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Sidelobe Suppression on Pulse Compression using Curve-Shaped Nonlinear Frequency Modulation

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Abstract—Pulse compression is a method for improving the range resolution of the radar systems. Linear Frequency Modulation (LFM) is a type of pulse compression which is commonly used in the radar applications because of its simplicity and Doppler tolerance. However this method provides relatively high first peak sidelobe level within around -13.3 dB. This paper presents a developed curve-shaped Nonlinear Frequency Modulation (NLFM) using second degree polynomial approach for radar pulse compression in order to reduce the sidelobe level. The radar signal is assumed has bandwidth 30 MHz while the length of pulse signal as long as 10e-6 s. The curve-shaped chirp waveform is formed by the polynomial equation utilizing the LFM waveform as the base line. According to the simulation results and analysis, using a certain polynomial equation, the curve-shaped NLFM with negative orientation provides lower sidelobe level than the LFM. The best first peak sidelobe level achieved by this proposed NLFM is approximately -18.6 dB.

Keywords—sidelobe suppression; pulse compression; curve-shaped; NLFM; radar

I. INTRODUCTION

Radar system is an object detection system using the modulated electromagnetic waves. As a target detection system, its perfromance is determined by its accuracy on the object detection process. On the other hand, the radar pulse compression is a method to improve the radar detection range resolution by maintaining the power level required for transmitting the radar signal [1-3].

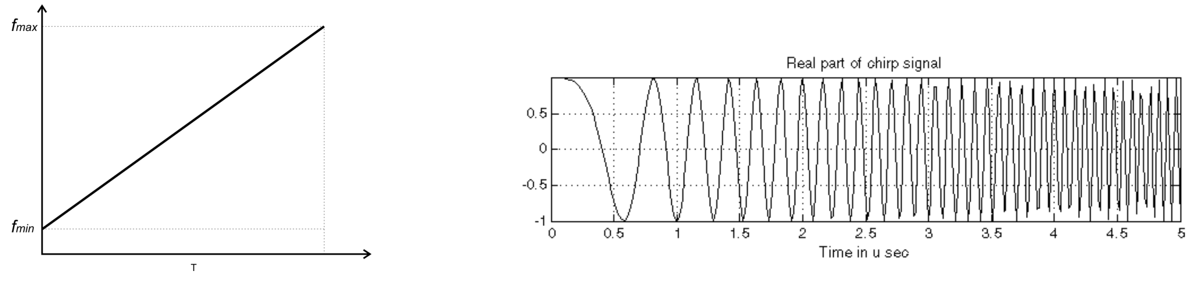
There are two well known pulse compression methods in the radar systems including LFM and NLFM. LFM is a pulse compression type which is commonly used in current radar systems because of its simplicity and Doppler tolerant [1, 4-5]. However, this pulse compression has a drawback in its high sidelobe level [3, 5]. This existing sidelobe will decrease the radar detectability especially on the weak echoes of target. Therefore, NLFM was introduced to overcome this lack. NLFM is known as a high performed method which has lower sidelobe level than the LFM without any extended processing such as frequency windowing or weighthing [3, 6-7]. Nevertheless, until now, the development of NLFM is still conducted to obtain the highest performed pulse compression especially in the case of peak sidelobe level and Doppler shifts.

Some attempts to improve the performance of NLFM have been reported as follows. In 2008, an adaptive waveform of LFM has been developed aiming to reduce its adjacent-band interference to other spectral users [4]. Then in 2009, another adaptive radar waveform technique was introduced using a phase-only adaptive technique to minimize the resulting waveform's power in specific areas [8]. In the same year, a simple two and tri-stages NLFM has been introduced. This research results showed that the proposed method provides the peak sidelobe leval to the mainlobe up to --19dB without any weighthing methods [3]. In 2014, a tangent function was used for determining the frequency modulation on NLFM which its parameters configured experimentally. This method has reduced the sidelobe by at least 10dB [5]. Then, the S–shaped NLFM based on instaneous frequency has been investigated and analyzed in 2015. This research showed that the method was robust and the detection rate was more than 90% within SNR 0dB or higher regardless of the modulation parameters [9].

This paper will extend the research about chirp waveform of NLFM radar pulse compression by novel approach. The proposed waveform chirp has the curve shape which is modified from the LFM chirp using second degree polynomial equation approach. The analysis and investigation will be limited to the orientation of the curve and the sidelobe suppression effect performed. The aim of this research is to obtain the novel chirp waveform which has low sidelobe level without any extended processing such as signal weighthing or windowing. The mainlobe width will also be considered regarding the pulse compression performance.

