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Research paper

Modified PWNLFM Signal for Side-Lobe Reduction

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Abstract

Many applications in radar systems require low range side-lobe performance which is achieved by pulse compression processing. Most used chirp signal for this processing is linear frequency modulation (LFM) signal but with a presence of first high side-lobe level. Suppression of this side-lobe requires weighting function causing the reduction in signal to noise ratio at the receiver owing to mismatch loss. Non-linear chirp signals are introduced as a solution and became most practiced signals aimed at reducing side-lobes. In this paper, an overall piece wise non-linear frequency modulation chirp signal is designed by merging two stages, one with linear function and the other with a tangent based non-linear function. Simulation results show significant reduction in the sidelobe level of autocorrelation function when NLFM is generated in this method.

Keywords: ACF; *LFM; NLFM; PSLR; PWNLFM.*

1. Introduction

Pulse compression is a favorable technique which influences target parameter estimates by employing different signal models such as Frequency modulation (FM) and Phase modulation (PM) [1, 2]. Since 1940s Linear Frequency Modulated (LFM) signal is the most used pulse compression waveform as it can be generated easily and bandwidth can be effectively used as the frequency is linearly swept over to cover the entire signal bandwidth. The compressed waveform at the receiver has a side-lobe at -13dB which can be a hindrance while detecting closely spaced targets and thus can be reduced by using windowing and optimization techniques but at the cost of reduced signal to noise ratio and much wider main lobe width [3, 4]. Non-linear Frequency Modulation (NLFM) is introduced to decrease the side-lobe level without the use of extra filtering avoiding the mismatch losses [5, 6]. NLFM signals have a vast applicability in radar systems with a good range resolution, good interference mitigation, better signal to noise ratio (SNR), low-cost, and has a spectral weighting function inherently in their modulation function which effectively which gives a pure matched filter output with low side-lobe levels [7, 8]. This paper mainly focuses on NLFM signal design by fusing piecewise LFM and NLFM functions and the resultant function is capable of generating an overall NLFM waveform.

2. Non-Linear Frequency Modulation (NLFM)

NLFM signals are part of an important family of continuous modulation functions which plays a significant role in pulse compression radar systems [9, 10]. Non-linear frequency modulation favorably shape the power spectral density in such a way that the matched filter output i.e. the autocorrelation function has reduced sidelobes from its LFM counterpart to a large extent. An NLFM signal also provides a better detection characteristic and is more precise in determining the range compared to other methods available in literature [11] as (dual apodization (DA), spatially variant apodization (SVA) and leakage energy minimization (LEM)). Conversely accurate NLFM signal design and processing is still a difficult task as generally radar designer aims at having an easily produced and processed signal to meet the bandwidth constraints, target performance characteristics and sidelobe reduction goals [11, 12]. All time desire for research would be looking forward for improved methods to design radar pulses with a rectangular envelope but with appropriate FM laws such that the matched filter output shows favorable results. In radar systems theory numerous research work has been done to design optimum (level of sidelobe suppression) NLFM signals, all the work done generally can be categorized into two directions. One is based on design of NLFM signal using LFM signals introducing predistortion on short intervals into a temporal domain or spectral domain and the other is the design by using predefined power spectral density function using different methods as stationary phase principle, iterative methods and explicit functions cluster method [12]. In this paper we have presented a sidelobe reduction technique using new NLFM function. In the first part of the paper two-stage LFM signal design is described and later the new NLFM signal design methodology is discussed.

3. Simple Two-Stage LFM

For any random frequency modulation signal x(t) defined by equation (1), the real part of the signal is given by following equation (2)

$$x(t) = A\, e^{j\varphi(t)} \tag{1}$$

$$r_x(t) = \cos\big(\varphi(t)\big) \tag{2}$$

Where φ(t) is the phase of the modulation function obtained by integrating the frequency function f(t) as given in the equation (3)

$$\varphi(t) = 2\pi \int_0^t f(t)\, dt \qquad (3)$$

Real part of the chirp signal can be obtained by substituting equation (3) in (2)

$$r_x(t) = cos\,[2\pi \int_0^t f(t) dt] \qquad (4)$$

A simple two-stage LFM signal is designed primarily by concatenating its instantaneous frequency functions divided as piece-wise linear functions with different sweep rates defined by the ratio of bandwidth and the pulse width as per the following equations 5 and 6.

$$f_1(\tau) = \alpha_0 \tau \qquad 0 \le \tau \le T_1 \qquad (5)$$

$$f_2(\tau) = \beta_1 + \alpha_1(\tau - T_1) \qquad T_1 \le \tau \le T_1 + T_2 \qquad (6)$$

