Phase only pattern synthesis for antenna array using genetic algorithm for radar application

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The present paper describes the phase only pattern synthesis for the active phased array antenna using genetic algorithm. The phase only synthesis is required to broaden and shape the beam in transmit mode of operation where all elements are fed through the saturated power of transmit/receive modules (TRM). This technique is very useful in multifunctional radar application where broadened beam can occupy more search volume (reduction in frame time). The real coded genetic algorithm (GA), which has ability to find solution of complex problems, has been exploited to get the required shaping of the beam. GA based software is a high performance optimizer and is very easy to understand and implement.

Keywords: Phase only pattern synthesis, Genetic algorithm, Active phased array antenna, Triangular grid

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1 Introduction

Active phased array antennas have matured rapidly in recent years and this technology is set to become the norm in complex and advanced radar system. A phased array antenna can electronically steer the direction of antenna beam instantaneously. Electronically steered radar may track a great multiplicity of targets, illuminate a number of targets with RF energy and guide missiles towards them and perform complete search with automatic target selection and handover to tracking. Complete flexibility is possible if limitation set by total use of time (revisit time) is achieved. In situations like this, a combination of a broadened transmit beam and multiple simultaneous receive beams may be utilized to alleviate the problem.

This paper describes the method for optimally broadening the beam, in transmit mode, for the triangular grid planar array. Here, antenna element is in triangular grid to avoid the grating lobe for larger scan volume compared to rectangular grid. In triangular grid, the total number of elements is less compared to rectangular grid in phased array antenna for the same scan requirement. Brown et al.\(^2\) has shown that the broadening factor of more than 2.5 have more power in main beam region as compared to the smaller array having same main beam coverage. So, it is beneficial to perform beam broadening better than 2.5 times as power in the main beam is very important for achieving the required range of radar. There are different levels of complexities in synthesizing the required beam shape in transmit and receive mode of operations. Beam pattern synthesis, required to achieve the desired shape, is difficult in the case of active phased arrays utilizing solid state devices operating in saturation mode during transmit because of only one degree of freedom (i.e. phase only can be changed). However, in receive mode of operation, beam pattern synthesis is less complex because of two degree of freedom (i.e. both amplitude and phase can be varied). Phase only synthesis of transmit beam with pre-fixed amplitude distributions is presented using modified Woodward-Lawson technique. Chakraborthy et al.\(^4\) have explored phase only perturbations to obtain a shaped pattern. Orchard et al.\(^5\) have used the conventional polynomial representation of the antenna element.

Genetic algorithm (GA) is combination of genetics and evolution to find good results within the constraint of the variables. It offers an alternative to traditional local search algorithms. Genetic algorithm is an increasingly popular method of optimization being applied to many fields including electromagnetic. Khzmalyan\(^8\) used the phase only synthesis for shaping the beam using fast iterating numerical method.
In this paper, optimization formulation using real-coded GA is employed so that binary to real and vice versa can be avoided. Experimental validation of the proposed beam shaping technique has been carried out by designing and realizing a semi active array antenna.

2 Genetic algorithm (GA)

Genetic algorithm is trial and error search algorithm that is motivated by the Darwin's theory of "Survival of fittest". GA is used for optimization of general purpose problem without having local minima. It is quite simple and powerful. A genetic algorithm was chosen for this application because it is an efficient method to perform search of a very large, discrete space of phase settings to achieve the required pattern of the array. The GA is summarized in following steps:

(i) Initiate the population within the constraints having M chromosomes.
(ii) Evaluate the cost of each chromosome using the cost function.
(iii) Select the best chromosome and generate the new chromosome using the cross over from best chromosome.
(iv) Select the random chromosome from chromosome and do mutation for avoiding deadlock situation.
(v) Again evaluate the cost of each chromosome using the cost function.
(vi) Repeat steps 3 to 5 until the required cost function is achieved. The best individual in the population is taken as the final answer.
(vii) The flow diagram of the same is given in Fig. 1. A comprehensive approach for GA optimization is discussed in detail by Johnson & Samii.

3 Application to beam broadeningbeam shaping

In this paper, application of beam broadening and beam shaping using phase only synthesis is enumerated. The first application illustrates beam broadening in both the planes for a planar array antenna and the second application shows the beam shaping done to achieve a cosecant squared pattern in elevation plane of a planar array.

