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Some Aspects of Sidelobe Reduction in Pulse Compression Radars Using NLFM Signal Processing

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Abstract—It is well known that in the pulse compression radar theory, the sidelobe reduction using nonlinear frequency modulation (NLFM) signal processing represents a major and present research direction. Accordingly, the main objective of this paper is to propose an interesting approach related to the design of efficient NLFM waveforms namely, a temporal predistortioning method of LFM signals by suitable nonlinear frequency laws. Some aspects concerning the optimization of the specific parameters involved into analyzed NLFM processing procedure are also included. The achieved experimental results confirm the significant sidelobe suppression related to other NLFM processing techniques.

1. INTRODUCTION

According to literature [1, 2], it is well known that pulse compression techniques are widely employed inside of modern radar systems (e.g., (I)SAR, GPR, etc.) in order to increase the range resolution. As the range resolution is inverse proportional with the frequency band (B) of the transmitted signals, in the last period of time, in radar theory, a lot of suitable wideband signals (e.g., chirp, short radio pulse, signals with discrete frequency modulation, unsinusoidal signals) were designed and analyzed at processing performance level.

Generally, one of the most important requests imposed on the wideband signals is to assure for the sidelobes of the compression (matched) filter response the lowest level. The presence in the response of significant sidelobes may cause interference with other near echo signals, and have unwanted effects in the detection process and ambiguities in the estimating of the target range [3]. Consequently, a major research direction in the high-resolution radar literature is related to the designing of improved FM waveforms with rectangular envelope and suitable modified FM laws, so that the matched filter response contains lower sidelobes than in the standard LFM case [4].

In this research domain, the nonlinear FM (NLFM) signals represent an important class of continuous phase modulation waveforms with applicability inside pulse compression radar systems. They have been claimed to provide a high-range resolution, an improved SNR, low cost, good interference mitigation, and spectrum weighting function inherently in their modulation function which offers the advantage that a pure matched filter gives low sidelobes. The NLFM signals also assure better detection rate characteristics, and they are more accurate in range determination than other processing methods (e.g., dual apodization (DA), spatially variant apodization (SVA), leakage energy minimization (LEM) etc.) [5]. However, the major drawback assigned to the most part of common NLFM waveforms seems to be their Doppler intolerance, which requires, for example, using several filters (i.e., filter bank) at the receiver [4].

In pulse compression radar theory, there are many interesting research works which have been done to investigate and design optimal (as sidelobe level) NLFM signals [6, 7]. Generally, all these processing techniques can be divided into two major research directions, namely: a) designing of pseudo-NLFM (or

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piecewise) waveforms which are in fact, LM signals predistortioned on short intervals (e.g., at the pulse ends) into temporal domain or corrected into spectral domain [1, 8–10]; b) designing of proper (e.g., as desired shape of the energy/power spectral density (E/PSD) etc.) pure (continuous) NLFM waveforms using usually, iterative methods [11–13], stationary phase principle [14–16], Zak transform [17, 18], suitable weighting/convolutional functions [19–22], explicit functions cluster algorithm [23, 24] or marginal Fisher's information-based techniques [25] etc. Also, many of the above described NLFM methods are implemented by standard computational algorithms, but some interesting approaches connected with the artificial intelligence (AI) paradigms are also discussed in literature [26–28].

This paper aims at presenting an interesting approach related to the design of efficient (as sidelobe suppression etc.) NLFM waveforms namely, a temporal predistortioning method of LFM signals by suitable continuous nonlinear frequency laws. Some aspects concerning the optimization of the specific parameters involved analyzed NLFM technique are also included. Finally, the most important conclusions are discussed.

2. TEMPORAL PREDISTORTIONING OF NLFM LAWS

In practice, some concrete situations can appear when, by reasons of simplicity of the pulse compression radar system designing process and lower cost, the LFM signal base (i.e., $B \times T$ product) must be reduced at the values less than 100 [2, 16]. In this case, the singular use of all standard weighting windows is not efficient because of the disturbative behavior assigned to the Fresnel ripples, which is translated into significant level of the matched filter sidelobes [2, 4]. Consequently, a high-potential solution of this drawback can be represented by the temporal predistortioning of the LFM law [1, 3].

According to [11], the frequency modulation law of a temporal predistortioned FM signal can be generally written as follows (Figure 1):

$$f(t) = \begin{cases} f_d(t), & t \in (0, \Delta t] \\ f_{\mathrm{LFM}}(t) = -\dfrac{\Delta F}{2} + \dfrac{\Delta F}{T} t, & t \in (\Delta t, T - \Delta t] \\ -f_d(T-t), & t \in (T - \Delta t,\, T] \end{cases} . \tag{1}$$

The values assigned to the parameters of the predistortioning function $f_d(t)$ can be chosen in order to assure a continuity of the FM law slope in the points $t = \Delta t$ and $t = T - \Delta t$. However, this is not a mandatory condition.

