Envelope Modification of the Hyperbolic Frequency Modulated Signal with LC-Filters in order to have a Better Range Resolution in Radar Systems

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***Abstract*—The theme of this paper is to realize a continuous time domain window similar to the Hamming window. Windowing is used in signal processing to smooth the spectral content and for reducing the spectral leakage as well. Long time duration windows with narrow spectral content can provide much better smoothing compared with short duration windows with broad spectral content. The other advantage of the windowing in the time domain is the reduction of sidelobe levels in the output of the matched filter (MF). In radar systems which use the MF, this reduction in the relative sidelobe level improves the resolution of the system. Radar systems use the hyperbolic frequency modulated (HFM) signals to have the better range and velocity resolutions since these waveforms are Doppler invariant. To further improve the range resolution, the envelope of the HFM signal has been modified using a continuous time domain Hamming window and its Doppler invariant property has been observed. In order to realize the practical circuit that implements the analogous continuous time domain Hamming window for the HFM signal, Butterworth notch filter, and Butterworth highpass filters (HPF) has been considered and it is observed that HPF is approximating the characteristics of the Hamming window.**

***Index Terms*—Auto-correlation, Doppler invariance, hyperbolic frequency modulation, matched filter, notch filter, relative sidelobe level.**

I. Introduction

IN digital signal processing [1], windowing is used in order to smooth the spectrum of a given signal. For better smoothing of a given spectrum, the spectrum of the windowing signal has to be a narrow band in nature. Since time and frequency are inversely related [2], this narrow band (in frequency domain) windowing signal has to be very long in the time domain. However, it is not practically possible to use such long duration windows on the signals (such as a finite duration pulse rather than a continuous wave); the amplitude of the windowing signal has to be altered in order to have the control on the spectral leakage. This has led to the wide variety of windows in the literature [3]-[5] and depending on the requirement of the application, an appropriate window will be selected.

Hamming window is extensively used in the communication systems and radar systems due to the advantage of minimizing the largest sidelobe in the spectrum [6]. Even though windowing is used more with the discrete time signals, amplitude tapering or amplitude modulation (modification) is also being used by the time-varying amplifiers whose gain will be controlled as a function of time. Designing of time-varying amplifiers is complicated but they are still necessary for sophisticated systems [7].

Radar systems [8] use a wide variety of waveforms in order to improve the range resolution. Along with the range, velocity information is also important in order to track the targets. For determining range and velocity simultaneously, most of the radar systems use the linear frequency modulated (LFM) signals [9]-[11]. But these LFM signals produce distortion in the output of the matched filters if the received signal is coming from a moving target which is also called as Doppler distortion. In order to avoid this problem, the hyperbolic frequency modulated signals are explored and suggested their use for high radial velocity targets [12]-[16]. The further improvement in the range resolution is still possible with the amplitude tapering and hence this paper considers the continuous time domain windowing on the HFM signals. This is being achieved with the help of a highpass filter and notch filter [17-19].

This paper is organized as follows. The next section formulates the problem and Section III presents the problem solution with numerical simulations. Section IV presents the conclusion of the analysis carried out with different filters.

II. Problem Formulation

If there is a relative velocity between the target and radar system, the reflected received signal which is Doppler-distorted can be expressed as [8]:

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$$x_r(t) = x(\gamma t - \varphi_0) \quad (1)$$

In Equ.1, $x(t)$ is the transmitted signal and γ is the scale factor that comes from the relative velocity between target and radar system. φ_0 represents the delay that comes from the round trip time of the target due to it position. The scaling factor γ can be expressed as:

$$\gamma = 1 \pm 2(v/c) \quad (2)$$

In Equ.2, the plus sign is used for the approaching target and the minus sign is for the receding target. γ is equal to one for a stationary target. This received signal is applied to the matched filter whose impulse response has been taken as the transmitted signal $x(t)$. The matched filter maximizes the peak signal to noise ratio. If the transmitted radar signal is hyperbolic frequency modulated then it can be represented as [18]:

$$x(t) = A(t)\cos\left(\frac{2\pi}{k} \times \log(1 - kf_{\min}t)\right) \quad (3)$$

