Effects of Highpass Filtering on Transmitted Signals of Non-Linear Frequency Modulated Radar Systems

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Abstract. This paper presents an advantage of highpass filtering of a transmitted signal of nonlinear frequency modulated (NLFM) radar systems. Radar systems use NLFM signals for sidelobe level reduction in the output of the matched filter (MF). This paper suggests a further reduction in sidelobe levels of output of matched filters by highpass filtering. The output of matched filter is the autocorrelation of the input signal. Numerical simulations are performed on highpass filtered NLFM signals and the results obtained are compared with conventional linear frequency modulated (LFM) signal. From these results, it is proposed that highpass filtering on NLFM can be used to further improve the output of the matched filter considerably by reducing relative sidelobe levels.

Keywords: Non-linear frequency modulation, highpass filter, matched filter, auto-correlation, peak sidelobe level.

1. Introduction

In a radar system [1], a high-frequency carrier signal is modulated in its frequency and will be transmitted into free space in pulse mode. The reflected signal from the target will be processed by the radar receiver to obtain the position (range) and velocity of the target. The time delay between the transmitted pulse and received pulse is used in range measurement while a change in the frequency of the carrier is used in determining velocity with the help of Doppler shift in the received signal.

The received signal is passed through a matched filter [2] to maximize peak signal to noise ratio at the output for better target detection. The peak in the output of the matched filter is used to determine the range of the target. If a target has to be identified very precisely than the output of the matched filter has to have a very sharp peak and must be similar to an impulse function with no spillover in the time domain. Hence it is required to have a powerful pulse from the output of the matched filter. So many techniques have been proposed for achieving this [3-4]. However, this paper suggests a simple novel method for achieving this with a simple highpass filter (HPF).

For better resolution in range and velocity, the carrier signal is modulated in frequency. Radar systems use NLFM [5-6] signals for better range and velocity resolutions. Even though the LFM signals are used extensively in radar systems, still NLFM signals are also used in radar systems since they are more Doppler tolerant [7-8]. Extensive research has been carried out on the NLFM signals; however, the analysis presented in this paper is entirely novel and can be used in radar applications.

2. Problem formulation

Figure 1 represents a modified block diagram of a radar system that uses NLFM. In conventional radar systems, NLFM signal in pulse mode is directly applied to the antenna. However, for improving radar systems performance, a highpass filter has been added in the system. The primary objective of this analysis is to observe the effects of highpass filtering on NLFM signals before transmitting into free space by the antenna.

A radar transmitted signal with NLFM can be represented in mathematical form as:

$$x(t) = A(t) \times e^{j\varphi(t)} \times Rect\left(\left(t - \frac{\tau}{2}\right) / \tau\right) \quad (1)$$

Here $A(t)$ represents the amplitude modulation, $\varphi(t)$ represents the phase modulation of a sinusoid. $\varphi(t)$ is also called a phase function which is a non-linear function of time. This phase function represents the angle modulation (either frequency modulation or phase modulation) of the sinusoid carrier. The relationship between instantaneous frequency and phase function are given as:

$$f_{inst} = \frac{1}{2\pi}\frac{d\varphi}{dt} \quad (2)$$

Most radar systems operate in pulse mode. Here $Rect(t/\tau)$ represents a standard rectangular pulse of duration τ seconds starting from $-\tau/2$ to $+\tau/2$. A delay of $\tau/2$ has been used to observe the signals from a reference time of zero seconds.

There are infinitely many possibilities for obtaining the NLFM signals based on the phase function. For an LFM, $\varphi(t)$ varies as t^n and is used in practical applications due to the inherent advantage of the generation of LFM signal. However, LFM signals are more Doppler variant in higher velocity target environments, and hence these signals are replaced by hyperbolic frequency modulated signals where the target velocity is relatively high.

Hyperbolic non-linear phase functions are used in deriving the poly-phase sequences as well that have low relative sidelobe levels.