The phase modulation law of the signal is next obtained through (1) by stage integrating and

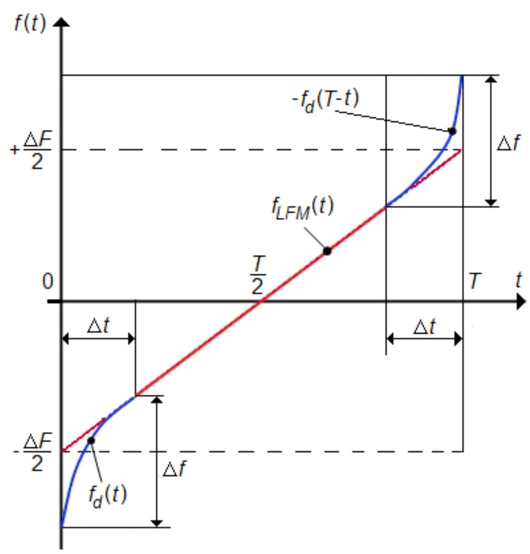

Figure 1. The temporal predistortioning technique of the LFM law.

setting this time as mandatory, the condition of phase continuity:

$$\varphi(t) = \begin{cases} \varphi_{d1}(t) = 2\pi \cdot \int\limits_0^t f_d(t)dt, & t \in (0, \Delta t] \\ \varphi_{\mathrm{LFM}}(t) = \varphi_d(\Delta t) + 2\pi \cdot \int\limits_{\Delta t}^t f_{\mathrm{LFM}}(t)dt, & t \in (\Delta t, T - \Delta t] \\ \varphi_{d2}(t) = \varphi_{\mathrm{LFM}}(T - \Delta t) - 2\pi \cdot \int\limits_{T-\Delta t}^t f_d(T - t)dt, & t \in (T - \Delta t, T] \end{cases} . \quad (2)$$

Consequently, this NLFM processing technique allows a significant decreasing of the Fresnel ripples and the sidelobe level assigned to the matched filter response, respectively (Figure 2). It is important to note that this sidelobe reduction is similar to the ones achieved in the case of signals with high-values of the signal base (i.e., more than 100).

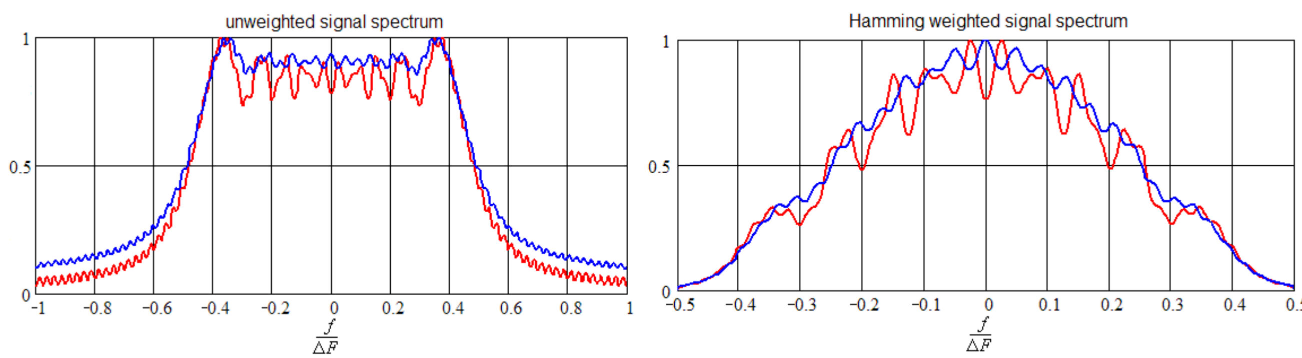

Figure 2. The absolute of the spectral density function for unpredistortioned (red) and predistortioned (blue) FM signals (an *arcsine* predistortioning function was used).

Reference [4] fully describes the predistorsioning function, which was first proposed by Cook and Bernfeld. The (pseudo) optimal values indicated by these authors were $\Delta t = 1/\Delta F$ and $\Delta f = 0.75 \cdot \Delta F$. For these values and signal base (denoted next by BT) of 40 and 80, a decreasing of the sidelobes assigned to the compression-weighting (Hamming) filter responses from -29.3 dB to -34.7 dB and from -35.5 dB to -38.4 dB, respectively, were achieved. According to [11], more appropriate values for predistortioning function parameters are $\Delta t = 1/\Delta F$ and $\Delta f = 0.55 \cdot \Delta F$ (in this case, as optimization criterion, the local behavior of the sidelobe level was effective used etc.)

3. THE PROPOSED TEMPORAL PREDISTORTIONING TECHNIQUE

The primary idea of Cook and Bernfeld is extended in [11] to the nonlinear predistortioning case. In other words, some examples of nonlinear predistortioning functions are given in [11].