II. RADAR PULSE COMPRESSION

Pulse compression is a signal processing method aiming to improve the range resolution of radar systems. The range resolution of radar can be increased by using very short pulse but it will reduce the signal quality because that it will decrease the average transmitted power. Hence, since the signal quality has strong relationship with the transmitted power, the best way to increase the range resolution is by increasing the pulse width [2]. By pulse compression method, the radar can transmit the relatively long pulse by preserving its average transmitted power.



(a) (b)

Fig. 1. Linear Frequency Modulation (LFM) (a) chirp waveform, (b) real part of transmitted signal

A. Linear Frequency Modulation (LFM)

LFM waveform is a linear chirp which is commonly used in the radar application because that it can be easily generated and also it has good range resolution. Moreover, it is reliable facing the Doppler shifts. The LFM waveform has period which varies inversely with the bandwidth. This LFM has the first peak sidelobe level around -13.3 dB to the mainlobe. The relationship between frequency and the time (chirp waveform) is illustrated by Fig. 1(a) while the real part of pulse signal transmitted is illutrated by Fig.1 (b). Then, the waveform of LFM can determined mathematically as below,

$$s(t)\begin{cases} exp\left\{j2\pi\left(f_c t-\frac{1}{2}kt^2\right)\right\}, & -\frac{\tau}{2}\le t\le\frac{\tau}{2} \\ 0 \quad , & elsewhere\end{cases} \qquad (1)$$

where f_c is the carrier frequency, k is the chirp slope and t is the instaneous time [3]. If τ is defined as the duration of LFM pulse signal so that the bandwidth of the signal is defined by,

$$B = k\tau. \qquad (2)$$

Then, the instaneous frequency $f(t)$can be described as belows,

$$f(t) = f_c + kt \qquad (3)$$

B. Nonlinear Frequency Modulation (NLFM)

On the other hand, NLFM waveform is another type of pulse compression method signal used by the radar system. According to the previous research it is noticed that the NLFM provides better performance pulse compression than LFM. This method has higher SNR than LFM. Also it has better range resolution than LFM. Contrasting with the LFM, the relationship between frequency and time of the signal is not linear. There are some popular NLFM chirp such as Cosine spectrum shape waveform, raised cosine waveform, tangent based waveform and truncated Gaussian waveform [6]. Eq.4 below shows the arbitrary of the NLFM chirp waveform,

$$s(t) = \exp(j\emptyset(t)) \qquad (4)$$

where $\emptyset(t)$ is the instaneous frequency which will be obtained using the differential of the phase modulation [3].

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C. Matched Filter

Matched filter is a method of signal processing for improving the signal quality of radar echoes. This filter is designed from the fact that the coded signal can be determined by both the frequency response of the coding filter. Match filter has frequency response which is the complex conjugate of the coding filter. The compressed pulse, output of the matched filter, is the inverse Fourier transform of the product of matched filter response and the signal spectrum [10]. Eq. 5 below is the expression of output of the match filter,

$$y(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}|H(\omega)|^2 \exp(j\omega t)\, d\omega \qquad (5)$$

where $y(t)$ is the output of matched filter, $H(\omega)$ is impulse response of coding filter.

III. Research Methodology

For simulation works, the bandwidth of chirp waveform assumed was 30MHz while the pulse duration as long as $10e^{-6}$ s. The curved chirp was built from the LFM base line. The second degree polynomial equation used was $ax^2 + bx + c$ where a, b and c were the constants configured in the designing step and x was the instaneous time of the chirp. The curve will be designed into two possible orientations that were positive and negative. See Fig. 2, a random point is selected then it was dragged in two orientation areas. Using three points; beginning point, last point and dragged point; a curve line will be formed using polynomial equation which then became a chirp waveform for simulating a radar pulse signal. The degree and equation of curvature chirp was selected experimentally using above method in order to analyze the effect and also to obtain the lowest sidelobe level.

The analysis of the curved chirp effect will be investigated depend on the first peak sidelobe level and the width of mainlobe. Also, those both values will be compared with the conventional LFM and existing NLFM developed by previous researches.