Since many of the non-linear hyperbolic functions can be expressed in simple polynomials over its domain and ranges with reasonable approximations, this paper considers $\varphi(t)$ to be varied in t^n form where n is an integer value ranging from two to six. Since LFM signals are used as a standard

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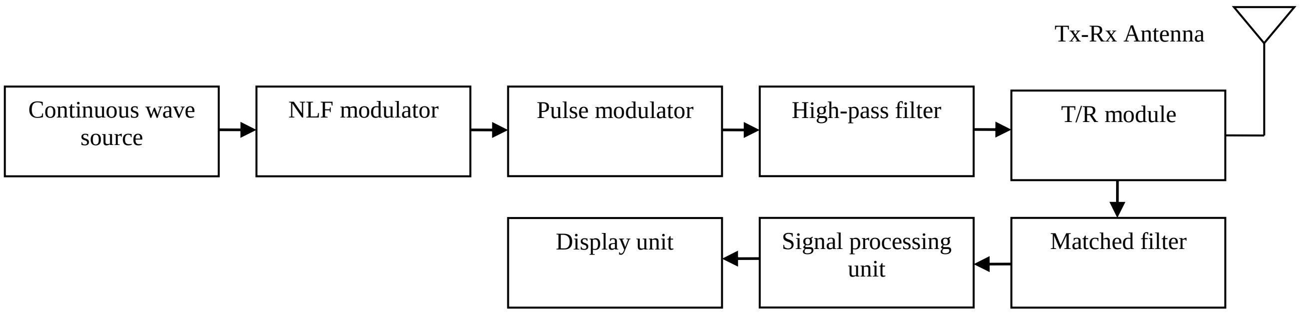

Fig.1. Block diagram of NLFM radar system with high-pass filter.

for comparison, all the results that are obtained using NLFM signals are compared with the LFM waveforms.

The main proposal of this paper is to investigate the effects of passing the signal $x(t)$ through the highpass filter and then apply to the transmitting antenna. Butterworth third order highpass filter is considered. The time domain analysis using the state-space and numerical methods are used to observe time domain signals. For simulation purposes, $A(t)$ is taken as unity and phase function has been expressed as:

$$\varphi(t) = 2\pi f_{min} t + \alpha t^n \qquad (3)$$

where, f_{min} is the minimum frequency of the signal and α has to be derived depending on the value of n, to keep the minimum and maximum frequencies of all the NLFM signals kept constant. The parameter α can be obtained using:

$$\alpha = \frac{1}{2\pi} \frac{f_{max} - f_{min}}{n\tau^{n-1}} \qquad (4)$$

where τ is the overall duration of the pulse.

3. Simulations and results discussions

For simulation purposes, the duration of the pulse (τ) is taken as 2 seconds. For all non-linear frequency modulated signals (from $n = 2$ to $n = 6$), the starting frequency (f_{min}) and ending frequency (f_{max}) are taken as $10Hz$ and $60Hz$. These values can be scaled up according to the practical requirements. Values of α obtained for these values of starting frequency and ending frequency are 1.9894 for $n = 2$, 0.6631 for $n = 3$, 0.2486 for $n = 4$, 0.0995 for $n = 5$ and 0.0414 for $n = 6$.

Figure 2 represents the profiles of the instantaneous frequencies throughout the pulse. From this figure, it is observed that the difference in instantaneous frequencies for $n = 5$ and $n = 6$ is small and it is further decreasing with increasing the order of non-linearity. Hence the number of non-linear cases considered in this analysis can be assumed to provide a reasonably agreeable generalization for higher orders (for $n > 6$).

