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Array Design with Accelerated Particle Swarm Optimization

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Abstract

Different methods of array pattern synthesis are reported in the literature. Each method is characterized by its merits and demerits. But here, Accelerated Particle Swarm Optimization (APSO) is used for pattern synthesis of antenna arrays with linear array geometry. The major concern is to find an appropriate excitation levels to yield a desired radiation pattern. Here, an attempt is made to synthesize arrays to achieve a low sidelobe level (SLL). Well known analytical technique, Taylor method is also applied for array synthesis to control the SLL. The patterns are numerically computed for different number of elements and the results obtained using APSO are compared with Taylor method.

Key words

Accelerated Particle Swarm Optimization, Taylor method, Sidelobe level, Pattern synthesis

1. Introduction

Antenna arrays are very helpful in enhancing the performance of the communication system. The design of such an array depends on the geometrical configuration, spacing between the elements, amplitude and phase excitation of individual elements [1]. Pattern synthesis consists of finding the excitations that produce a radiation pattern as close as possible to the desired pattern. Radiation pattern of an antenna is one of the most important specifications for all applications [2-4]. The main requirement to be satisfied in solving pattern synthesis problem is to minimize the maximum sidelobe level. Low sidelobe levels can significantly improve the antenna efficiency. Optimization of antenna arrays to achieve a desired response is of considerable interest in electromagnetics. Variation in the amplitude excitation of each element in the array can help in achieving a low SLL.

Various analytical and numerical methods have been used to synthesize the radiation pattern with low SLL which are useful in point to point communications and in direction finding. All the classical techniques are based on the array excitations to meet the pattern synthesis requirements for a linear array [5-6]. Stone developed the binomial distributions which possess a radiation pattern with no sidelobes [7]. Dolph proposed the Chebyshev distribution which gives the smallest beam width for a prescribed SLL or the lowest SLL for a desired beam width [8]. Taylor's work is based on the synthesis of continuous line sources to optimize the SLL [9]. Taylor's patterns contain a specified number of equal level sidelobes, close to the main lobe and the remaining sidelobes decay monotonically. Due to the decaying behavior of the sidelobes, this distribution is more practical for use in radar systems to reduce the interfering signals. Later, Villeneuve extended the Taylor's work to discrete arrays [10].

Synthesis of an array is a highly non-linear and most important electromagnetic optimization problem. The classical and gradient methods have become inefficient to deal with complex problems involving several parameters. Therefore, evolutionary optimization methods are reliable and a good option to solve the pattern synthesis problems.

The synthesis of an antenna array is solved by many optimization methods. Marcano et al. [11] has described the synthesis of complex radiation patterns for both linear and planar arrays using Genetic algorithm (GA). Murino et al. [12] reported a method involving Simulated Annealing (SA) to find a set of array coefficients to improve the antenna performance. Design of linear antenna array synthesis is described using Ant Colony Optimization (ACO) [13]. The method of Tabu Search is used in the design of uniform linear arrays for sidelobe level reduction at a fixed beam width [14]. In [15], Differential Evolution (DE) algorithm is used for sidelobe level reduction in linear and planar arrays. Synthesis of linear antenna array patterns with prescribed nulls using Bacterial Foraging Algorithm (BFA) is reported by Guney [16]. In fact, Particle Swarm Optimization (PSO) [17] has shown its potential in solving complex problems related to the design of antenna arrays which are useful for different electromagnetic applications [18-20].

In the present work, antenna array design problem is considered to determine the optimum excitation levels that produce the radiation pattern with a reduced relative sidelobe level.

Introducing these excitation levels to each element of the array the patterns are computed for different arrays. One of the variants of PSO, Accelerated Particle Swarm Optimization (APSO) [20] is employed in this paper to achieve a low SLL. The resultant patterns obtained using APSO are compared with those of Taylor method.

The rest of the paper is organized as follows. In Section 2, the Array Synthesis using Taylor method is discussed. Section 3, deals with the concepts of Accelerated Particle Swarm Optimization. In section 4, Array Synthesis using Accelerated Particle Swarm Optimization and formulation of fitness function is explained. The synthesized patterns with low SLLs are presented in Section 5. Finally, conclusions are drawn in Section 6.

