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Short communication

Suppression of grating lobes in stepped frequency LFM pulse train using PSO

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ABSTRACT

Frequency stepping technique is used in radar to achieve high range resolution and this technique requires inexpensive transmitter hardware. However, its matched filter output introduces undesired peaks known as grating lobes. In this letter efficient particle swarm optimization (PSO) based technique is proposed which judiciously determines the parameters of a linear frequency modulated (LFM) pulse train that enables effective suppression of grating lobes. Simulation results have been provided to demonstrate the efficacy of the proposed method.

1. Introduction

Wide bandwidth is required in radar for good range resolution because resolution is strongly dependant on bandwidth. Due to hardware limitations, the signal processing with more bandwidth is practically impossible. However, the effect of the wide bandwidth can be realized by suitable manipulation of the characteristics of narrowband signals. Such collection of narrowband signals is called 'synthetic wideband waveform' or 'stepped frequency waveform' or 'frequency jumped train'. But the matched filter output of such signal is associated with grating lobes which arise due to constant frequency step Δf. These grating lobes appear in the form of high spikes and hence reduce the range resolution capability of LFM pulse train. Different techniques for acceptable suppression or complete rejection of grating lobes are dealt in [1–3,5–8]. Maron [6,7] has proposed to use variable pulse widths to suppress the grating lobes but it leads to loss of periodicity of pulse train. Rabideau [8] has proposed a technique to generate nonlinear synthetic wideband waveform which has yielded enhanced performance in terms of higher range resolution, lower sidelobe and reduced grating lobes due to non-uniform distribution of energy over the desired frequency band. In [1] a novel extended correlation method is proposed to suppress the grating lobes without loss of any range resolution. LFM pulses are replaced by nonlinear LFM pulses in [2,3] to suppress the range sidelobes near the mainlobe along with the grating lobes. However, nonlinear LFM pulses are not Doppler tolerant.

Levanon and Mozeson [5] have outlined an analytical search procedure to remove first two grating lobes by appropriately establishing relations among the values of pulse duration (T_p), bandwidth (B) and frequency step (Δf) of an LFM pulse train. They have also shown in some cases that nullifying first two grating lobes also removes all the grating lobes. To establish the required relation between the parameters T_p, B and Δf using this approach for more than two grating lobes is too difficult. In this paper a novel PSO based technique has been suggested which aims to suppress or eliminate all the grating lobes by judiciously choosing appropriate values of T_p, B and Δf.

2. Stepped frequency pulse train

For $\tau \le T_p$, the matched filter output of stepped frequency pulse train having pulse repetition time T_r is obtained as [5]

$$\left|R(\tau)\right| = \left|\left(1-\frac{|\tau|}{T_p}\right)\operatorname{sin}c\left[B\tau\left(1-\frac{|\tau|}{T_p}\right)\right]\right|\left|\frac{\sin(N\pi\tau\Delta f)}{N\sin(\pi\tau\Delta f)}\right| \quad (1)$$

where $k=\frac{B_1}{T_p}$, $k_s=\frac{\Delta f}{T_r}$ and $B=|(k+k_s)|T_p$.

In (1) the expression of $R(\tau)$ consists of product of two terms out of which the first term is the autocorrelation function of a single LFM pulse and is given by

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$$\left|R_1(\tau)\right| = \left|\left(1-\frac{|\tau|}{T_p}\right)\sin c\left[B\tau\left(1-\frac{|\tau|}{T_p}\right)\right]\right| \tag{2}$$

and the second term

$$\left|R_2(\tau)\right| = \left|\frac{\sin(N\pi\tau\Delta f)}{N\sin(\pi\tau\Delta f)}\right| \tag{3}$$

produces the grating lobes at $\tau_g = \frac{g}{\Delta f}$, where $g = 1, 2\ldots\lfloor T_p\Delta f\rfloor$.

The values of T_p, B and Δf are chosen such that nulls or minima of $R_1(\tau)$ fall on the peaks (grating lobes) of $R_2(\tau)$ for complete rejection or acceptable suppression of grating lobes. The value of $N\Delta f$ should be greater than B in order to achieve a meaningful increase in the bandwidth. In essence, appropriate choice of the values of T_p, B and Δf has been made by the use of PSO algorithm so that it enables either complete elimination or suppression of the grating lobes.

3. Problem formulation

The PSO [4,9] is a stochastic global optimization technique which has been successfully applied to solve many complex problems in engineering and science. In this algorithm a solution is called as a particle in the search space and the population of particles is called a swarm. The fitness values for all the particles are determined by evaluating objective function which is to be optimized.