These NLFM signals are passed through third order Butterworth highpass filter [9] and the spectra of these NLFM signals with highpass filtering and without highpass filtering are shown in Figure 3. From this figure, it is observed that the spectral content in the NLFM signals is varying inversely $(1 / f)$ with the frequency. From this figure, it is also observed that highpass filtering is adjusting the spectral content to vary linearly $(-f)$. The optimal cutoff frequency of the filter is selected such that the highpass filtered output gives the minimum peak after the matched filter.F

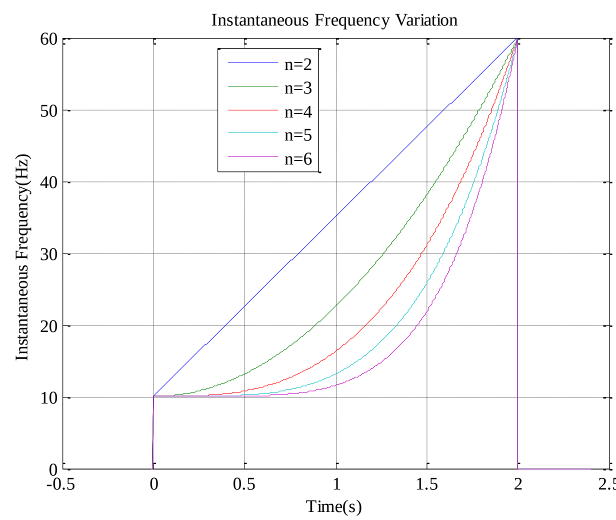

Fig.2. Variation of instantaneous frequency with time.

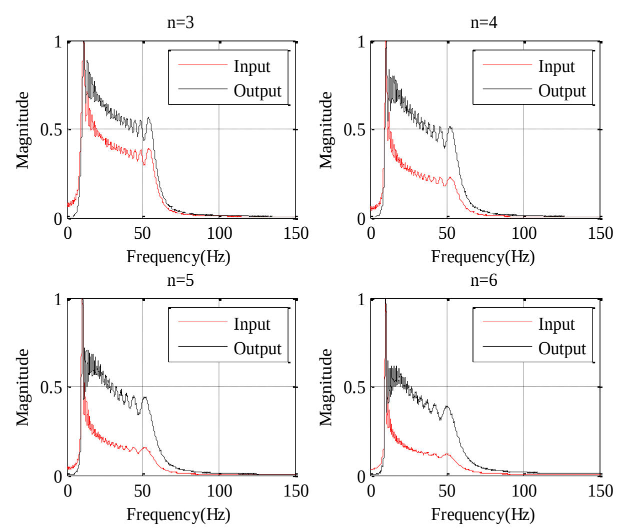

Fig.3. Spectrum of NLFM signals before (input) and after highpass filtering (output) with optimal values of cutoff frequency.

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It is also possible to consider the higher order filters such as fifth and seventh orders. However, in order to re-distribute the energy little uniformly, filters with sharp roll-off are not preferred. The second order filter can also be used, but in order to have symmetry of filter, third order T-type LC filter is considered. All simulations are carried out in MATLAB [10].

Auto-correlation functions for the filtered signals are obtained and shown from Figure 4 to Figure 7. In the same figure, LFM modulated signal is also plotted for the comparison with other orders. From simulations, it is observed that HPF does not affect LFM signal. Another observation made from this figure is that using highpass filtering, all optimized outputs are converging to similar waveforms for different orders. Minimum relative peak sidelobe levels with optimal filtering are shown in Figure 8. The cutoff frequency of highpass filter for various orders and the minimum relative peak sidelobe levels with HPF and without HPF values are shown in Table.1. From this table, it is observed that increasing the order (n) has the adverse effect of increased RPSL without a filter, but with a highpass filter, RPSL is gradually decreasing from 0.2753 to 0.2631. From this figure, it can be concluded that there is an optimal cutoff frequency for a highpass filter for minimizing the PSL for each order of non-linearity.