2. Array synthesis using Taylor method

It is necessary to design an antenna system with narrow beam width and low sidelobe levels. For this discussion, the Taylor distribution is used for array pattern synthesis. The Taylor method exhibits an optimum compromise between beam width and sidelobe level.

Taylor $\bar{n}$ ***method***

In Taylor $\bar{n}$ design, patterns contain a specified number of sidelobes, close to the main lobe at equal level and the remaining sidelobes decay monotonically. However, practically the closest few sidelobes decay slightly. This decay is a function of space over which these sidelobes are required to be at the same level. If this space increases, the rate of decay of the closest sidelobes decreases.

The expression for the desired pattern as given by Taylor is

$$F(u) = \cosh(\pi A)\frac{\sin(u')}{u'}\prod_{n=1}^{\bar{n}-1}\left(\frac{\dfrac{\left(u'^{2}\right)}{\sigma^2\pi^2\left\{A^2+(n-0.5)^2\right\}}}{\left\{1-\dfrac{(u')^2}{(\pi n)^2}\right\}}\right) \tag{1}$$

Here, $\bar{n}$ is an integer which divides the radiation pattern into a uniform sidelobe region surrounding the main beam and the region of decaying sidelobes.

Here, $u' = \frac{2L}{\lambda}u$

$u = \sin\theta$

θ = angle measured from maximum radiation

$\frac{2L}{\lambda}$ = array length

$$\sigma = \frac{\bar{n}}{\left(A^2 + (\bar{n} - 0.5)^2\right)^{1/2}}$$

Here, A is an adjustable real parameter having the property that $\cosh(\pi A)$ is the sidelobe ratio.

Using the equation (1), the amplitude distribution of the array is found. Applying Woodward's method, aperture distribution $A(x)$ is given by

$$A(x) = \sum_{n=-\infty}^{\infty} a_n e^{-jn\pi x} \tag{2}$$

Here, $x = X/(L/2)$, X being a variable point on the array.

The pattern $E(u)$ related to $A(x)$ is given by

$$E(u) = \int_{-1}^{1} A(x) e^{jux} dx \tag{3}$$

From equation (2.3) and (2.4), we get

$$E(u) = \sum_{n=1}^{\infty} a_n \frac{\sin(u - n\pi)}{(u - n\pi)} \tag{4}$$

This gives $a_n = E(u)|_{u=n\pi}$

Therefore, the expression for $E(u)$ reduces to

$$E(u) = \sum_{n=1}^{\infty} E(n\pi) \frac{\sin(u - n\pi)}{(u - n\pi)} \tag{5}$$

The aperture distribution is obtained in the form of

$$A(x) = a_0 + 2\sum_{n=1}^{\infty} 2a_n \cos(n\pi x) \tag{6}$$

$$A(x) = E(0) + 2\sum_{n=1}^{\infty} [E(n\pi)\cos(n\pi x)] \tag{7}$$

and $E(n\pi) = 0$ for $n \geq \bar{n}$.

3. Accelerated particle swarm optimization (APSO)

Particle Swarm Optimization (PSO) algorithm was introduced by Eberhart and Kennedy in the year 1995 which is an intelligent and novel population based stochastic search algorithm developed to solve non linear optimization problems. It is an evolutionary algorithm inspired by the social behaviour of bird flocks, fish schools and bee swarms. In PSO, each swarm consists of agents called particles, where each particle represents a potential solution in the search space. Interaction and sharing of information among the particles is the main source of swarms searching capability.

In PSO, the particles are allowed to move systematically in the search space. Each and every particle adjusts its coordinates according to its own experience and that of the other particles. This states that each particle has memory of its own or self best position called as personal best and it is represented as pbest. Another best value obtained by the neighbourhood experiences is called the global best and it is represented as gbest. The particles are initially generated randomly in the search space. The working of PSO is associated with two basic components, the velocity vector component and the position vector component. For each iteration the position and velocity of the particles are updated by using the following equations

$$V_n(t+1)=w\cdot V_n(t)+c_1\cdot r_1(pbest_n - X_n(t))+c_2\cdot r_2(gbest - X_n(t)) \quad (8)$$

$$X_n(t+1)=X_n(t)+V_n(t+1) \quad (9)$$

here X_n and V_n are the position and velocity vectors of the particle n respectively. $pbest_n$ and $gbest$ are the personal best of the n particle and global best respectively.