Where f_1 is the instantaneous frequency of the first stage with a sweep rate of α_o and f_2 is the instantaneous frequency function of the second stage with a sweep rate of α_1. The total pulse width of the chirp signal τ is divided into two time slots with respective pulse widths T_1 and T_2. If β_1 and β_2 are the corresponding bandwidths of the first stage and second stage LFM functions, then the corresponding sweep rates can be defined as

$$\alpha_0 = \frac{\beta_1}{T_1} \qquad \alpha_1 = \frac{\beta_2}{T_2}$$

The phase variation of this concatenated NLFM function can be obtained by integrating equations (5) and (6) as given in equations (7) and (8).

$$\varphi_1(\tau) = \int f_1\,(\tau) = \pi\, \alpha_0\, \tau^2 \qquad 0 \le \tau \le T_1 \qquad (7)$$

$$\varphi_2(\tau) = \int f_2\,(\tau) = 2\pi \left(\beta_1\, \tau + \alpha_1 \left(\frac{\tau^2}{2} - T_1\right)\right)$$

$$T_1 \le \tau \le T_1 + T_2 \qquad (8)$$

Using the above equations the simple two-stage LFM signal is simulated so that an overall NLFM signal obtained over the total pulse duration τ. The instantaneous frequency variation and the chirp signal of the NLFM signal generated using two-stage LFM are shown in fig 1 & fig 2 for the total duration of τ=10µs(1e7s) with T_1=0.25µs, T_2=0.75µs, bandwidth β=20MHz(2e7Hz) with β_1=0.32MHz, β_2=1.68MHz. Autocorrelation function which is nothing but the matched filter output is shown in fig 3. From fig 3 it can be observed that the first sidelobe level is at -18dB. When compared to normal LFM which has the first sidelobe at -13dB this simple two-stage LFM signal can be interesting as they are accomplished in reducing sidelobe levels without the use of any further added filtering.