In Equ.3, k is a constant factor and $f_{\min}$ is the starting frequency of the HFM signal. Depending on the pulse duration (τ) and maximum frequency ($f_{\max}$) of the HFM signal, the constant k can be derived as:

$$k = \frac{f_{\max} - f_{\min}}{f_{\max} \times f_{\min}} \times \frac{1}{\tau} \quad (4)$$

The main purpose of this paper is to consider the envelope modification of HFM signal analogous to the Hamming window in order to see the improvement in the range resolution by decreasing the relative peak sidelobe level (RPSL) in the output of the MF. Along with this, it is also required to observe the rate of decay of the sidelobe levels in the output of the MF due to filtering and this has to be compared with the Hamming windowing. Thirdly, the implementation of the Hamming window using the LC-notch filter and LC-highpass filter has been considered. Lastly, the effect of windowing and filtering on the output of the MF in presence of Doppler velocities has to be considered. Analysis of all these has been presented in this paper.

III. Problem Solution and Simulation Results

To perform the simulations, the starting frequency ($f_{\min}$) of the HFM signal is taken as 100Hz and the ending frequency ($f_{\max}$) as 300Hz. The duration of the pulse (τ) has been taken as 2s. The value of k obtained for these values is 0.0025. Four different cases have been considered. In first case, simulations are carried out without any windowing. This is represents as simply HFMS. In the second case, simulations are carried out by windowing the HFMS with the Hamming window. Subsequently simulations are performed by filtering the HFMS with the notch filter and lastly passing the HFMS through the highpass filter. A comparative analysis has been carried out for these four cases and conclusions are made after careful observations from the frequency domain and time domain waveforms.

The notch filter considered in this paper is a sixth order Butterworth filter while the highpass filter is a third order Butterworth filter. These filters have been designed for a characteristic impedance of 50 ohms system. All simulations are carried out in MATLAB [19]. The notch filter is characterized by its center frequency and the 3-dB bandwidth. The center frequency and 3-dB bandwidth of the notch filter have been chosen such that the spectrum of the notch filtered hyperbolic frequency modulated the signal and the windowed signal is almost similar. A linear search has been carried out and the values of the center frequency have been obtained as f_c =40Hz and the 3-dB bandwidth has been obtained as 150Hz. Since the highpass filter has only one degree of freedom in the form of 3-dB cutoff frequency, the cutoff frequency of the highpass filter has been again obtained by a linear search such that there is a minimum difference between the windowed spectrum and the highpass filtered spectrum. The optimal value of the cutoff frequency of the highpass filter has been obtained as 190Hz. The spectra for all the above mentioned four cases have been represented in Fig. 1.

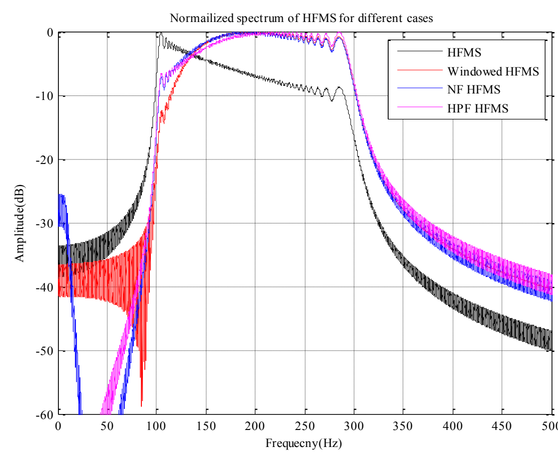

Fig. 1. The spectrum of the original, windowed, notch filtered and highpass filtered HFM signals.

From the Fig.1, it is observed that the highpass filtering is good at matching the spectrum of the windowed signal with the filtered signal. Even though there is no much difference between the spectrum of the notch filtered signal and the highpass filtered signal over the actual range of the HFM signal, there is a huge difference at the lower frequencies. Since the notch filter is giving highest gain (unity) at lower frequencies compared with all other cases this leads to slightly higher levels of sidelobe in the time domain.

The time domain signals of the original hyperbolic frequency modulated the signal, Hamming windowed signal, notch filtered signal and highpass filtered signal are represented in Fig. 2.