In pulse compression radar theory, a lot of examples related to this basic idea are indicated [1, 8, 9]. However, as a common designing characteristic, all these approaches investigate only the case of LFM signal base more than 100, and in many situations, the effective way (usually, pseudo optimal) to choose the specific parameters assigned to the tested predistortioning functions is not clearly described. Generally, the majority of these approaches discuss piecewise linear waveforms (with one or two predistortioning stages) [1, 9], but some examples of piecewise nonlinear laws as "DDFC" modulation function [8], polynomial function [9], etc. are also indicated.

Unlike the drawbacks mentioned above, the predistortioning technique of LFM law proposed in this paper is applied to a signal base less than 100 and is based on the use of two promising (as ability to assure a significant sidelobe suppression) nonlinear predistortioning functions, namely: *arcsine* and t^n (only the second polynomial predistortioning function was partially tested in literature, but in a particular case (i.e., for polynomial functions with order more than one and the predistortioning applied only to a single LFM law end etc.) [9]). In addition, as for novelty, this technique gives a concrete modality to optimize (as sidelobe reduction criterion) the specific parameters of the used predistortioning laws. Finally, this proposed optimization method can be easily extrapolated for other types of nonlinear predistortioning functions.

In the case of predistortioning function by *arcsine* type, the frequency modulation law of the temporal predistortioned FM signal can be written as follows:

$$f(t)=\begin{cases}\frac{2}{\pi}\cdot\Delta f\cdot\arcsin\left(\frac{t-\Delta t}{\Delta t}\right)-\frac{\Delta F}{2}+\frac{\Delta F}{T}\cdot\Delta t, & t\in(0,\Delta t]\\ f_{\text{LFM}}(t)=-\frac{\Delta F}{2}+\frac{\Delta F}{T}t, & t\in(\Delta t,T-\Delta t]\\ \frac{\Delta F}{2}-\frac{\Delta F}{T}\cdot\Delta t+\frac{2}{\pi}\cdot\Delta f\cdot\arcsin\left(\frac{t-T+\Delta t}{\Delta t}\right), & t\in(T-\Delta t,\,T]\end{cases}. \tag{3}$$

The phase modulation law of this signal is next obtained through (3) by stage integrating and setting the condition of the phase continuity into predistortioning points:

$$\varphi(t)=\begin{cases}\varphi_{d1}(t)=2\pi\cdot\left\{\frac{2}{\pi}\cdot\Delta f\cdot\Delta t\cdot\left[\frac{t-\Delta t}{\Delta t}\cdot\arcsin\left(\frac{t-\Delta t}{\Delta t}\right)+\left(1-\left(\frac{t-\Delta t}{\Delta t}\right)^2\right)^{0.5}\right]\right.\\ \qquad\left.+t\cdot\left(\frac{\Delta F}{T}\cdot\Delta t-\frac{\Delta F}{2}\right)-\Delta f\cdot\Delta t\right\}, & t\in(0,\Delta t]\\ \varphi_{\text{LFM}}(t)=\varphi_{d1}(\Delta t)+2\pi\cdot\left(\frac{\Delta F}{T}\cdot\frac{t^2}{2}-\frac{\Delta F}{T}\cdot\frac{\Delta t^2}{2}-\frac{\Delta F}{2}\cdot t+\frac{\Delta F\cdot\Delta t}{2}\right), & t\in(\Delta t,T-\Delta t]\\ \varphi_{d2}(t)=\varphi_{\text{LFM}}(T-\Delta t)+2\pi\cdot(t-T+\Delta t)\cdot\left(\frac{\Delta F}{2}-\frac{\Delta F}{T}\cdot\Delta t\right)\\ \qquad+4\cdot\Delta f\cdot\Delta t\cdot\left[\frac{t-T+\Delta t}{\Delta t}\cdot\arcsin\left(\frac{t-T+\Delta t}{\Delta t}\right)+\left(1-\left(\frac{t-T+\Delta t}{\Delta t}\right)^2\right)^{0.5}-1\right],\\ & t\in(T-\Delta t,\,T]\end{cases}. \tag{4}$$

In the case of predistortioning function by t^n type, the frequency modulation law of the temporal predistortioned FM signal can be written as follows:

$$f(t)=\begin{cases}\Delta f\cdot\left(\frac{t}{\Delta t}\right)^n-\left(\frac{\Delta F}{2}+\Delta f\right)+\frac{\Delta F}{T}\cdot\Delta t, & t\in(0,\Delta t]\\ f_{\text{LFM}}(t)=-\frac{\Delta F}{2}+\frac{\Delta F}{T}t, & t\in(\Delta t,T-\Delta t]\\ \frac{\Delta F}{2}-\frac{\Delta F}{T}\cdot\Delta t+\Delta f-\Delta f\cdot\left(\frac{T-t}{\Delta t}\right)^n, & t\in(T-\Delta t,\,T]\end{cases}. \tag{5}$$

