Comparison of Optimization Approaches for Designing Nonuniform Helical Antennas

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***Abstract*—Comparison of various optimization approaches for the design of nonuniform helical antennas is presented. The considered helices have linearly varying radius and pitch. Results show that this design has many similar (or suboptimal) solutions with significant differences in geometry. Combination of particle swarm optimization and Nelder-Mead simplex algorithm proved to be a robust and an efficient optimization approach.**

Keywords*—*nonuniform helices; optimization; particle swarm optimization; Nelder-Mead simplex

I. Introduction

Helical antennas have been known and used for 80 years [1]. Their modifications [2] and the optimal design for uniform helices have been thoroughly researched [3], [4]. Nonuniform helices are examined [5]–[7], but design rules in the general case are unknown.

In order to design a nonuniform helical antenna with radius and pitch varying linearly, we use numerical electromagnetic (EM) solvers, AWAS [9] and WIPL-D [10], coupled with robust optimization algorithms, such as: random search, gradient method, Nelder-Mead simplex [11], and particle swarm optimization (PSO) [12]. We present statistical comparison of various optimization approaches in order to reliably and efficiently find the best possible design for this class of nonuniform helices.

II. Nonuniform Helical Antennas

A. Model of Nonuniform Helical Antennas

Sketch of a considered nonuniform helical antenna is shown in Fig. 1. The wire radius, d, the helix total length, L, and the size of the square reflector, b, are predefined. The radius of antenna turns, r, and the pitch, p, are linear functions of the z-coordinate, measured along the antenna axis, namely, $r(z) = a_r z + b_r$ and $p(z) = a_p z + b_p$. Optimization is used to find the starting and ending values: $r(0)$, $r(L)$, $p(0)$, and $p(L)$, which are further normalized to the free-space wavelength, λ, at the central frequency. The corresponding coefficients a_r, b_r, a_p and b_p are calculated from optimized variables and are used to define the geometry.

Limits for the optimized variables are: $25 \cdot 10^{-3} \le r(0)/\lambda \le 40 \cdot 10^{-3}$, $30 \cdot 10^{-3} \le r(L)/\lambda \le 50 \cdot 10^{-3}$, $10^{-2} \le p(0)/\lambda, p(L)/\lambda \le 5 \cdot 10^{-2}$, based on experience.

The antenna is excited at the junction between the reflector and the first helical turn. Materials are lossy with specific conductivity considered to be 20 MS/m.

The models of the antenna are made in customized versions of software AWAS and WIPL-D, to allow automatic construction of the geometry and a specific definition of the cost-function for the optimization.

B. Design Criteria and Definition of the Cost-Function

The optimal helix should satisfy the following requirements at the central frequency: (1) have the maximal gain in the main radiating direction (along z-axis) and (2) have an axial ratio equal to one.

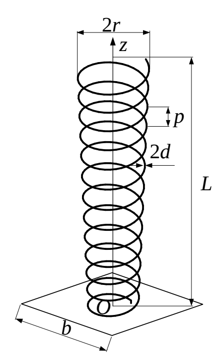

Fig. 1. Sketch of a nonuniform helical antenna.

The cost-function is calculated as follows. The modulus of the total far field is $E_{\mathrm{tot}} = \sqrt{E_\theta^2 + E_\phi^2} + \delta$, where E_θ and E_ϕ are moduli of the θ and ϕ components of the complex electric far field multiplied by the distance r. The variable $\delta = 10^{-12}$ V/m ensures that E_{tot} is always greater than zero. The axial ratio is included as $rgr = 20\log_{10}\left(E_{\mathrm{r}} / E_{\mathrm{tot}} + 10^{-12}\right)$, where $E_{\mathrm{r}} = \left|0.5\left(-E_\theta + \mathrm{j}E_\phi\right)\right|$. The cost-function is finally $f = 100 - g_{[\mathrm{dBi}]} - rgr$, where $g_{[\mathrm{dBi}]}$ is the gain in dBi.

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For the combination of the optimization variables that produce infeasible geometry, the cost-function is set to 150, which is larger than the largest f for all feasible geometries.

From the optimization point of view, this cost-function is a special case of constrained NLP (nonlinear programming) class of problems. Therefore, we will use the gradient method, Nelder-Mead simplex algorithm, and the particle swarm optimization, along with a random search.