The position of ith particle in a D-dimensional search space is given by

$$X_i = [x_{i1}, x_{i2}\ldots x_{iD}]^T \tag{4}$$

and the velocity of ith particle is expressed as

$$V_i = [v_{i1}, v_{i2}\ldots v_{iD}]^T \tag{5}$$

Let $pbest_i$ be the best position i.e. the best fitness value obtained by the ith particle at time t. So

$$pbest_i = [pbest_{i1}, pbest_{i2}, \ldots, pbest_{iD}]^T \tag{6}$$

The fittest particle found in the swarm at time t is

$$gbest = [gbest_1, gbest_2, \ldots, gbest_D]^T \tag{7}$$

The velocity and position of ith particle for dth dimension are updated as

$$v_{id}(t+1) = w v_{id}(t) + c_1 r_1\big(pbest_{id}(t) - x_{id}(t)\big) + c_2 r_2\big(gbest_d(t) - x_{id}(t)\big) \tag{8}$$

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \tag{9}$$

where $d = 1, 2, \ldots, D$ and w is a positive constant or positive linear or nonlinear function of time [9]. w is called inertia weight which plays the role of balancing the local and global searches. c_1 and c_2 are two positive constants known as acceleration coefficients. r_1 and r_2 are two random numbers in between 0 and 1. The first term on the right hand side of (8) corresponds to the previous velocity which provides the necessary momentum and the second term stands for the cognitive component which represents the personal thinking of each particle. The cognitive component promotes the particles to move towards their own best position. The third term is called as social component which constitutes the cooperative effect of the particles in finding the global optimal solution. The social component always drags the particle towards the global particle found so far.

The function $R_1(\tau)$ in (2) must be minimum or zero at $\tau = \tau_g$ so that the grating lobes would be suppressed or nullified. The fitness function which is to be minimized by using PSO is defined as

$$f = \sum_g \left|\left(1-\frac{|\tau_g|}{T_p}\right)\sin c\left[B\tau\left(1-\frac{|\tau_g|}{T_p}\right)\right]\right| \tag{10}$$

subject to $N\Delta f > B$.

If $f = 0$ then each term in the summation is zero which results in complete elimination of grating lobes otherwise the grating lobes are suppressed to a minimum level.

In this paper PSO is used to find out the required values of T_p, B and Δf for a given $T_p\Delta f$ so that f is minimized. The value of B is taken as $(c+1)\Delta f$ (where c is a positive number) to ensure $B > \Delta f$. Therefore the two parameters T_p and c are to be estimated using PSO such that f is minimized.

4. Methodology

The fitness function defined in (8) is minimized to determine the parameters of LFM pulse train. The various steps are

1. The population of size M is initialized randomly in the given search space and each particle in the population which consists of two dimensions corresponds to $T_p\Delta f$ and c. Random velocities are assigned to each particle.
2. The fitness function for each chromosome is evaluated according to (10). The particle having the best fitness value is called as *gbest*. Initially the *pbest* for a particle assumed as particle position itself.
3. The velocity and position of each particle are updated as given in (8) and (9) respectively.
4. The fitness function value is evaluated for the new position for each particle and compared with the corresponding *pbest* positions fitness value. If for a particle the new position fitness is better than that of *pbest* then the *pbest* will be replaced by new particle. The particle having the best fitness value among all the *pbests* is selected as *gbest*.

Steps 3 and 4 repeated until the predefined condition is satisfied.

5. Simulation results

To carry out PSO based estimation task the swarm size and number of generations are chosen to be 100 and 150 respectively. The particles are randomly initialized in the defined search space $T_p\Delta f \in [2, 15]$ and $c \in [1, 10]$. The velocities are generated randomly from the search space $[1, 10]$. The values of c_1 and c_2 are taken as 2 and that of w is 0.4. The velocity and position of the particles are updated as (8) and (9) respectively. At the end of all the generations if f attains a zero value then each term of the

Table 1
Values of $T_p\Delta f$, T_pB for $N = 8$ and $f = 0$.

$T_p\Delta f$	T_pB	$B/\Delta f$
2	4	2
2.5	12.5	5
3	9	3
3.5	24.5	7
4	16	4
5	12.5	2.5
6	36	6
7	24.5	3.5
9	40.5	4.5
11	60.5	5.5
13	84.5	6.5