Application of the Taguchi Method to the Design of Circular Antenna Arrays

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Abstract

The main consideration in circular antenna array (CAA) design is to suppress the maximum sidelobe level (MSL). Also, lower dynamic range ratio (DRR) and smaller physical size (circumference) of CAA are preferable in some practical applications. In this paper MSL, DRR, and circumference of 10-element non-uniform CAA designs are examined using Taguchi method (TM). TM is a design optimization method and developed on the basis of the orthogonal array (OA) concept. TM can effectively explore the search space and select optimal values for design parameters. Optimal set of excitation amplitudes and element positions of CAAs for three different instances are determined by TM. The experimental results of TM show better performances compared to those of Genetic Algorithm, Particle Swarm Algorithm, standard ABC, and modified ABC algorithm.

1. Introduction

Circular antenna array (CAA), all its elements placed in a circular ring, has gained attention due to its capability of scanning in all directions without a considerable change in the beam pattern, providing 360^o azimuth coverage, and compensating mutual coupling effects as they do not have any edge elements [1]. Hence, CAA finds wide range of application areas including radar, air and space navigation, sonar, direction-finding, seismology, and medical diagnosis and treatment [1, 2].

On the other hand, challenge in circular array design is to determine appropriate set of amplitudes and positions of the array elements that generate desirable radiation pattern. Due to the various parameters and objectives involved, optimization methods are employed to find the best possible circular antenna design. The classical optimization methods are not suitable for optimal design of CAA as they are easily stuck at local minima, usually very slow and highly sensitive to arbitrary chosen starting solution. Meta-heuristics methods have the advantages of overcoming these drawbacks.

Meta-heuristics methods are suitable for global optimization and have some balance between local search and global exploration; thus, have potential to find acceptable and feasible solutions. Several meta-heuristics like Genetic Algorithm (GA), Particle Swarm Algorithm (PSO), standard ABC, and modified ABC (ABCinv) algorithm have been employed for the optimal design of CCA design problem [3–5]. Although meta-heuristics can produce good-quality solutions, there is no guarantee that the best solutions are reached. Also, they require a very large number of iterations (experiments) to converge especially experimental cost and processing time grow with the number of objectives considered. Taguchi method (TM) helps to save processing time and to reduce experimental cost.

TM [6] is based on the principle of design of experiment and uses orthogonal arrays (OA) and signal-to-noise ratios (SNRs). The key advantages of Taguchi optimization are its simplicity and efficiency in optimizing design parameters with less number of experiments and convergence to the optimum solution rapidly [7, 8].

TM was first developed for the optimization of manufacturing processes [6] and then applied to several engineering fields, e.g., power electronics and hardware design. However, TM has recently introduced to electromagnetics community [9] and very few studies have been done to investigate the TM capabilities in electromagnetics problems [10–16].

The objective of this work is to assess the performance of TM on CAA design problem. The amplitudes and positions of CAA elements are determined by TM to achieve desired radiation pattern. Validation is performed through a comparison between TM and other meta-heuristics of GA, PSO, ABC, and ABCinv on MSL, DRR, and circumference instances.

The remainder of the paper is organized as follows. In Section 2, design equations for the CAA design problem are presented. TM and its application in CAA design optimization is briefly explained in Section 3. In Section 4, the comparative numerical results obtained using TM and several meta-heuristics, namely, GA, PSO, ABC, and ABCinv are given. Finally, the conclusion and future works are presented in Section 5.

2. Design equations

Assume that the antenna elements placed non-uniformly on a circle of radius a in the x–y plane. Fig.1 illustrates the configuration of CAA where there are N-isotropic elements. The array factor of circular array configuration is given by [1]:

$$AF(\theta) = \sum_{i=1}^{N} I_n \exp\left(jka\cos\left(\theta - \phi_n\right) + \alpha_n \right) \quad (1)$$

where

$$ka = \sum_{i=1}^{N} d_i \quad (2)$$

$$\phi_n = \left(2\pi \sum_{i=1}^{n} d_i \right) \bigg/ \left(\sum_{i=1}^{N} d_i \right) \quad (3)$$