The particle w is an inertia factor of the particle which plays an important role in PSO was introduced by Eberhart and Shi [22]. r_1 and r_2 are two uniformly distributed random numbers in the range [0,1]. c_1 and c_2 are specific parameters which control the influence of the personal and global best values [23].

In recent years, various attempts have been made to improve the performance of standard PSO. One among the variants of PSO is APSO which extends the standard PSO algorithm. The standard PSO uses both $pbest$ and $gbest$. The proposed algorithm APSO uses gbest only as it could accelerate the convergence of the algorithm. This version of APSO was developed by X S Yang in 2008. The position and velocity of the particles are initialized randomly and are updated with time. Each particle updates its velocity vector by using the following equation

$$V_n(t+1)=V_n(t)+\alpha\cdot c_n+\beta(gbest - X_n(t)) \quad (10)$$

here c_n is a random number generated in the interval (0,1).

The position vector is updated by using the simple equation given by

$$X_n(t+1)=X_n(t)+V_n(t+1) \quad (11)$$

To increase the convergence even further, we can update the position using the below equation

$$X_n(t+1)=(1-\beta)X_n(t)+\beta\cdot gbest+\alpha\cdot c_n \quad (12)$$

The typical values for APSO are α = 0.1 to 0.4 and β = 0.1 to 0.7, here α = 0.2 and β = 0.4 are taken as the initial values. The advantage of using this algorithm is to reduce the randomness with less number of iterations. This can be achieved by using a monotonically decreasing function given by

$$\alpha=\gamma^t \qquad (0<\gamma<1) \quad (13)$$

Here, γ is the control parameter which is taken as 0.95 and t is the number of iterations or time steps where $t\in[0,t_{max}]$ and t_{max} is the maximum value of the iterations. Accelerated particle swarm optimization technique is illustrated in fig 1.

4. Array synthesis using APSO

The linear array is one of the most commonly used array structure. A 2N element array distributed symmetrically about x axis is considered as shown in Fig.2. The radiating elements in the array are considered to be point sources with half wavelength inter element spacing between them.