In a similar way, the phase modulation law of this signal is given by equation:

$$\varphi(t)=\begin{cases}\varphi_{d1}(t)=2\pi\cdot\left[\frac{\Delta f\cdot\Delta t}{n+1}\cdot\left(\frac{t}{\Delta t}\right)^{n+1}+t\cdot\left(\frac{\Delta F}{t}\cdot\Delta t-\Delta f-\frac{\Delta F}{2}\right)\right], & t\in(0,\Delta t]\\ \varphi_{\text{LFM}}(t)=\varphi_{d1}(\Delta t)+2\pi\cdot\left(\frac{\Delta F}{t}\cdot\frac{t^2}{2}-\frac{\Delta F}{t}\cdot\frac{\Delta t^2}{2}-\frac{\Delta F}{2}\cdot t+\frac{\Delta F\cdot\Delta t}{2}\right), & t\in(\Delta t,T-\Delta t]\\ \varphi_{d2}(t)=\varphi_{\text{LFM}}(T-\Delta t)+2\pi\cdot\left[t\cdot\left(\frac{\Delta F}{2}-\frac{\Delta F}{T}\cdot\Delta t+\Delta f\right)\right.\\ \quad\left.+\frac{\Delta f\cdot\Delta t}{n+1}\cdot\left(\frac{T-t}{\Delta t}\right)^{n+1}-(T-t)\cdot\left(\frac{\Delta F}{2}-\frac{\Delta F}{T}\cdot\Delta t+\Delta f\right)-\frac{\Delta f\cdot\Delta t}{n+1}\right], & t\in(T-\Delta t,\,T]\end{cases}. \tag{6}$$

As the sidelobes level assigned to the compression-weighting (Hamming) filter response depends on the values assigned to parameters (Δt, Δf) and (n, Δt, Δf) respectively, an optimization criterion for them has also been investigated. This optimization procedure can be designed using many action ways [8, 11], but all defined objective/error-functions have a common reason, namely, minimization of the sidelobes level.

Consequently, a first optimization criterion refers to the integrated behavior of the sidelobes assigned to the compression-weighting filter response $\rho(t)$. So, if t_1 is the time when the mainlobe of the response is canceled, the integrated mean m_{i_k} of the sidelobes for a discrete variation domain of the parameter Δf, Δf_k, $k = 1, 2, \ldots$, will be:

$$m_{i_k} = \frac{1}{T - t_1} \int_{t_1}^{T} \rho\left(t, \Delta f_k\right) \mathbf{d}t \cong \frac{1}{N - k_1} \cdot \sum_{k=k_1}^{N} \rho\left(t, \Delta f_k\right), \tag{7}$$

and the integrated mean square deviation σ_{i_k}:

$$\sigma_{i_k} = \sqrt{\frac{1}{T - t_1} \int_{t_1}^{T} \left[\rho\left(t, \Delta f_k\right) - m_{ik}\right]^2 \mathbf{d}t} \cong \sqrt{\frac{1}{N - k_1} \sum_{k=k_1}^{N} \left[\rho\left(t, \Delta f_k\right) - m_{ik}\right]^2}. \tag{8}$$

where N represents the number of sidelobes from [0, T] domain.

A second optimization criterion was based on the analysis of the local values of the sidelobes. Denoted with ρ_n, $n = 1, 2, \ldots, N$, the level of the N sidelobes of the response from [0, T] domain and their local mean m_{l_k} will be:

$$m_{l_k} = \frac{1}{N} \sum_{n=1}^{N} \left|\rho_n\left(\Delta f_k\right)\right|, \tag{9}$$

and the local mean square deviation σ_{l_k}:

$$\sigma_{l_k} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left(\left|\rho_n\left(\Delta f_k\right)\right| - m_{\rho_k}\right)^2}. \tag{10}$$

Finally, the effective objective-function was represented by the minimization of the two parameters (m_{i,l_k}, σ_{i,l_k}), namely:

$$\Delta f_{m_{opt}} = \left\{\Delta f_k \middle| m_{i,l_k} = \min\right\} \text{ and } \Delta f_{\sigma_{opt}} = \left\{\Delta f_k \middle| \sigma_{i,l_k} = \min\right\}. \tag{11}$$

4. EXPERIMENTAL RESULTS

The main objective of the experimental part of the paper was to demonstrate the sidelobe reduction potential of the proposed predistortioning techniques (including its specific optimization way) related to other NLFM laws described in some references [1, 9, 16], but in case of LFM signal base less than 100. Very importantly, in the majority of these reported NLFM laws, the processing advantage given by NLFM waveforms as sidelobe suppression is doubled by a proper window function (e.g., Nuttall [8], Kaiser [16] or Hamming (our study case) etc.).