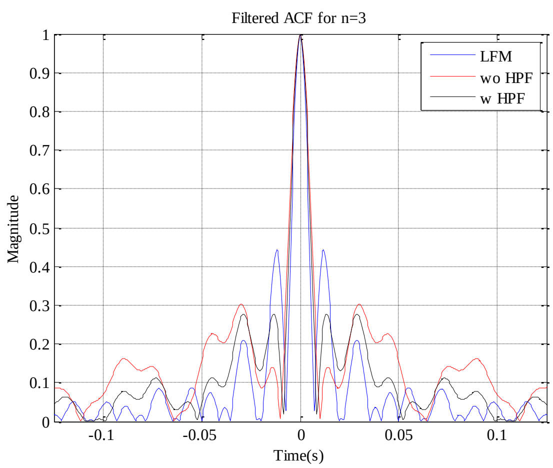

Fig.4. Auto-correlation functions without and with highpass filtering for n=3.

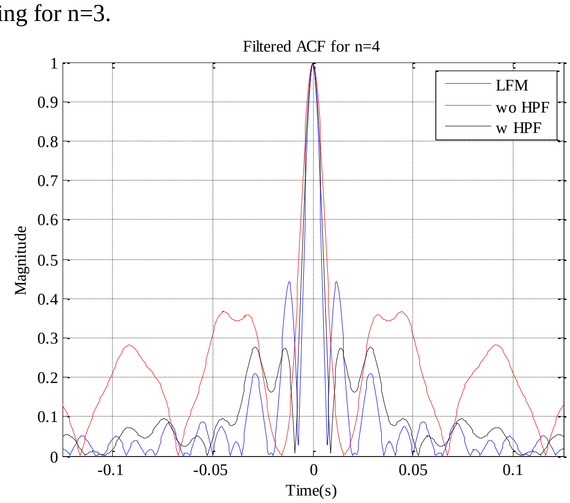

Fig.5. Auto-correlation functions without and with highpass filtering for n=4.

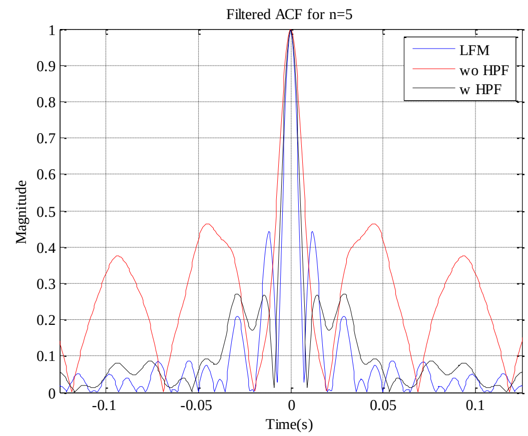

Fig.6. Auto-correlation functions without and with highpass filtering for n=5.

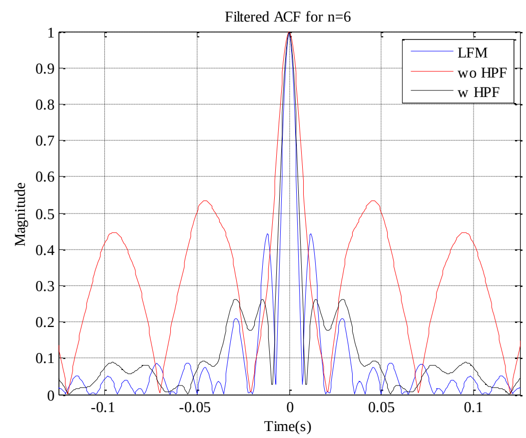

Fig.7 Auto-correlation functions without and with highpass filtering for n=6.