From the Fig.2, it is observed that the notch filtering slightly deviates at lower frequencies from the windowed signal. This is due to the fact that the notch filter has a gain equal to unity at the lower frequencies and hence it is not able to suppress the lower frequency components which are usually, the main reasons for the highest sidelobe levels in the output of the matched filter. From the same figure, it is observed that the variation of the envelope of the highpass filtered signal and windowed signal are almost same.

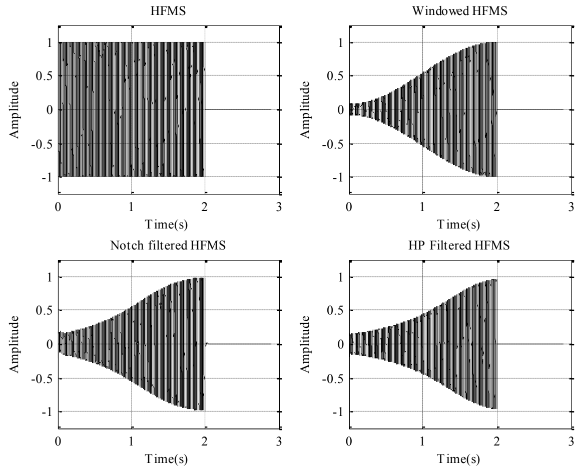

Fig. 2. Time domain signals of the original, windowed, notch filtered and highpass filtered HFM signals.

In order to see the effect of the filtering in the time domain, the auto-correlation functions have been obtained and represented in Fig. 3. From this figure, it is clear that there is an improvement in reducing the sidelobe levels near the origin. This indicates the improvement in the range resolution which is an advantage in the radar system.

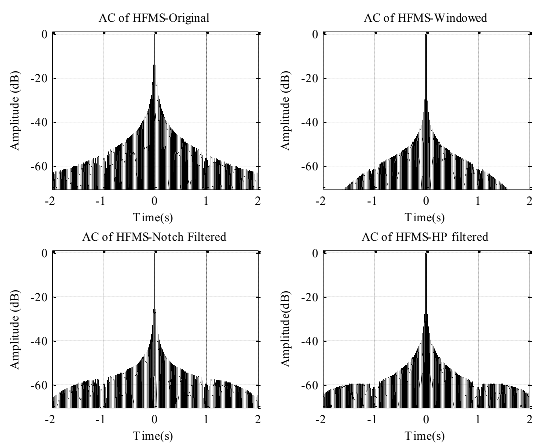

Fig. 3. ACF of the original, windowed, notch filtered and highpass filtered HFM signals.

Finally, in order to observe the effect of filtering on the Doppler invariant property, the output of the MF has been obtained when the relative velocity between the target and radar system such that the scaling factor $\gamma = 1.01$. The outputs are shown in Fig. 4 and from this figure it is observed that the filtering has no negative effects on the matched filter outputs.

Since there is no huge difference between the responses of the notch filter and highpass filters, the highpass filter is preferred over the notch filter since it has less number of components in comparison with the notch filter.

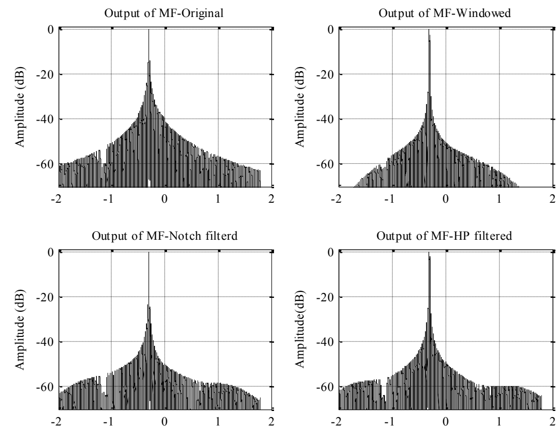

Fig. 4. Distortion of the original, windowed, notch filtered and highpass filtered HFM signals in presence of Doppler velocity.

IV. Conclusion

From the analysis with the notch filter and highpass filter, it is proposed that the highpass filtering can be used effectively on the hyperbolic frequency modulated signals in order to reduce the RPSL in the output of the MF and the improvement in the rate at which the sidelobe levels decrease. The HPF is smoothing the spectral content by distributing spectrum over the normalized frequency similar to that of a Hamming windowed signal. In addition to it, this paper also proposes the use of LC-HPF in radar systems to improve the range resolution, since it is very easy to implement the HPF either in lumped design (at low frequencies) or a distributed design (at higher frequencies). From this analysis, it is observed that the HPF is acting like a time-varying amplifier for HFM signals which can be easily used in replacing the conventionally used envelope modulators.