In the case of predistortioning function by *arcsine* type and for $BT = 40$, the results achieved after applying the optimization criteria given by (11) are illustrated in Figure 3. Consequently, using the integrated behavior of the sidelobes, the minimum mean was found for $\Delta f_{m_{opt}} = 0.81 \cdot \Delta F$, and the minimum mean square deviation for $\Delta f_{\sigma_{opt}} = 0.88 \cdot \Delta F$ (Figure 3(a)). Also, focusing this time on the local behavior of the sidelobes, the optimal values of the frequency step are identical and equal to the previous value, namely 0.88 (Figure 3(b)).

All Equations (7)–(10) were solved using specific numerical methods belonging to Matlab package.

Using as input conditions $BT = 40$ and $\Delta t = 1/\Delta F$, the shape of the normalized envelope of the compression-weighting (Hamming) filter response achieved in the case of *arcsine* predistortioning

Table 1. Experimental results.

n	$\Delta f_{opt}/\Delta F\,(BT=40,\ \Delta t=1/\Delta F)$			
	minimum integrated average values		minimum local average values	
	m_i	σ_i	m_l	σ_l
1/4	1.70	1.70	1.65	1.65
1/3	1.35	1.35	1.30	1.30
1/2	0.98	0.95	0.98	0.98
2	0.40	0.43	0.38	0.38
3	0.33	0.35	0.33	0.33
4	0.30	0.28	0.33	0.33

function $-\rho_p(\tau, \Delta f)$ is depicted in Figure 4. On the same chart, the shape in case of optimal value of the frequency step (i.e., $\Delta f_{opt} = 0.88 \cdot \Delta F$) $-\rho_p(\tau, \Delta f_{opt})$ and the normalized envelope of the compression-weighting (Hamming) filter response achieved in the case of unpredistortioning FM signal $-\rho(\tau)$ (as reference) are also illustrated.

As can be seen from the previous figure, an average sidelobe decreasing more than -40 dB was generally demonstrated. Related to other experimental results reported in [1, 4, 9], an additional sidelobe suppression, approximately 6 dB, was also achieved. Finally, related to NLFM technique described in [16], the level of sidelobes was slightly decreased (i.e., 2 dB approximately).

In the case of predistortioning function by t^n type, using a similar predistortioning time interval (i.e., $\Delta t = 1/\Delta F$) and values for n power less and more than one respectively, the obtained results are indicated in Table 1 and synthetically illustrated in Figure 5. As it is known, in this set of pictures, $\rho_k(\cdot)$ denotes the normalized envelope of the compression filter response, $\rho_k^w(\cdot)$ the normalized envelope of the compression-weighting (Hamming) filter response, and $\rho_k^{wp}(\cdot)$ the normalized envelope of the compression-weighting (Hamming) filter response using a t^n predistortioning law.