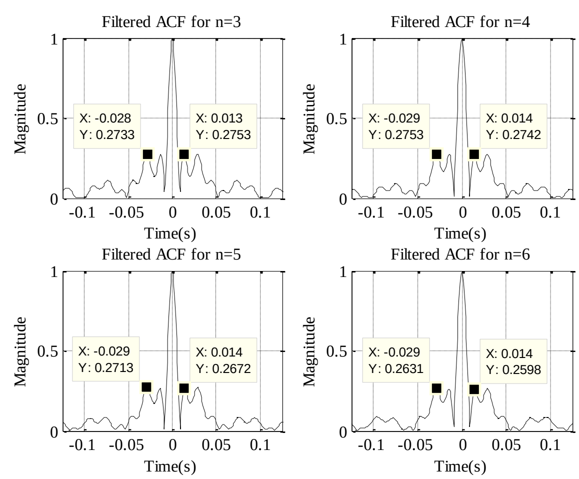

Fig.8. Variation of PSL with optimal cutoff frequencies.

Table 1: Relative peak sidelobe levels for different order with HPF and without HPF.

S.No	Order (n)	Cutoff frequency (f_c) (Hz)	RPSL without HPF	RPSL with HPF
1	2	-	0.4421	0.4421
2	3	11.4	0.3033	0.2753
3	4	13.5	0.3662	0.2753
4	5	14.4	0.4643	0.2713
5	6	15.0	0.5348	0.2631

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The other important observation from this table is that for given pulse duration and the instantaneous frequency deviations, higher order non-linearity with filtering is provided much-reduced PSL in auto-correlation in comparison with the LFM signal even without filtering.

Time domain waveforms after the highpass filtering are shown in Figure 9. From this figure, it is observed that the filtering is incorporating the amplitude modulation on NLFM signals, which is an advantage as far as reduction in the sidelobe levels is concerned. These time domain signals are represented for optimal values of the cutoff frequency, which are obtained by a linear search for the minimal value of peak sidelobe level. From the same figure, it is observed that the output pulses are not stretched too much at $t = 2$ seconds which indicates that the dispersion provided by the HPF is small.

In communication/radar systems amplitude modulation is more prone to noise and it is preferred less rather than angle modulations. However, the amplitude modulation of NLFM signals using highpass filtering improves the response of matched filter output in terms of sidelobe levels.

4. Conclusion

This paper proposes a simple but effective method of generating amplitude modulated NLFM pulse that produces a minimum peak sidelobe levels in the output of the matched filter. From the analysis, it is concluded that an optimal highpass filtering on NLFM can be used effectively and efficiently for further reducing the sidelobe level of matched filter outputs, which improves the detection capabilities of the radar system. Since filtering itself is providing amplitude modulation for NLFM signal without using any external amplitude modulator, the suggested method of highpass filtering NLFM signal before transmitting is simple and easy to implement in real time NLFM radar systems.

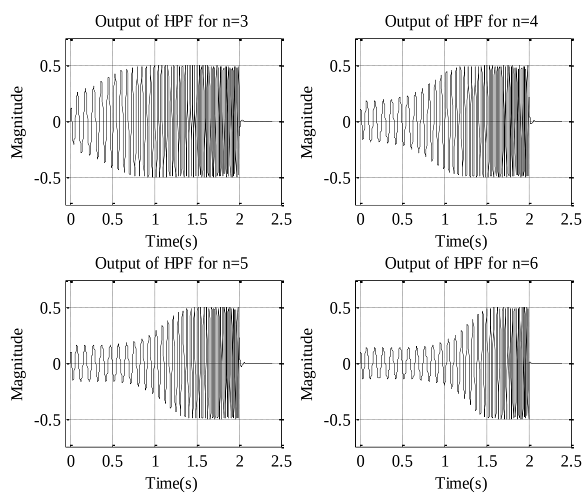

Fig.9. Time domain signals after filtering.

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Biography of the author

Salman Raju Talluri has completed his M.Tech from IITK in 2009 and obtained his Ph.D. titled "Analysis of non-linear transmission lines for opposite phase and group velocities" in 2017 from the Jaypee University of Information Technology, Solan, Himachal Pradesh, India. His areas of interest include non-linear transmission lines, microwave engineering, and antenna arrays. He is currently working as an assistant professor in Jaypee University of Information Technology, Solan. He was with the Astra microwave products limited, Hyderabad for one year 2006 to 2007.

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