$$\alpha_n = -ka\cos\left(\theta_0 - \phi_n\right) \quad (4)$$

I_n is the excitation amplitude of the nth element, d_n is the distance between element n and element $n+1$, $k=2\pi/\lambda$ is the wave number, λ is the signal wavelength, θ is the angle of incidence, θ_0 is the maximum radiation angle in $\theta \in [-\pi, \pi]$. For all design examples, θ_0 is chosen as zero. Considering the practical issues, the design goal is to determine optimum I_n and d_n values in order to obtain maximum sidelobe level (MSL) reduction in the radiation pattern with minimum dynamic range ratio (DRR) and minimum circumference ka. To achieve this goal and evaluate the performance of the CAA, the multi-objective function equation is formulated as:

$$F = -w_1 * \left|AF(\theta_{msl})\right| / \left|AF(\theta_0)\right| f_1 - w_2 * DRR - w_3 * ka \qquad (5)$$

where w_1, w_2, and w_3 are the weighting coefficients, $AF(\theta_{msl})$ is the value of the array factor where MSL reduction is attained at angle θ_{msl}, DRR is the ratio of the maximum to minimum amplitude values of the array elements, ka is the physical size (circumference). The optimization problem in Eq. (5) is the maximization of function F to find the amplitudes [I_1, I_2,..., I_N] and the separations between the elements [d_1, d_2,..., d_N] in order to obtain a radiation pattern with better optimal SLL reduction, lower DRR, and smaller circumference values.

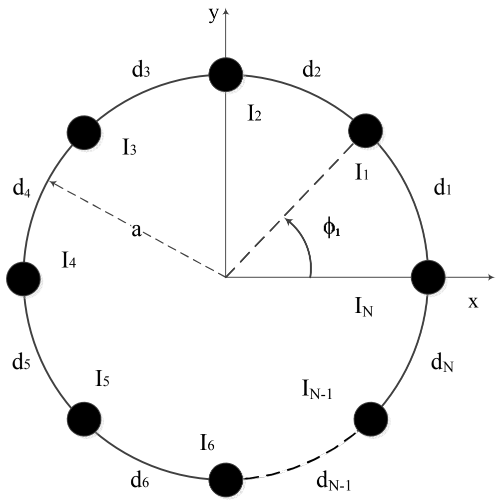

Fig. 1. Configuration of CAA with N-isotropic elements

3. Taguchi Method

In this section, Taguchi method (TM) [6] and its usage in CAA design are explained. TM, introduced by Genichi Taguchi, is a statistical experimental design procedure to explore the search space and select optimal values for the parameters of a design system. TM tests the main causes of variations in the experimentations with the analysis of variances. TM uses two mathematical tools: orthogonal arrays (OAs) for experimental design to reduce a large number of design parameters into a much smaller number of experiments; thus, minimizes the time required for experimental investigation, and signal-to-noise ratios (SNRs) for performance index to measure quality. TM makes best use of the output response and minimizes the variance of the output response [7, 8].

Parameter design in TM provides us the best values of the system parameters and decides the specification of the settings by reducing the fluctuation in the quality characteristics. TM is essentially performed to maximize the SNR. S (signal) stands for mean and N (noise) stands for standard deviation. As SNR gets higher, the output response improves. For this reason, minimizing the effect of random noise factors has important impact on the process performance. Concerning the target design, there are three types of quality characteristics exists in TM in the analysis of SNRs: "*higher is the better*", "*nominal is the best*", and "*lower is the better*". More description about these characteristics can be found at [6].

The flowchart of TM is outlined in Fig. 2. As can be observed from Fig.1, in the first step, objectives of the problem are identified. The objectives of CAA design problem are defined by Eq. (5). Then parameter characteristics which affect the aim of the problem and levels are selected. Following step is one of the most important procedures in TM. In this step, controllable factors are chosen. Parameters are classified by two groups as controllable and uncontrollable parameters. The controllable parameters in CAA design are the amplitudes and positions of array elements and have two levels: lower bound and upper bound. We optimize the performance characteristics using only the controllable factors.