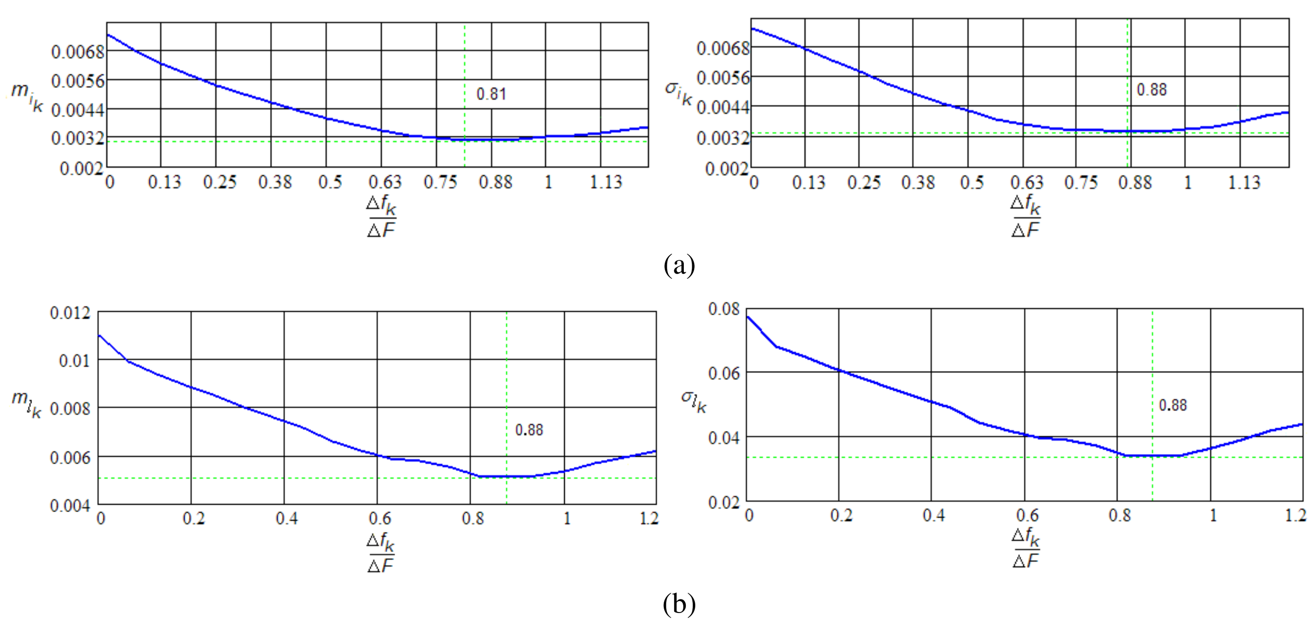

Figure 3. The average values of the sidelobes as a function by the frequency step (an *arcsine* predistortioning function was used). (a) For integrated average values of the sidelobes. (b) For local average values of the sidelobes.

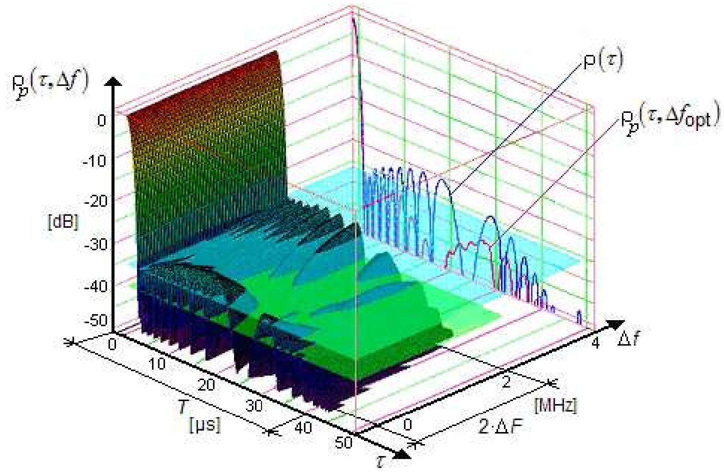

Figure 4. The shape of the normalized envelope of the compression-weighting (Hamming) filter response achieved in case of *arcsine* predistortioned/unpredistortioned FM signal.

Based on the above reported experimental results, some important remarks can be made. Firstly, for the power values less than one (excepting the case of $n = 0.5$), the frequency step optimizing the sidelobes level is more than frequency deviation. Secondly, for the power values more than one, this step represents a fraction of this. Next, for values of n more than one, a significant decreasing of the sidelobes from the vicinity of the mainlobe is observed, while for values less than one, this decreasing belongs to the far sidelobes. Finally, because the far sidelobes are under -40 dB anyway, an important conclusion is that the power values more than one are preferred in concrete pulse compression radar applications.

The sidelobe suppression level assigned to this predistortioning law is similar to the one achieved in the case of *arcsine* law. Consequently, related to the experimental results reported in [1, 9, 16], an average sidelobe reduction of 6 dB was also obtained. Finally, in both study cases, the applying of the sidelobe suppression techniques has, as major disadvantage, an average increasing of the mainlobe width with 20% (measured at -4 dB level).

Table 2. Experimental results.

n	$\Delta f_{opt}/\Delta F$			
	minimum integrated average values		minimum local average values	
	m_i	σ_i	m_l	σ_l
$BT = 40,\ \Delta t = 0.5/\Delta F$				
1/2	1.90	2.40	2.00	2.00
2	0.83	1.00	0.73	0.73
$BT = 40,\ \Delta t = 0.75/\Delta F$				
1/2	1.27	1.40	1.33	1.33
2	0.57	0.60	0.57	0.57
$BT = 40,\ \Delta t = 1.5/\Delta F$				
1/2	2.00	1.00	1.87	1.87
2	0.23	0.20	0.23	0.23
$BT = 40,\ \Delta t = 3/\Delta F$				
1/2	1.20	1.07	1.20	1.20
2	0.60	0.13	0.13	0.13