The objective is to find an optimization approach that will find the global optimum most reliably and efficiently.

III. Comparison of Optimization Algorithms

As a solution is not known for this problem, in the general case, we either use random search or PSO as the first stage in the optimization process.

In order to statistically compare the outcomes of all used approaches, we independently restarted each approach 100 times. For each independent run of the optimization, the minimal cost-function and the best found solution are saved. The solutions are classified into 180 bins where the gain is in the range $g_k \in 0.1[k, k+1)\,\mathrm{dBi}$, $k = 0,1,2,...179$. The probability, p_k, of finding a solution with the bin g_k is estimated as $p_k = N / N_{\mathrm{tot}}$, where N is the total number of found solutions within g_k, and N_{tot} is the total number of independent runs, i.e., the total number of solutions found.

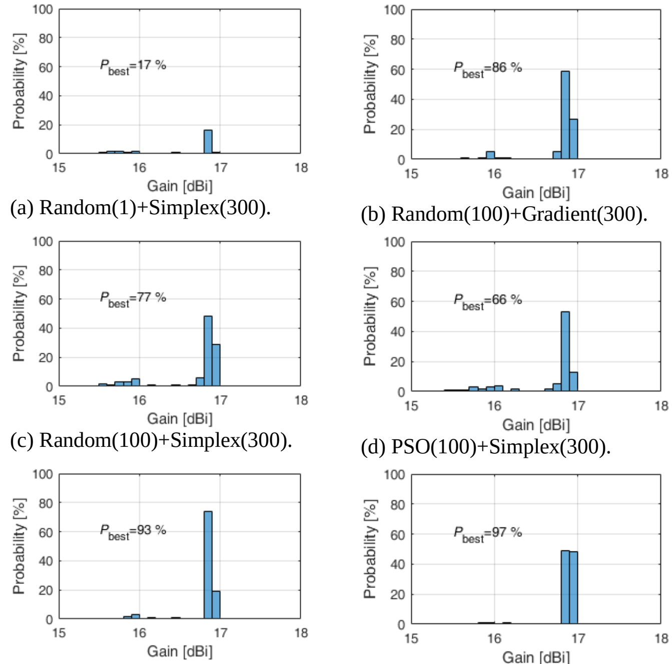
As the first optimization approach, a local optimization algorithm, gradient, or Nelder-Mead simplex is started from a random point in the optimization space. The second approach is to generate a set of random points, select the one with the lowest cost-function, and start a local optimization algorithm from it. The third approach uses PSO to find a good starting point for Nelder-Mead simplex.

Results for a $L = 5\lambda$ helix are shown in Fig. 2 where P_{best} is probability for $g \geq 16.8\,\mathrm{dBi}$. The number in brackets stands for the maximum number of iterations for the algorithm.

IV. Conclusions

The presented results show that starting a local optimization from a random point (Fig. 2a) has the probability of 17 % for finding (the best) solutions with $g \geq 16.8\,\mathrm{dBi}$. Starting a local optimization from the best among 100 random trials significantly improves the probability of finding good solutions (Fig. 2b–c). Due to the fact that the cost-function is discontinuous and flat in some parts of the optimization space, the gradient method is less robust than the simplex. Using PSO with a maximum of 100 iterations (Fig. 2d) has similar performances as 100 random trials. However, PSO with 300 iterations followed by Nelder-Mead simplex (Fig. 2e) increases the probability of finding good solutions to 93 %. Finally, Nelder-Mead simplex started from the best solution found by PSO in 1000 iterations (Fig 2d) increases the probability of finding the best solutions to 97 %. The results also show that the design of nonuniform helices has many suboptimal solutions. Even solutions with gain variation of less than 0.1 dB do significantly differ in geometry.

The combination of PSO and Nelder-Mead simplex is a reliable and robust choice for the design of nonuniform helices.



(a) Random(1)+Simplex(300). (b) Random(100)+Gradient(300).

(c) Random(100)+Simplex(300). (d) PSO(100)+Simplex(300).

(e) PSO(300)+Simplex(300). (f) PSO(1000)+Simplex(300).

Fig. 2. Probability of finding helix with gain classified into 0.1 dB bins.

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