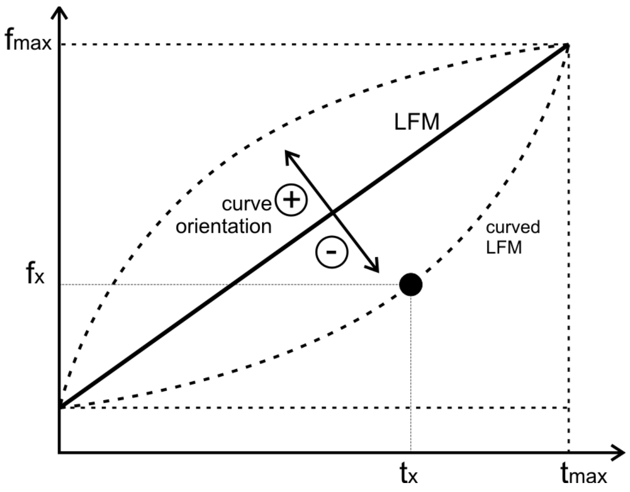

Fig. 2. Designing the curve-shaped waveform chirp

IV. Result and Discussion

The design of the curve was configured experimentally. Therefore, the changing of the parameter was done step by step for searching the best performed curved chirp. Four curve polynomial equations were selected for investigating the effects and their result on the peak sidelobe level (PSL) showed on the Table 1. Then, the chirp waveform illustration can be seen on Fig. 3.

Firstly, the investigation was about the orientation of the curve-shaped chirp. Seeing the effect of the curve-shaped waveform on the positive orientation as Table 1, Fig. 4(a) and Fig. 4(b) shown, it can be observed that on the positive orientation, the peak sidelobe level increases following the degree of curvature chirp. Then, as seen on Fig. 4(a) and 4(b), though on this positive orientation the mainlobe width became narrow, but this effect is not significant enough with the first peak sidelobe level rises.

Contrastly, as the investigation results on the negative orientation effects to the sidelobe level showed by Table 1 and depicted in Fig 4(c) and 4(d), it can be inferred that curve-shaped chirp with negative orientation in specific equation could decrease the sidelobe at a certain level. Moreover, when the degree of curvature was higher, the mainlobe become wider significantly even the sidelobe level becomes higher than before.

TABLE I. Curve-Shaped Chirp Waveform

No	Curve Model	Curve Orientation	Polynomial Equation	PSL (dB)
1	I	+	$-2e^{17} x^2 + 5e^{12} x$	-9.5
2	II	+	$-1e^{17} x^2 + 4e^{12} x$	-10.82
3	III	-	$1e^{17} x^2 + 2e^{12} x + 3e^{-8}$	-18.6
4	IV	-	$2e^{17} x^2 + 1e^{12} x + 7e^{-8}$	-15.8

According to all of those results (Table 1 and Fig. 4), the best curve-shaped NFLM proposed was the chirp waveform with the curve equation $1e^{17} x^2 + 2e^{12} x + 3e^{-8}$ which has the peak sidelobe level around -18.6 dB. This means that sidelobe level of proposed waveform was about 5.3 dB lower than the conventional LFM which is approximately -13.3 dB. However, this value is still higher than the developed multistage NLFM or tangent based NLFM. Therefore the development of the curve shaped NLFM need to be extended further for achieving the better performance.

V. Conclusion

The curve-shaped NLFM has been investigated in this paper. The curve-shaped chirp waveform has been designed using second degree polynomial approach. The curved waveform is determined experimentally using the LFM chirp waveform as the base line. According to the simulation and analysis, the negative oriented curve chirp provides better sidelobe suppression than the positive orientation though it widens the mainlobe width. The best performance achieved of curve-shaped waveform is the chirp with polynomial equation $1e^{17} x^2 + 2e^{12} x + 3e^{-8}$ with peak sidelobe level to mainlobe approximately -18.6 dB or about 5.3 dB lower than the LFM. The further analysis to this chirp is needed especially in the case of facing of the Doppler shifts and background noises. Others, the investigation on the curve-waveform modification is also possible for obtaining the better performance.