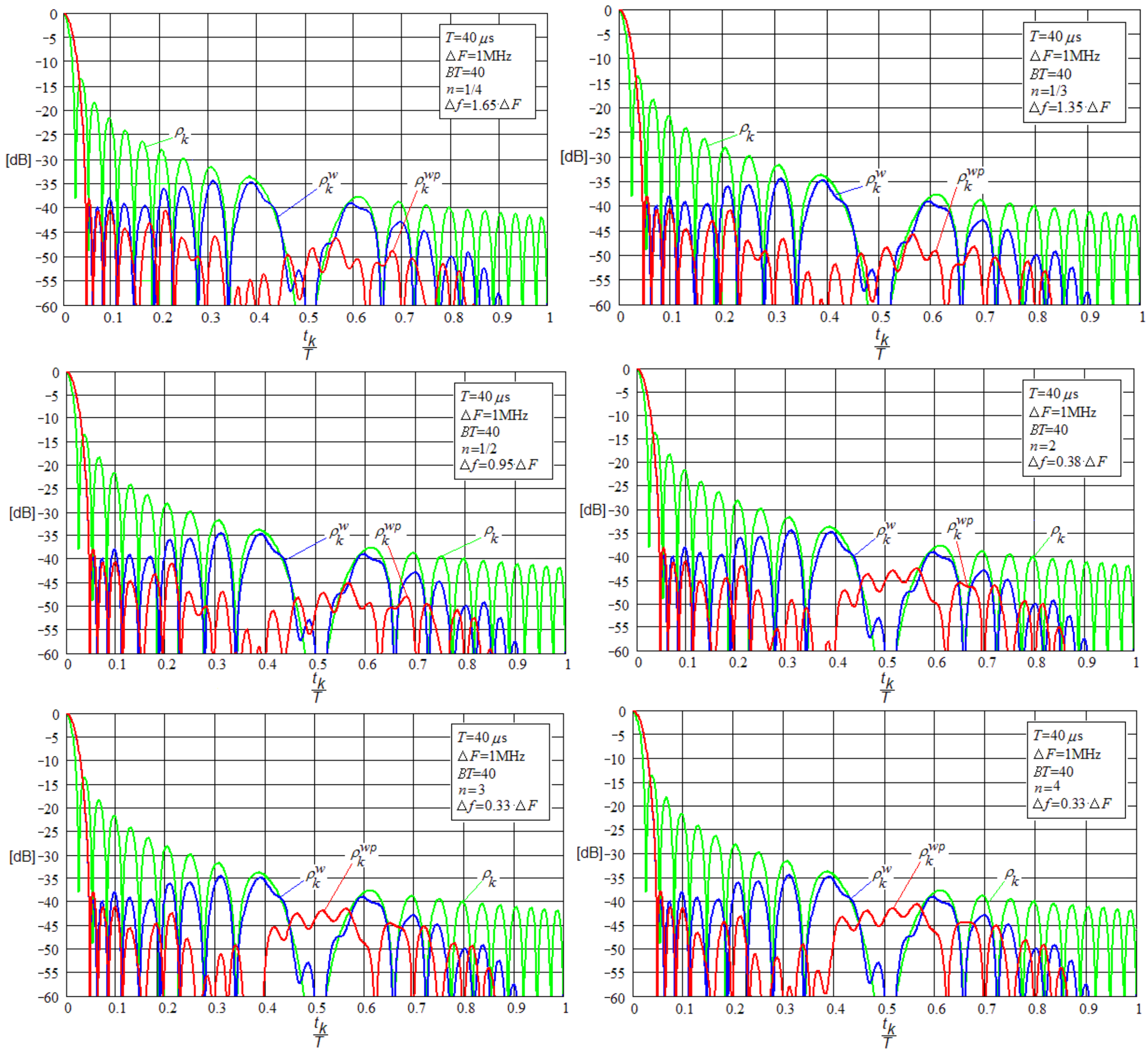

Figure 5. The normalized compression-weighting (Hamming) filter response in case of t^n predistortioning law.

To have a full view on the optimization of the parameters assigned to t^n predistortioning law, it is interesting to study the influence of the predistortioning time interval Δt on the sidelobes level. Because at the values of this interval much smaller than $1/\Delta F$, the effect on Fresnel ripples is insignificant, and at the values much higher than $1/\Delta F$, the effect consists in the increasing of the frequency range assigned to the predistortioned signal [4]. It is interesting to quantify the influence of Δt only for values around of $1/\Delta F$. After simulation stage, the obtained results are indicated in Table 2 and illustrated in Figure 6.

Based on the above reported experimental results, some important remarks can also be made. Firstly, it can be concluded that the values assigned to the predistortioning time interval Δt have an important optimization effect on the sidelobes level. Secondly, for values of Δt more than $1/\Delta F$, the power values more than one lead to a decreasing of the sidelobes from the vicinity of the mainlobe, while values less than one lead to a decreasing of the far sidelobes. Finally, the values of Δt less than $1/\Delta F$ have the highest influence on the sidelobes level.

