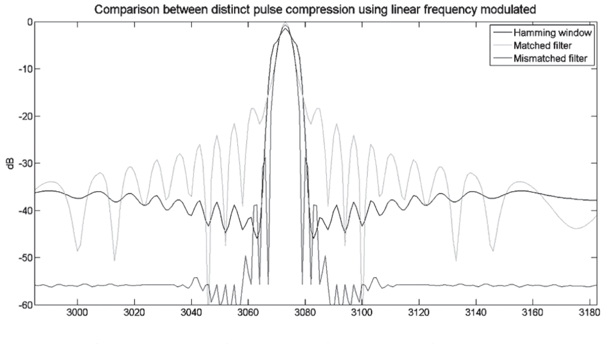

Fig. 1. Comparison between distinct pulse compression using linear frequency modulated

The next simulation consists of a comparison between mismatched and matched filtering when linear frequency modulated are employed and matched filtering when random frequency modulated are employed as transmitted waveforms. Since the transmitted signal is represented by a stochastic process, a better way to evaluate the performance of such signals is trough the analysis of the expected value of the output of the coherent receptor. This affirmative is confirmed in figure 2, where a single pulse is compressed. Note that the sidelobe level of the pulse compression output is too high, approximately -15dB.

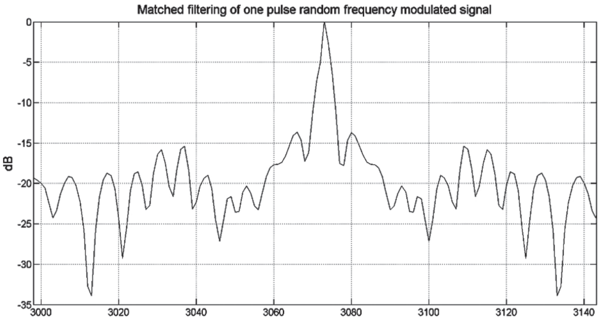

Fig. 2. Pulse compression's output of a single random frequency modulated signal

The comparison between the three different pulse compression methods above mentioned, considering an average of 1000 pulse compression's output for random waveforms, is shown in figure 3 while figure 4 highlights the main lobe and the sidelobes with higher intensity.

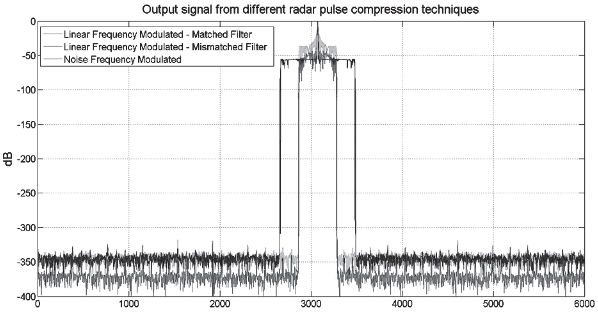

Fig. 3. Power spectral density of transmitted signal

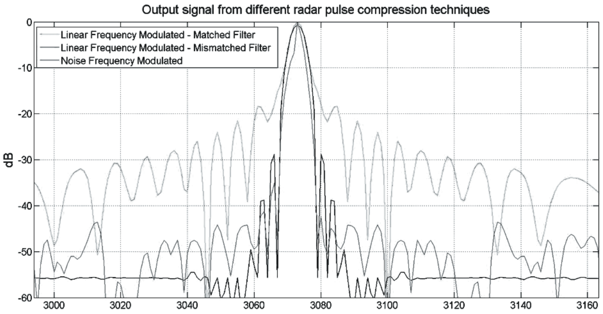

Fig. 4. Power spectral density of transmitted signal

CONCLUSION

In this paper, we have presented a comparison on the performance of radar systems that employ linear frequency modulated and random frequency modulated transmit signals. It was also taken into consideration two distinct techniques of peak-to-side lobe ratio improvement when using linear frequency modulation.

It was taken into consideration a wideband randomly frequency modulated signal, which features a bell shaped autocorrelation function, more specifically a Gaussian distribution shape, very attractive for radar systems. It was shown that aside from the intuitive advantages that arise when random signals are employed as radar transmit waveform, such as low probability of interception, immunity to similar systems interference, intentional or not [10] and suppression of range ambiguity, other performance related advantages of such systems can be highlighted.

Mathematical analysis and simulations results showed that when the application requires low sidelobe levels, random frequency modulation systems have better performance then classical linear frequency modulation systems, despite of any improvement technique applied. It was shown that not only optimal peak signal to side lobe ratio can be achieved through coherent integration, but also signal to noise ratio remains unchanged when compared to classical linear frequency modulation.

Furthermore, for applications that require the higher resolution as possible for a given bandwidth, random frequency modulation should also be employed. It was shown that random frequency modulation matched filter's output is narrower than deterministic linear frequency modulation response to such detectors for a given signal's bandwidth.

The two linear frequency modulation sidelobe suppression techniques analyzed had significant tradeoffs involving side- lobe levels, signal to noise ratio and range resolution, not to mention the considerable increase in signal processing complexity when mismatched filters are applied. Therefore, the performance of radar systems that employ linear frequency modulation along with any of the analyzed sidelobes suppression techniques will never overcome random frequency modulation systems performance, despite of the analysis perspective.