References

[1] Ingle, Vinay K., and John G. Proakis. *Digital Signal Processing Using MATLAB: A Problem Solving Companion*. Cengage Learning, 2016.

[2] Oppenheim, Alan V. *Discrete-time signal processing*. Pearson Education India, 1999.

[3] Aggarwal, Apoorva, Tarun Kumar Rawat, and Dharmendra Kumar Upadhyay. "Design of optimal digital FIR filters using evolutionary and swarm optimization techniques." *AEU-International Journal of Electronics and Communications,* vol.70, no.4, pp. 373-385, 2016.

[4] Kuyu, Yigit Cagatay, and Fahri Vatansever. "A new intelligent decision making system combining classical methods, evolutionary algorithms and statistical techniques for optimal digital FIR filter design and their performance evaluation." *AEU-International Journal of Electronics and Communications,* vol.70, no.12, pp.1651-1666, 2016.

[5] Xu, Zhihuo, Yunkai Deng, and Yu Wang. "Exploring lower peak sidelobe windows with the same mainlobe as rectangular window via nature-inspired methodology*", AEU-International Journal of Electronics and Communications*, vol. 69, no. 4, pp. 776–780, 2015.

[6] Harris, Fredric J. "On the use of windows for harmonic analysis with the discrete Fourier transform." *Proceedings of the IEEE,* vol. 66, no.1, pp 51-83, 1978.

[7] Chen, Chun-Chieh, Nan-Ku Lu, and Yi-Zhi Zeng. "Low gain error, linear-in-dB variable gain amplifier with programmable gain range and gain steps." *AEU-International Journal of Electronics and Communications,*vol. 64,no.12,pp.1203-1206,2010.

[8] Mahafza, Bassem R. *Radar systems analysis and design using MATLAB*. CRC press, 2002.

[9] Skolnik, Merrill Ivan. "*Radar handbook*." (1970).
[10] Chen, Victor C., et al. "Micro-Doppler effect in radar: phenomenon, model, and simulation study." *IEEE Transactions on Aerospace and electronic systems,* vol.42, no.1, pp. 2-21, 2016.
[11] Galati, Gaspare, and Gabriele Pavan. "Optimal chirp waveforms for long/medium range surveillance radar." *Radar Symposium (IRS), 2015 16th International. IEEE,* pp.260-265, 2015.
[12] Zhang, Lan, et al. "HFM spread spectrum modulation scheme in shallow water acoustic channels." *Oceans, 2012. IEEE*, pp.1-6, 2012.
[13] Zhu, Shengqi, et al. "A new Doppler ambiguity resolution technique for SAR data based on SPECAN processing." *AEU-International Journal of Electronics and Communications* vol.65, no.11 pp.906-914, 2011.
[14] Zhou, Meng, Jun Jason Zhang, and Antonia Papandreou-Suppappola. "Hyperbolic frequency modulation for multiple users in underwater acoustic communications." *Acoustics, Speech and Signal Processing (ICASSP), 2014 IEEE International Conference on. IEEE, 2014*, pp.3498-3502.
[15] Song, Xiufeng, Peter Willett, and Shengli Zhou. "Range bias modeling for hyperbolic-frequency-modulated waveforms in target tracking." *IEEE journal of Oceanic Engineering,*vol. 37,no.4, pp.670-679,2012.
[16] Yang, J., and T. K. Sarkar. "Doppler-invariant pulse compression for targets moving in an arbitrary direction." *Microwave and Optical Technology Letters,* vol.49, no.6, pp.1449-1453, 2007.
[17] Pozar, David M. *Microwave engineering*. John Wiley & Sons, 2009.
[18] Yang, Jie, and Tapan K. Sarkar. "A novel Doppler-tolerant polyphase codes for pulse compression based on hyperbolic frequency modulation." *Digital Signal Processing* vol.17, no.6, pp. 1019-1029, 2017.
[19] MATLAB, version 7.10.0 (R2010a). Natick, Massachusetts: *The MathWorks* Inc., 2010.