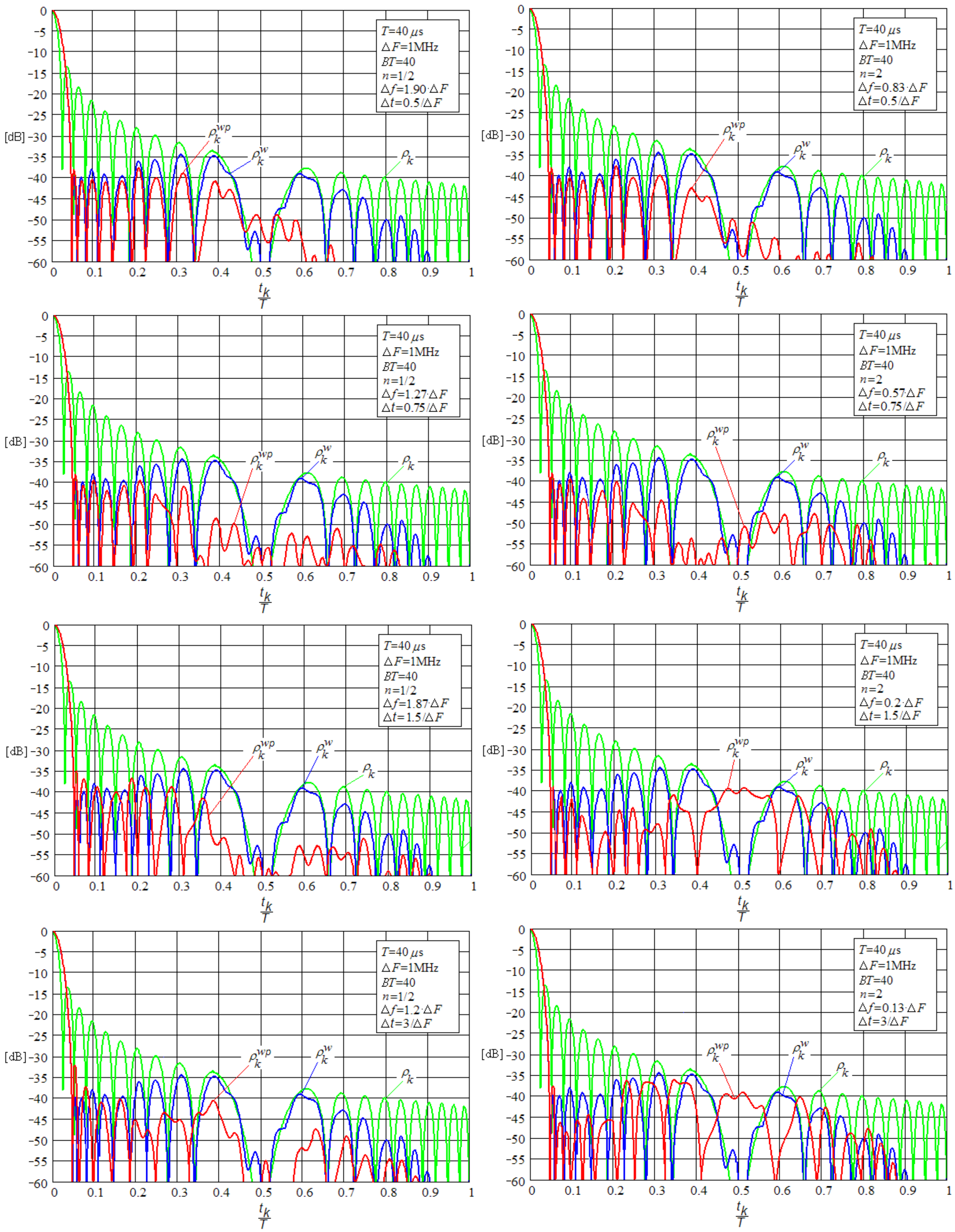

Figure 6. The normalized compression-weighting (Hamming) filter response as a function of time interval Δt (in case of t^n predistortioning law).

5. CONCLUSION

This paper presents in a synthetically manner, an interesting approach related to design of efficient NLFM waveforms as sidelobe reduction technique, namely, a temporal predistortioning method of LFM signals by suitable nonlinear frequency laws.

The NLFM processing algorithm has the advantage to improve the shape of the compression-weighting (Hamming) filter response for low values of the signal base (i.e., less than 100) and to assure a significant sidelobe suppression (i.e., more than $-40\,\mathrm{dB}$) similar to the one achieved in the case of signals with high-values of the base (i.e., more than 100), or other piecewise linear/nonlinear techniques [4, 8, 9, 16]. In addition, using the proposed optimization procedures of the parameters assigned to the nonlinear predistortioning laws, an additional decreasing of the sidelobe level more than 6 dB is also acquired. Generally, NLFM signals generated by predistortioning (frequency/temporal) techniques have some major drawbacks, namely: the mainlobe width and signal processing losses are increased, and the range resolution can be sometimes significantly reduced. However, in our study case and according to special literature [1, 4], the worsening of the range resolution (which is a very important tactical characteristic of a (military) radar) can be considered one acceptable.

In summary, the proposed NLFM processing algorithm has been demonstrated to be an effective sidelobe reduction technique having a great applicability inside the pulse compression radar systems. Although the above described algorithm is focused to solve some particular drawbacks of the LFM signals (e.g., the case of small signal base etc.), by their structure and especially, the associated optimization method, it leads to experimental results similar to sidelobe reduction level, with other well-known NLFM processing techniques reported in modern radar theory.

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