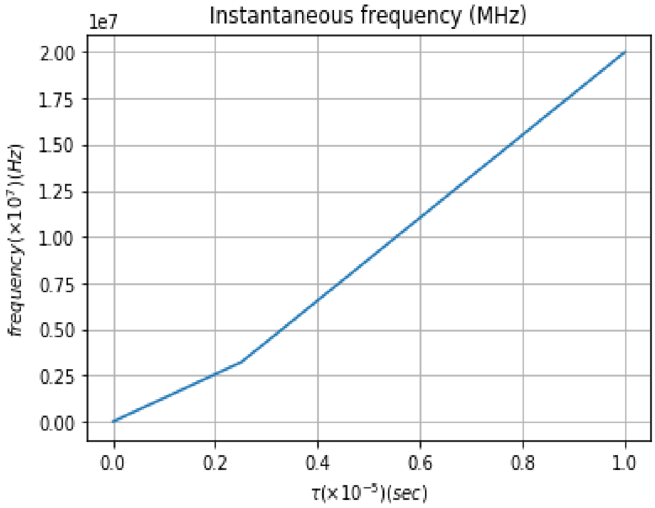

Fig. 1: The Instantaneous frequency variation of simple Two-stage LFM

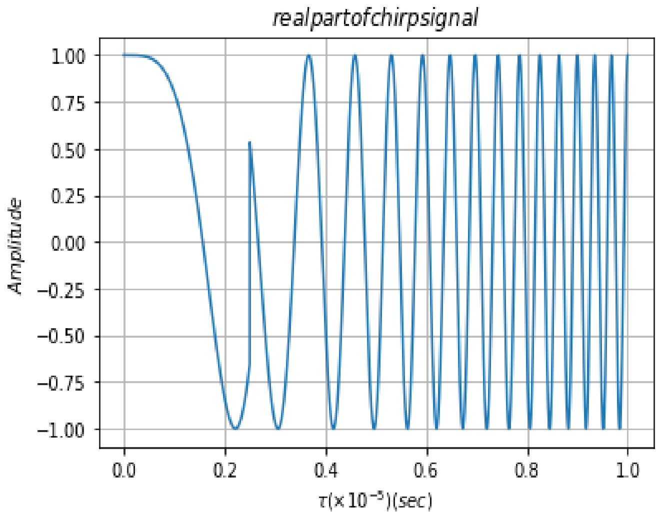

Fig. 2: The Real part of the chirp signal of simple two-stage LFM

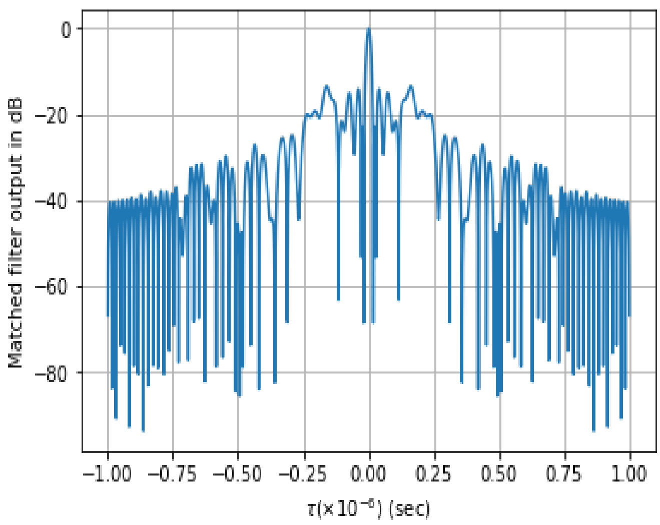

Fig. 3: Autocorrelation output of simple two-stage LFM

4. Modified Piece-wise NLFM Design

Instead of two LFM variations for both the stages one stage can be modified by using different modulation function. In this paper, a tangent function has been used to vary the instantaneous frequency of the second stage of piece-wise NLFM signal. This modified PWNLFM signal consists of one stage with LFM sweep followed by the NLFM sweep by using tangent function. f_1 is the frequency function of the first segment with a linear sweep as shown in equation (9) and f_2 is the frequency function of the second segment with a non-linear slope as shown in equation (10)

$$f_1(\tau) = \alpha_0 \tau \qquad 0 \le \tau \le T_1 \tag{9}$$

$$f_2(\tau) = \beta_1 + f(t) \qquad T_1 \le \tau \le T_1 + T_2 \tag{10}$$

Where

$$f(t) = \tan(t) \qquad 0 \le t \le \frac{\pi}{2}$$

Thus the phase of this modified PWNLFM signal is obtained by integrating the frequency functions in equation (9) and (10) as shown in below equations (11) and (12). The overall chirp signal can be obtained by using equation (4).

$$\varphi_1(\tau) = \int f_1(\tau) = \pi\, \alpha_0 \tau^2 \qquad 0 \le \tau \le T_1 \tag{11}$$

$$\varphi_2(\tau) = \int f_2(\tau) = 2\pi\,(\beta_1\, \tau + \alpha_1 \ln|\sec(\tau)| + c)$$

$$T_1 \le \tau \le T_1 + T_2 \tag{12}$$

C is the constant, using the above equations new NLFM signal is obtained over the total pulse duration τ. The chirp signal of the new NLFM signal and instantaneous frequency variation for different values of α1 are shown in fig 4 and fig 5 for the total duration of τ=10μs(1e7s) and bandwidth β=20MHz(2e7Hz) and the autocorrelation function which is nothing but the matched filter output for different values of α1 is shown in fig 6. From fig 1 and fig 5 it is observed that with the increase in the non linearity there is a significant improvement in the sidelobe level of the corresponding autocorrelation output. Compared to simple two-stage LFM signal with two LFM slopes this new NLFM signal with one LFM and other NLFM segments proved to be more effective in reducing sidelobes.