For the GA, initial population of 500 is considered for real coded phase only synthesis. For all the chromosomes, cost function is calculated. About 50% of the chromosomes have been discarded and 250 best chromosomes have been chosen for the crossover. Crossover refers to the mixing of information from both parents to create the children. In this application, one crossover implies that a child will receive the left side of the phases from the first parent and the right side from the second parent. The crossover location is randomly selected. The second child from this union receives the complement material not taken by the first child, i.e. the sibling receives the right side of the complex array weights from the first parent and the left side from the second parent, with the same crossover location. Following the creation of children by the crossovers, mutations are then applied to the children. In this application, a mutation means replacing a radiating element’s phase with a randomly chosen value, subject to specified constraints. The probability that a particular element is mutated is governed by the mutation rate. In this paper, a mutation rate of 6% is used, which implies that each element has a 6% chance of being replaced with a new randomly chosen value. The mutation range governs how far a mutated element weight may be from its original (pre mutation) value. If assume that mutation range is 20° and old value is 200°, then new value should be in the range of 180° - 220°.

Beam broadening in both the planes is explained for a rectangular planar antenna array with 64 × 88 elements. The elements are arranged in triangular grid and the inter element spacing along x and y is 0.58 λ and 0.53 λ, respectively. The 3 dB beam width of this planar antenna for uniform distribution is calculated to be 1.32° in azimuth and 1.06° in elevation plane.

In radar application, transmit beam shaping is done to utilize the transmit power in an efficient manner for required coverage area. Antennae with cosecant squared pattern are specially designed for 3D surveillance radar. A cosecant squared pattern is an adapted distribution of the radiation pattern causing a more ideal space scanning. Cosecant squared pattern gain diminishes with increasing elevation angle. The pattern restricts power at high elevation angle since
an aircraft at high elevation angle is necessarily at close range and little power is required for detection. The cosecant squared pattern is a means of achieving more uniform signal strength at the input of the receiver as a target moves with a constant height within the beam. A 40 × 40 element planar array antenna has been chosen for synthesis of cosecant squared beam in elevation plane for 0° to 70°. Inter element spacing in elevation plane is taken as 0.55 λ.

4 Results

The pencil beam of the planar array is broadened by a factor of four in both the planes. The planar array of 64 × 88 elements, arranged in triangular grid, is decomposed into two linear arrays with 64 elements along x-axis and 88 elements along y-axis as shown in Fig. 2(a).

In a rectangular M by N array, phase command at each element is:

\[ \phi_{mn} = m \phi_x + n \phi_y \]  

where, \( m = 1,2,\ldots,M \) (row); \( n = 1,2,\ldots,N \) (column); \( \phi_x \) is phases along the x-axis and \( \phi_y \) is phase along y-axis.

This indicates that for phase computations, elements need to be arranged in rectangular grid. Hence, for computation of element phases of a triangular grid array, dummy elements are introduced in x-axis, thus, modifying triangular grid array to rectangular grid array with total number of elements becoming double (128 elements) along x-axis as shown in Fig. 2(b). Now, above formula can be used to compute phase values of individual elements of the planar array.

Once phase computations for all rectangular grid elements (including dummy elements) are done, phase values of dummy elements are discarded. In Fig. 2, actual element is present at position of filled circle. For the calculation of phases in planar array, dummy elements are used, which are represented by unfilled circle. These dummy elements are introduced only for phase computation purpose and do not exist physically.

The phases for all the elements of both the linear array are considered for optimization. The phase values for all the elements are kept within 0° and 360°. Uniform amplitude distribution is considered. The planar array phase values are arrived by adding the linear array phase values as follows:

\[
\text{Phase}_{\text{Planar}}(\text{odd, odd}) = \text{PhaseA (odd)} + \text{PhaseB (odd)} \quad \ldots (2)
\]

\[
\text{Phase}_{\text{Planar}}(\text{even, even}) = \text{PhaseA (even)} + \text{PhaseB (even)} \quad \ldots (3)
\]

Here, \( \text{Phase}_{\text{Planar}} \) is phases of elements in planar array. \( \text{PhaseA} \) is phases of x-axis elements and \( \text{PhaseB} \) is phases of y-axis elements. \( \text{PhaseA} \) and \( \text{PhaseB} \) are phase values, which are obtained by using GA to achieve the required beam broadening.

An array factor (AF) of linear array is shown as:

\[
\text{AF} = \sum_{n=1}^{N} \left( \alpha_n \exp \left( \frac{2 \pi}{\lambda} d_z \cos(\theta) \right) \right) + \varphi_n \]

where, \( \alpha_n \) is the uniform distribution amplitude; \( d_z \), inter element spacing; \( N \), total number of elements; and \( \varphi_n \), phase of individual element.

A GA is used to optimize the excitation phase \( \varphi_n \).