Mathematically, the array factor of a 2N element linear array is expressed as

$$E(\theta)=2\sum_{n=1}^{N}A_n \cos[\pi(n-0.5)\cos\theta] \quad (14)$$

Here,

A_n = amplitude excitation for n^{th} element

N = number of elements in the array

θ = angle between the line of observer and array axis

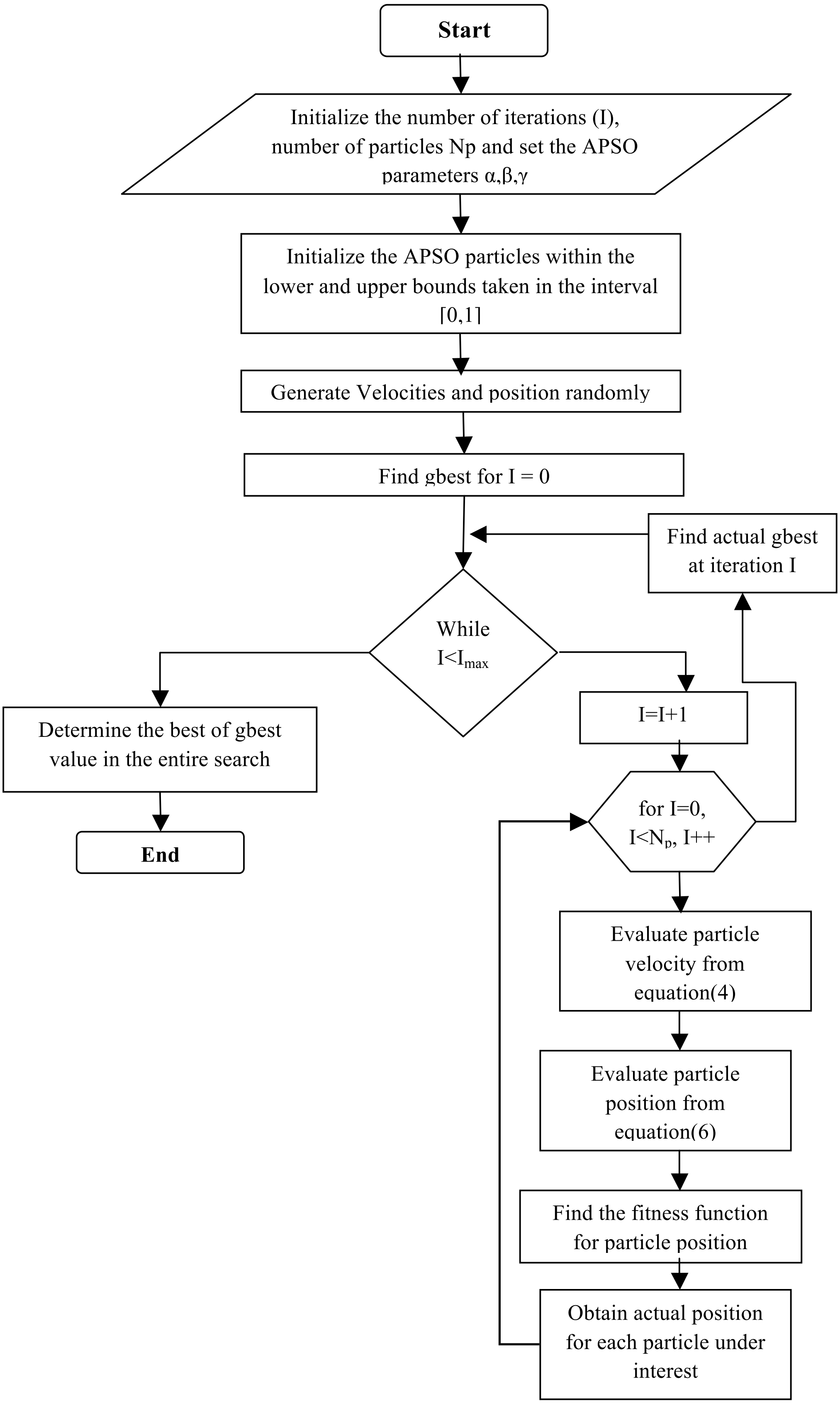

Fig.1. Accelerated Particle Swarm Optimization Technique

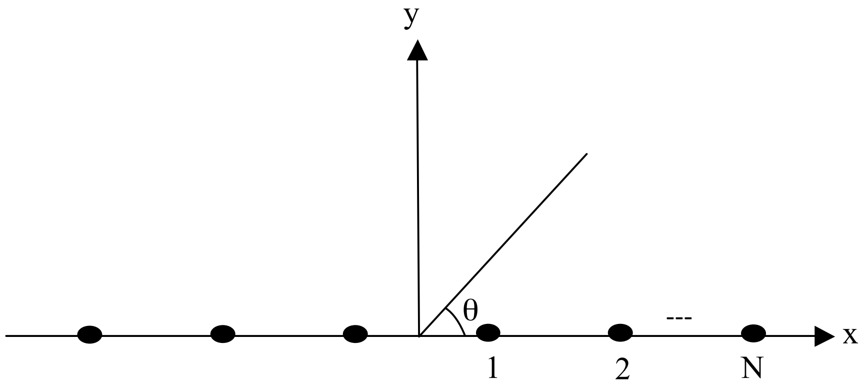

Fig.2.Geometry of the 2N element symmetric linear array placed along the x axis

The normalized array factor in dB is expressed as

$$E(\theta)=20\log_{10}\left(\frac{|E(\theta)|}{\max|E(\theta)|}\right) \qquad (15)$$

The fitness function considered for achieving a low SLL using APSO is expressed as

$$\text{Fitness} = \text{Min}\{\max[E_n(\theta)]\} \qquad 0 < \theta < \pi,\ \theta \neq \frac{\pi}{2} \qquad (16)$$

The fitness function associated with this array is used to minimize the maximum sidelobe level of its associated radiation pattern excluding the main beam.