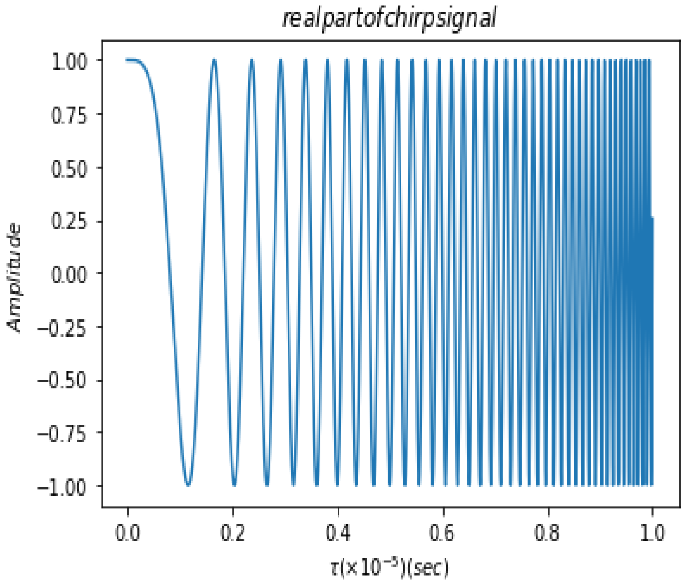

Fig. 4: Real part of the chirp signal of new NLFM signal

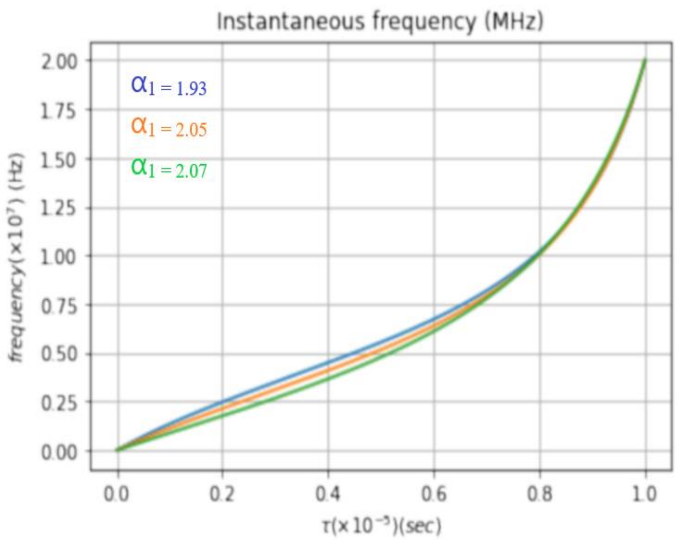

Fig. 5: Instantaneous frequency variation of new NLFM signal

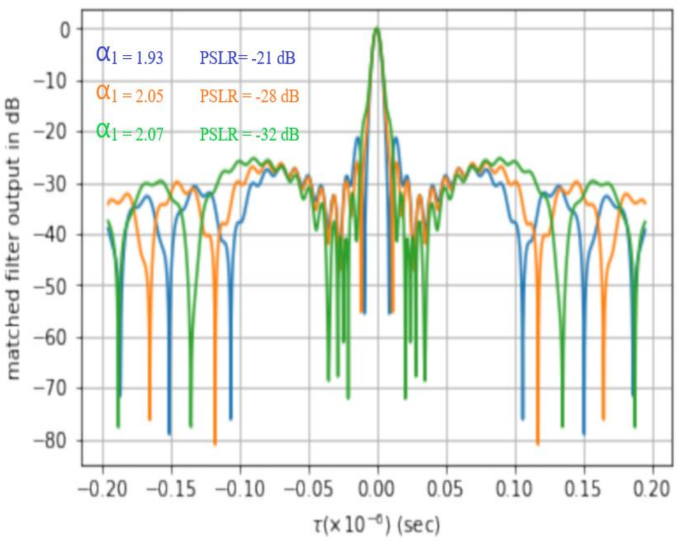

Fig. 6: Autocorrelation output of new NLFM signal

Table 1 shows the further analysis of this new NLFM signal carried out for different combinations of β_1, T_1 and β_2, T_2 to form potentially suitable functions which yield less side-lobe level. Below table shows the sweep rate ratios for different combinations. From the below table it can be observed that based on the values of sweep rate ratio there is a significant difference in the PSLR values of both the two-stage LFM and the proposed NLFM. So for the different combinations of pulse width and bandwidth, the value of ratio α_0 is decreases and the value of ratio α_1 is increases and thus there is an improvement in PSLR values for both the NLFM signals individually. The proposed NLFM yields less sidelobe levels at all values of T_1 and T_2 when the overall performances of the two are compared.

Table 1: Sweep Rate Ratios for Different Combinations of T_1, β_1, T_2 , β_2 and Corresponding PSLR values.

$\alpha_0 = \beta_1/T_1$	$\alpha_1 = \beta_2/T_2$	PSLR (dB) of simple two-stage LFM	PSLR (dB) for new NLFM
2.11	1.93	-18	-21
1.85	2.05	-19	-28
1.36	2.07	-20	-32
1.16	2.2	-21	-38

5. Conclusion

The NLFM signal is generated using the new concept of concatenating LFM and NLFM. It is observed that the proposed signal gives better PSLR values compared to simple two-stage LFM signal. It is also observed that the autocorrelation function exhibits better PSLR values by increasing time duration T2 over which the non-linear frequency variation exists in the proposed frequency function. The proposed tangent based NLFM signal can be considered as an effective technique to reduce the side-lobe levels without the use of any filtering techniques.

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