The objective function, \( F_o(\theta) \), used for beam broadening, can be expressed as:

\[
F_o(\theta) = \begin{cases} 
0.22 & -90° \leq \theta \leq -25° \\
1 & -25° \leq \theta \leq 25° \\
0.22 & 25° \leq \theta \leq 90° 
\end{cases} \quad \ldots (5)
\]

Cost function \( \Delta \), which is defined as difference in the specified and achieved antenna pattern side lobe levels summed across \( \theta \), can be expressed as:

\[
\Delta = a1 \sum_{-90°}^{-25°} (F(\theta) - F_o(\theta)) + a2 \sum_{-25°}^{25°} (F(\theta) - F_o(\theta)) + a3 \sum_{25°}^{90°} (F(\theta) - F_o(\theta)) \quad \ldots (6)
\]

Outside the main beam region, if \( (F(\theta) - F_o(\theta)) \) is negative at a particular \( \theta \) value, then \( (F(\theta) - F_o(\theta)) \) will be considered to be zero for calculation of cost function. Here, \( a1, a2 \) and \( a3 \) are weight of cost...
function. $F(\theta)$ is radiation pattern (in magnitude) for the given phase value of each element. Figure 3 shows the broadened beam in azimuth and elevation for planar array antenna. Figure 4 shows the comparison of the broadened beam with the pencil beam. Here, it is found that the ripples of broadened beam are within 1 dB. Figure 5 shows that phase values of linear array in azimuth and elevation. Figure 6 shows the 3D radiation pattern for the planar array antenna.

**Beam shaping**

Phase value calculation is done to generate Cosecant$^2$ beam shape pattern in elevation using 40 elements with inter-element spacing of $0.55 \lambda$. Here, beam shaping has to be done from $0^\circ$ to $70^\circ$ with uniform distribution. The desired Cosecant$^2$ beam can be described as:

\[
F_o(\theta) = \begin{cases} 
0.22 & -90^\circ \leq \theta \leq -0^\circ \\
1 & 0^\circ \leq \theta \leq 14^\circ \\
\csc^2(\theta) & 14^\circ \leq \theta \leq 70^\circ \\
0.22 & 70^\circ \leq \theta \leq 90^\circ 
\end{cases} \quad \cdots(7)
\]

Cost function is defined in similar fashion as:

\[
\Delta = a1\sum_{90}^{0} (F(\theta) - F_o(\theta)) + a2\sum_{0}^{14} (F(\theta) - F_o(\theta)) + a3\sum_{14}^{70} (F(\theta) - F_o(\theta)) + a4\sum_{70}^{90} (F(\theta) - F_o(\theta)) \quad \cdots(8)
\]

Using $a1$, $a2$, $a3$ and $a4$, weighting of cost function has been defined. In this, maximum weight is given for shaped region. The radiation pattern is shown in Fig. 7. Here, ripples are within ± 1 dB in shaped region.
5 Experimental validation

To experimentally validate the proposed technique, a semi active planar array consisting of 18 linear arrays has been designed and fabricated (Fig. 8). Each linear array is made of 20 triplate dipole elements integrated with 1:20 way airline corporate unequal power divider network to produce low side lobes in azimuth. Each linear array (row) of planar array is fed by a transmit/receive module providing equal amplitude and required phase to each row. To shape the elevation beam for near cosecant\(^2\) beam (to meet particular radar range requirement), proposed GA technique was used to synthesis phase values for each linear array. The same phase values were generated through T/R module feeding planar array and pattern measurement was carried out in Near Field Test Range. The simulated elevation pattern with constant amplitude and phase is shown in Fig. 9(a). The simulated and measured elevation pattern with synthesized phases to get the required shaping is shown in Fig. 9(b). As it can be seen, a very good agreement has been obtained between simulated and measured patterns.

6 Conclusions

The technology of beam broadening and beam shaping is widely used in phased array radars. In this paper, the global search ability of GAs is used to achieve beam broadening and beam shaping with the approach of phase-only by constructing an initial phase of linear distribution for a uniform planar array antenna. A method for computing phases of planar array elements with the use of phase coefficient of two orthogonal linear arrays has been described. In order to achieve the desired radiation pattern, the two dimensional problem can be reduced to one dimensional problem. Here, beam broadening by a factor of four in both the planes has been illustrated, which will also provide better beam efficiency\(^2\). The method presented here takes discrete phases values directly into account during synthesis. Also, GA has been presented for the design of shaped beam antenna patterns (Cosecant\(^2\)) of a planar array. The simulated and measured cosecant\(^2\) elevation pattern of a planar
array is found to be in close agreement with the desired beam shape.

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