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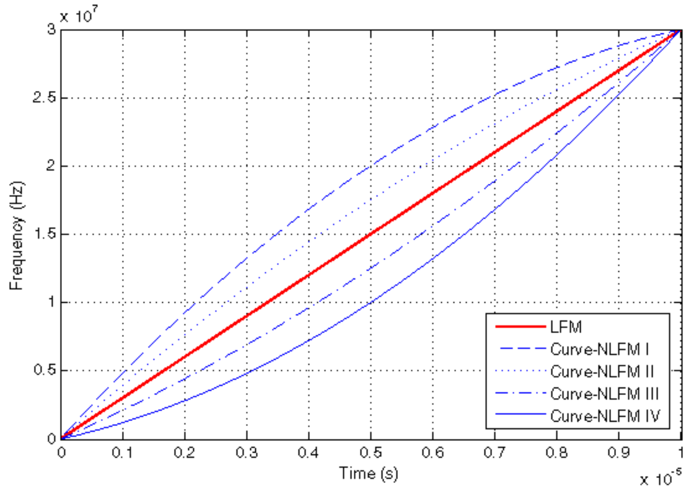
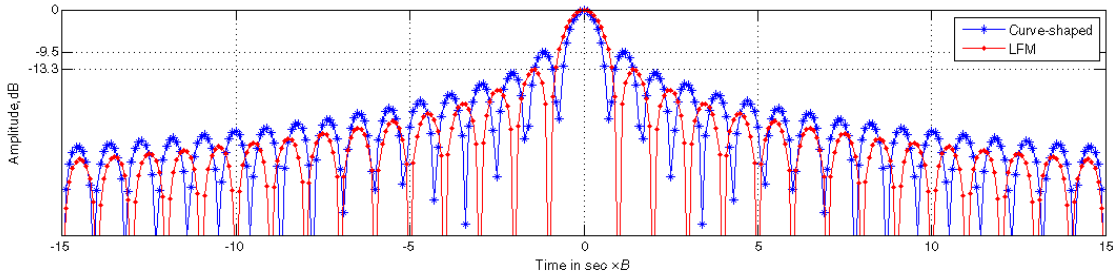
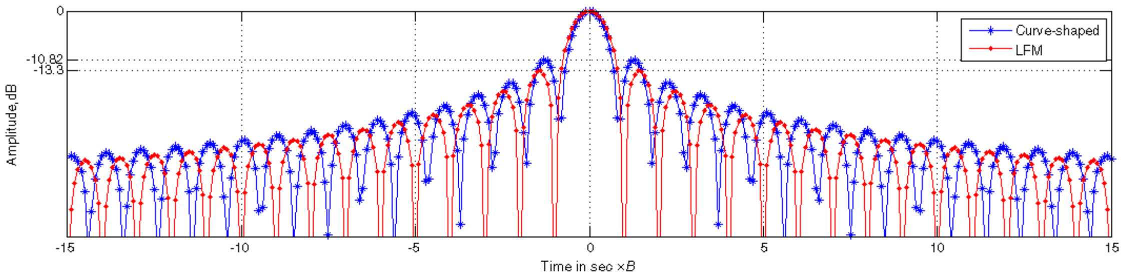


Fig. 3. Waveform chirp models of Curve-NLFM



(a)



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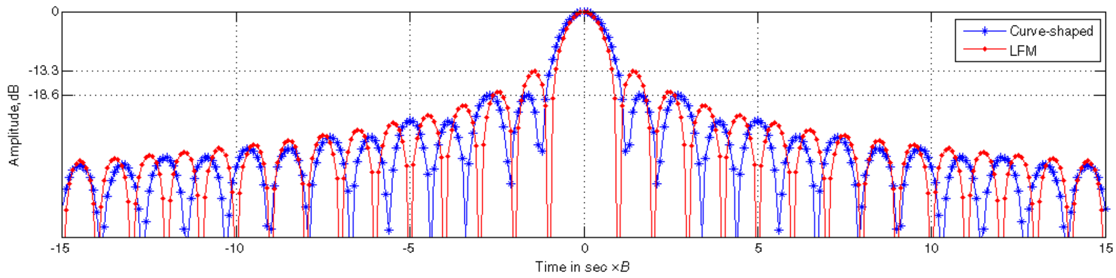
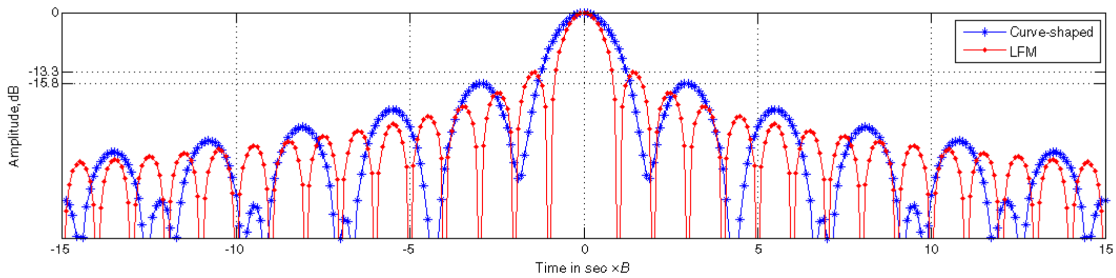


(c)



(d)

Fig. 4. Result of Matched Filter of curve-shaped NFLM (a) Model-I $-2e^{17} x^2+5e^{12} x$, PSL= -9.45dB, (b) Model-II $-1e^{17} x^2+4e^{12} x$, PSL= -10.82, (c) Model-III $1e^{17} x^2+2e^{12} x+3e^{-8}$, PSL-18.6dB, (d) Model-IV $2e^{17} x^2+1e^{12} x+7e^{-8}$, PSL-15.8dB

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