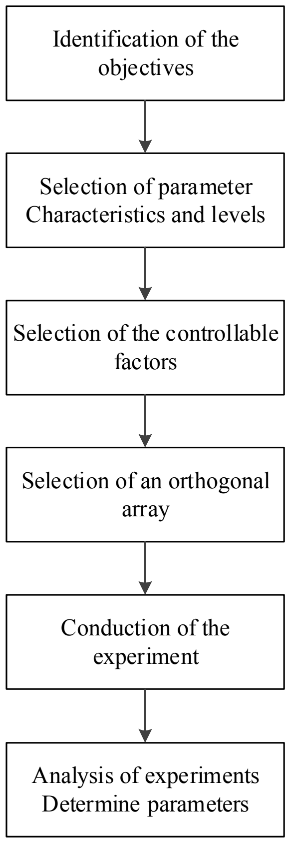

Fig. 2. The flowchart of TM

After selection of controllable parameters, OA is computed. To compute an appropriate OA for experiments, the total degrees of freedom need to be computed. The degrees of freedom (DOF) are the sum of one less of the number of each factor levels. For 10-element circular antenna design there are

20 parameters (10 parameters for I and 10 parameters for d) with two levels. Thus, total DOF is equal to 20x1=20. Once the required degrees of freedom are known, the next step is the selection of best OA to fit the specific task. OA evaluates the sequence of experiments with the combination of factors and levels. The total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. As a result, based on the number of parameters and their levels an orthogonal table L_{32} (2^{20}) was selected as experimental plan. In this work, "*higher is the better*" quality characteristics category was used because we want the objective function value be higher. Last step is the conduction of experiment and analysis. In this step, a total of thirty two experimental runs are conducted to determine the optimal levels of factors.

4. Numerical Results

In this section, the feasibility of TM on MSL reduction will be evaluated and the effect of the design parameters on MSL reduction, lower DRR, and smaller circumference cases are investigated.

To evaluate the efficiency of TM, TM was tested on 10-element non-uniform CAA design with three instances of MSL, circumference, and DRR. For all instances, weight factors w_1, w_2, and w_3 were chosen as 0.5, 0.1, and 0.4, respectively. $L_{32}(2^{20})$ experimental plan were used in all TM instances. For each instances, optimal parameters (amplitudes and positions) were determined by TM to achieve radiation pattern considering its focus (e.g., MSL reduction, lower DRR, smaller circumference). The optimal parameters obtained using TM are listed in Table 1.

Table 1. CAA parameters obtained by TM

Algorithms	$[d_1, d_2, d_3,.. d_N]$	$[I_1, I_2, I_3,\ldots., I_N]$
TM–1	0.3 0.9 0.52 0.98 0.43 0.38 0.82 0.38 0.79 0.44	0.8 0.48 0.45 0.89 0.58 0.45 0.55 0.5 0.71 0.7
TM–2	0.3 0.9 0.51 0.97 0.43 0.38 0.81 0.37 0.78 0.44	0.8 0.48 0.46 0.88 0.58 0.46 0.55 0.5 0.71 0.7
TM–3	0.3 0.9 0.52 0.98 0.43 0.38 0.82 0.38 0.79 0.44	0.8 0.48 0.45 0.89 0.58 0.45 0.55 0.5 0.71 0.7

In the first case, the parameters were determined by TM considering the multi-objective function values (F). Obtained parameters by TM for the first case are listed as TM–1 in Table 1. It is important to remember that if we reduce the values of MSL, DRR, and circumference, the multi-objective function values will increase. When we analyzed the effects of parameters of TM–1 on increasing multi-objective function, we determined the most effective design parameters were d_3, d_7, and d_9. After this stage, as a second instance, to get smaller physical size (circumference), d_3, d_7, and d_9 values were decreased by 0.01 and to obtain lower DRR, the lowest amplitude values found I_3 and I_6 were increased by 0.01. Then, optimal parameters were determined by TM and are given as TM–2 in Table 1. But, multi-objective function value gets smaller. We analyzed the effects of parameters of TM–2 on MSL suppression performance, d_3, d_4, d_7, d_8 and d_9 were identified to be the most effective parameters. In the third case, d_3, d_4, d_7, d_8 and d_9 were increased by 0.01. Further, I_3 and I_6 were decreased by 0.01 and I_4 was increased by 0.01. Again, parameters were determined by TM and are shown as TM–3 in Table 1.