5. Results

APSO algorithm is effectively used to determine the amplitude excitation coefficients to obtain the desired radiation pattern in two illustrative cases. Case1 deals with the design for relative sidelobe level of -35dB using APSO. Similarly, case2 deals with the design for relative sidelobe level of - 40dB respectively. The obtained excitation coefficients are applied to different array elements and the patterns are computed for N=40 and 80 elements. Radiation patterns of Taylor design are computed using equation (1) with its aperture distribution given by equation (7) with $\bar{n}=6$. The $\bar{n}$ parameter is used to define the near-in sidelobes which are held at the desired amplitude level.

Figures [3-6], depict the resultant radiation patterns and their normalized amplitude excitation levels of both APSO and Taylor design for a sidelobe level of -35dB. Figure [4] shows the optimized radiation pattern with relative sidelobe level of -35dB for N=40 elements. Figure [6] shows the optimized radiation pattern with relative sidelobe level of -35dB for N=80 elements. Figures [7-10], depict the normalized amplitude excitation levels and corresponding radiation patterns of both APSO and Taylor design for a sidelobe level of -40dB. Figure [8] shows the optimized radiation pattern with relative sidelobe level of -40dB for N=40 elements. Figure [10] shows the optimized radiation pattern with relative sidelobe level of -40dB for N=80 elements. It is observed that the radiation patterns obtained using APSO algorithm have equal sidelobe levels and the amplitude distributions along the array elements are decreasing from the centre of the array to the edges.

The results obtained using APSO algorithm are compared with those of Taylor method. The results reveal that the design of linear array with optimized excitation coefficients offers a considerable sidelobe level reduction without enhancing the beam width. The results also demonstrate that the APSO algorithm is an effective technique for array designs. All the simulations are carried out using Matlab.