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Leandro Pralon graduated from Brazilian Military Institute of Engineering in 2007 receiving his B.S. degree in Electrical Engineering. He received the M.Sc degree in Electrical Engineering from Pontifical Catholic University of Rio de Janeiro. Since 2008 he has been with the Radar Development Group of the Brazilian Army as an active researcher and developer.

Bruno Pompeo graduated from Brazilian Military Institute of Engineering in 2008 receiving his B.S. degree in Electrical Engineering. He received the M.Sc degree in Electrical Engineering from State University of Campinas. Now, he is an undergraduate student in Physics at the Federal University of Rio de Janeiro and since 2009 he has been with the Radar Development Group of the Brazilian Army as an active researcher and developer.

Bruno Cosenza, Electronic Engineer from Polytechnical School at Federal University of Rio de Janeiro (1986), master’s at Electric Engineering from Brazilian Military Institute of Engineering (1993) and doctorate at Electric Engineering from Pontifical Catholic University of Rio de Janeiro (2002). Since 2010 project manager of the Radar SABER M200 (a medium range radar).

Gabriel Beltrão received B.S. degrees in Telecommunications Technology and Electrical Engineering from Salvador University (UNIFACS) and University of Campinas (UNICAMP), both in Brazil, in 2007 and 2010, respectively. He received the M.Sc. degree in Electrical Engineering from the Faculty of Electrical and Computer Engineering, at the University of Campinas (UNICAMP), Brazil, in 2012. Since 2010, he works as a Signal Processing Engineer with the Radar Division, at Orbisat Industria e Aerolevantamento S/A. He is also a researcher in the Visual Communications Laboratory at the University of Campinas (UNICAMP).

Higor Cioqueta received B.S. degrees in Electronic Engineering from Minas Gerais Federal University (Brazil) and Technische Universitaet Berlin (Germany) in 2004. He received the M.Sc. degree in Electronic Engineering at the Technological Institute of Aeronautics, Brazil, in 2006. Since 2005, he has been working as a Signal Processing Engineer in projects related to weather radars, surveillance radars, and air traffic control systems at Atech S/A and Orbisat S/A, both in Brazil.

Joao Roberto Moreira Neto, for photograph and biography, see this issue, p. 93.

УДК 621.37

Сравнение характеристик радарной системы при использовании шумовых сигналов и сигналов с линейной частотной модуляцией с точки зрения подавления боковых лепестков / Б. Помпео, Л. Пралон, Г. Белтрао, Х. Чикуета, Б. Косенза, Дж. Морейра // Прикладная радиоэлектроника: науч.-техн. журнал. – 2013. – Том 12. – № 1. – С. 132–136.

Существует много методов улучшения подавления боковых лепестков, увеличения коэффициента усиления обработки и повышения разрешения по дальности на выходе фильтра приемника. Эти методы основаны на выборе формы зондирующего сигнала или характеристик приемного фильтра. В данной работе представлено сравнение производительности радиолокационных систем со сжатием импульсов, со случайной частотной модуляцией передаваемых сигналов, используемой в шумовых радарах, и с линейной частотной модуляцией сигналов. В отношении последнего проведен анализ методов уменьшения боковых лепестков сжатых по дальности импульсов, а именно, исследованы оконные функции и неоптимальные фильтры, использующие минимизацию Lp-норм. Путем моделирования оценены уровень боковых лепестков, разрешение по дальности, коэффициент усиления обработки и отношение сигнал-шум.

Ключевые слова: шумовой радар, ЛЧМ сигнал, боковые лепестки.

Табл. 1. Ил.4. Библиогр.: 12 назв.

УДК 621.37

Порівняння характеристик радарної системи при використанні шумових сигналів і сигналів з лінійною частотною модуляцією з точки зору заглушення бічних пелюсток / Б. Помпео, Л. Пралон, Г. Белтрао, Х. Чикуета, Б. Косенза, Дж. Морейра // Прикладна радіоелектроніка: наук.-техн. журнал. – 2013. – Том 12. – № 1. – С. 132-136.

Існує багато методів поліпшення заглушення бічних пелюсток, збільшення коефіцієнта посилення обробки та підвищення роздільної здатності за дальністю на виході фільтра приймача. Ці методи засновані на виборі форми зондуючого сигналу або характеристик приймального фільтра. В даній роботі представлено порівняння продуктивності радіолокаційних систем зі стискуванням імпульсів, з випадковою частотною модуляцією переданих сигналів, використовуваної в шумових радарах і з лінійною частотною модуляцією сигналів. Щодо останнього проведено аналіз методів зменшення бічних пелюсток стислих за дальністю імпульсів, а саме, досліджені віконні функції і неоптимальні фільтри, що використовують мінімізацію Lp-норм. Шляхом моделювання оцінені рівень бічних пелюсток, роздільна здатність за дальністю, коефіцієнт посилення обробки і відношення сигнал-шум.

Ключові слова: шумовий радар, ЛЧМ сигнал, бічні пелюстки.

Табл. 1. Іл. 4. Бібліогр.: 12 найм.