The experimental results for MSL, circumference, DRR, and F values are illustrated in Table 2. Comparative results of GA, PSO, ABC, and ABCinv algorithms are also presented in Table 2. The best results are highlighted in bold. The radiation patterns of GA, PSO, ABC, ABCinv, TM–1, TM–2, and TM–3 are depicted in Fig. 3.

Table 2. Comparative results of N = 10 elements CAA design

Algorithms	MSL (dB)	Circumference	DRR	F
GA [3]	–10.855	6.089	2.814	2.713
PSO [4]	–12.308	5.903	1.976	3.595
ABC [5]	–11.403	**5.837**	2.237	3.143
ABCinv [5]	–12.610	5.934	2.172	3.714
TM–1	–12.674	5.920	1.956	3.773
TM–2	–12.364	5.890	**1.913**	3.635
TM–3	**–12.840**	5.940	1.978	**3.846**

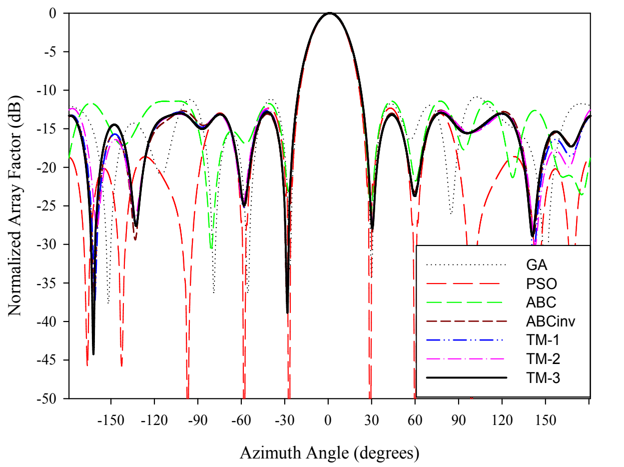

Fig. 3. Radiation pattern for N = 10 elements CAA design

From Fig. 3 and Table 2, it can be seen that the best MSL reduction is achieved using TM–3. Actually, MSL and DRR, and F values of TM–1 (first instance) are better than GA, PSO, ABC, and ABCinv. In this study, the aim is to find a solution which has minimum MSL, DRR, and circumference by TM. For this purpose, we analyze the effects of parameters for minimum MSL, DRR, and circumference. The setting of effective parameters for achieving our goal, we get TM–2 solution. It can be clearly seen from TM–2 results in Table 2 that lower DRR and smaller circumference worsen MSL and F values. However, the lowest DRR is achieved and MSL reduction is still better than GA, PSO, and ABC. In the third instance, DRR and circumference values increased. TM–3 provides a considerable MSL reduction (–12.84). Also, DRR of TM–3 is better than GA, ABC, ABCinv, and very close to PSO.

As a result, we can say that we can not reduce MSL, DDR and circumference simultaneously. If DRR and circumference are increased simultaneously, lower MSL can be achieved.

5. Conclusions

In this paper, for the first time, TM is applied to solve the CAA design problem. The efficiency of the TM is tested on 10-element non-uniform CAA design and compared with those of

GA, PSO, ABC, and ABCinv. Using TM, optimal CAA design parameters (amplitudes and positions) generating radiation pattern with best MSL reduction are obtained.

The effects of design parameters and also DRR and circumference values on the performance of MSL reduction are investigated. It is observed that there is a trade-off among MSL, DRR and circumference; such that, MSL reduction increases as DRR and circumference values increase, and MSL, DDR and circumference values can not be reduced at the same time.

TM can be very useful in challenging antenna optimization problems. Future works will be on developing an approach by combining TM with meta-heuristics algorithms.

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