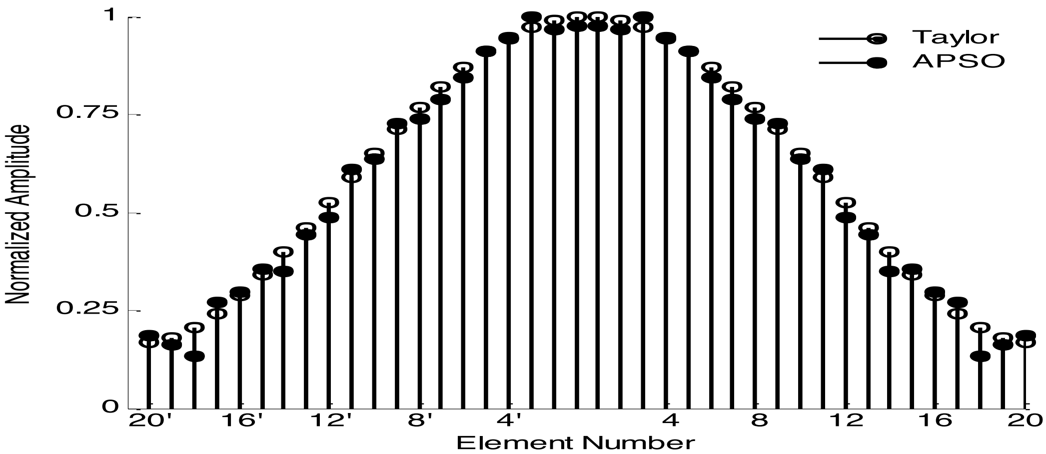

Fig.3 Amplitude Excitations of Taylor and APSO for N=40 elements

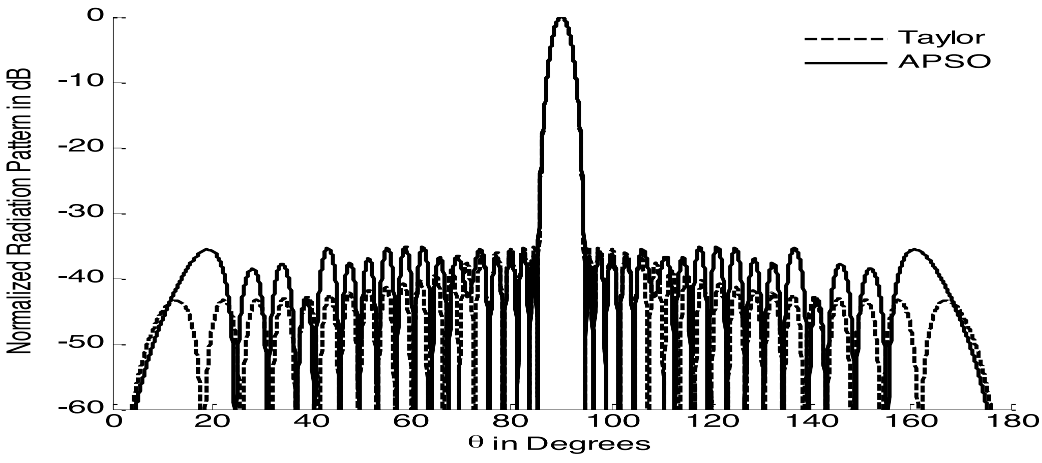

Fig.4 Radiation patterns of Taylor and APSO for N=40 elements

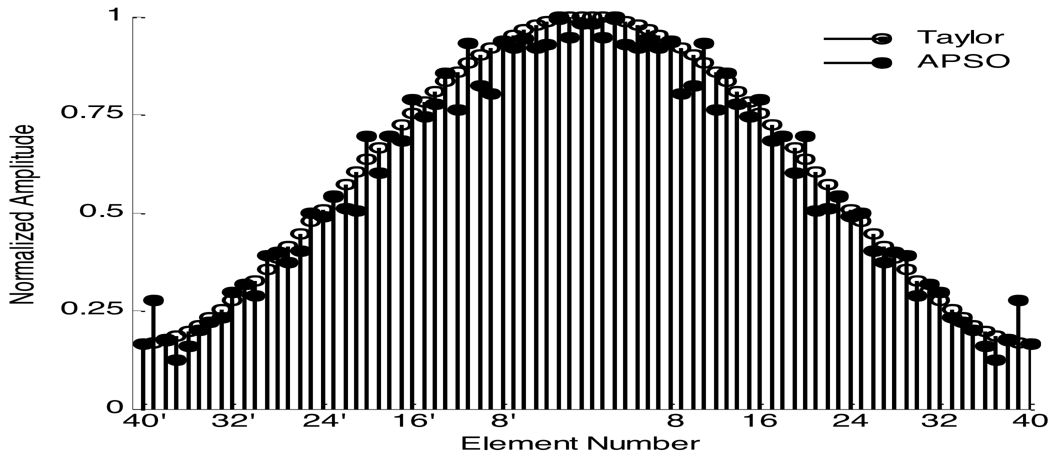

Fig.5 Amplitude Excitations of Taylor and APSO for N=80 elements

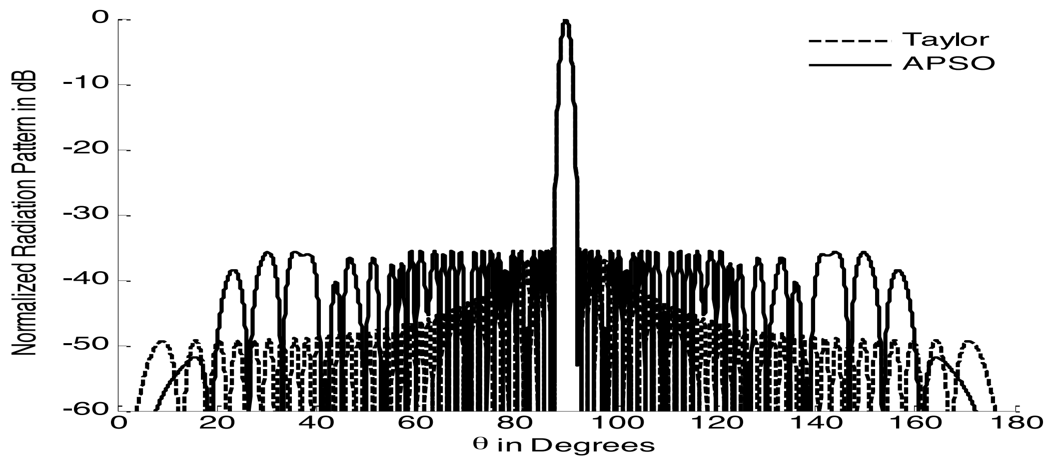

Fig.6 Radiation patterns of Taylor and APSO for N=80 elements

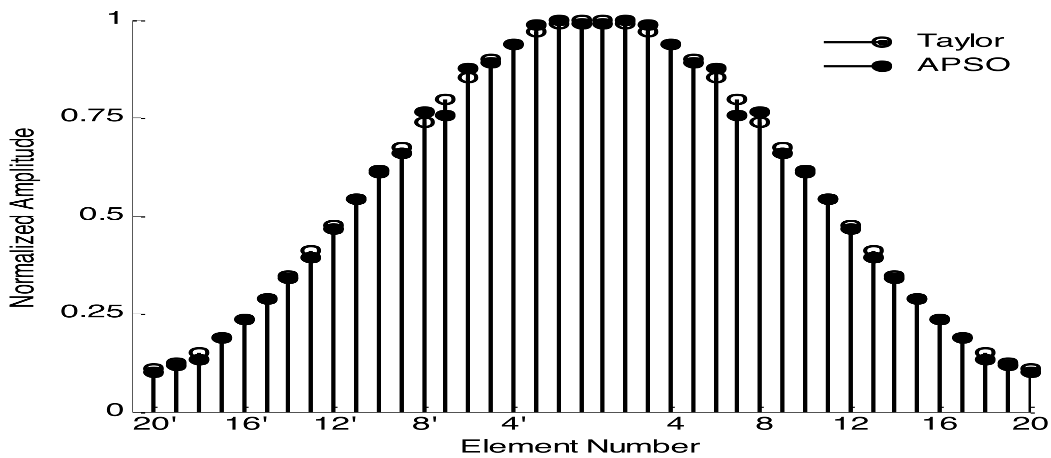

Fig.7 Amplitude Excitations of Taylor and APSO for N=40 elements

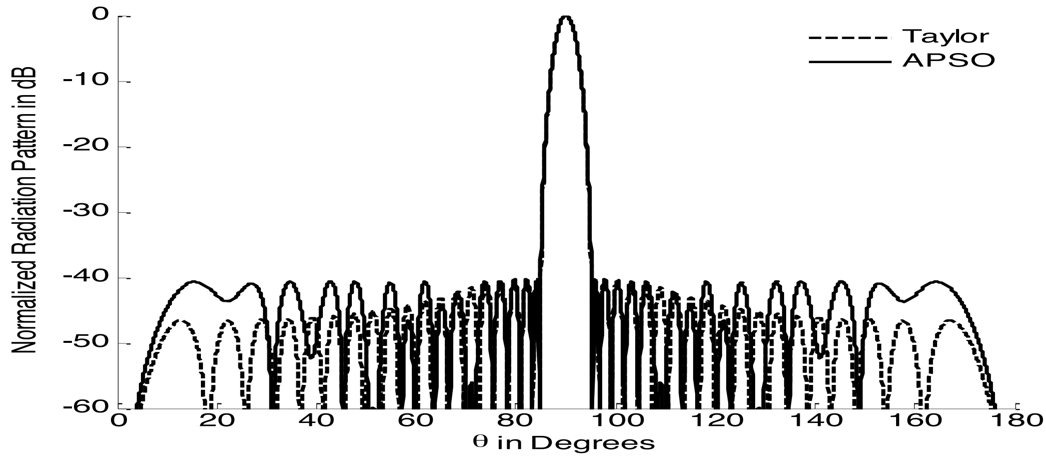

Fig.8 Radiation patterns of Taylor and APSO for N=40 elements

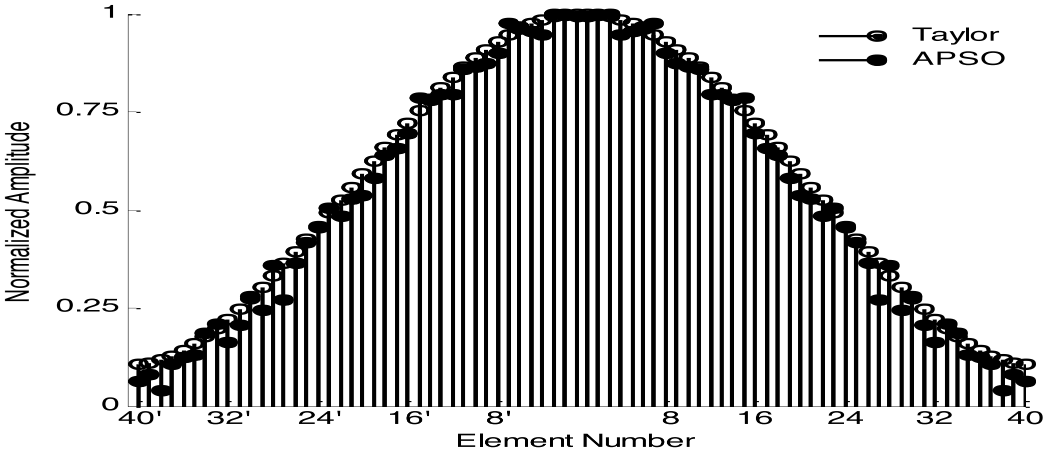

Fig.9 Amplitude Excitations of Taylor and APSO for N=80 elements

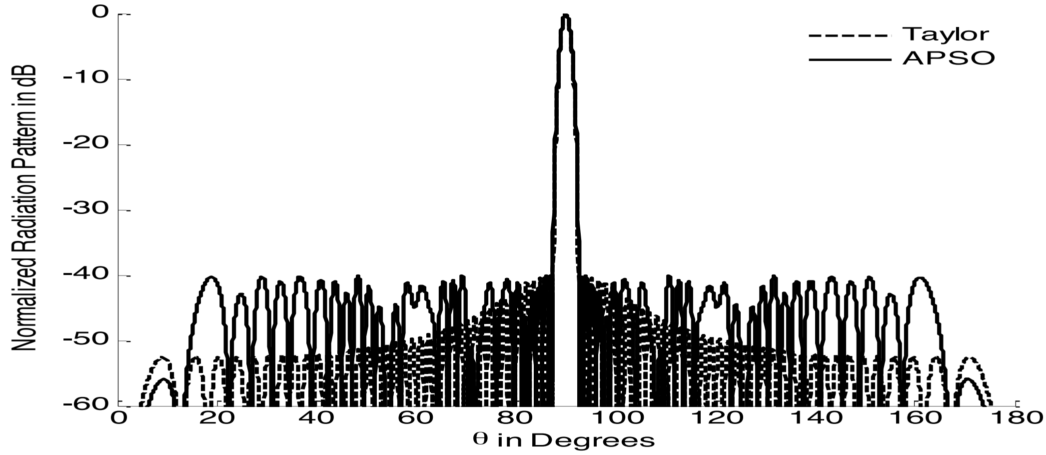

Fig.10 Radiation patterns of Taylor and APSO for N=80 elements

6. Conclusion

Synthesis of array patterns using APSO and Taylor methods are presented. The merit of APSO algorithm is that it can optimize a large number of discrete parameters. It is evident from the results that these methods are successfully used to design small and large arrays by optimizing the amplitude excitations to obtain radiation patterns with low sidelobe level. It has been possible to reduce the sidelobes to the extent of about -35dB and -40dB respectively. The simulations made on Taylor method indicate that it has been possible to control the number of sidelobes of equal height using the parameter $\bar{n}$. The obtained results reveal that the design offers a considerable reduction in SLL which decreases the interference problems without enhancing the beam width. The method can be extended to other geometries and constraints.

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