A Comparative Study Of Corrugated Horn Design By Evolutionary Techniques

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Abstract — Corrugated horn antennas are frequently used as the feed elements in ground-based reflector antennas for satellite and deep space communications. A particular application is the multi-frequency feed horns for the reflector antennas of JPL/NASA Deep Space Network (DSN). In this application, it is desirable to design a horn that has a nearly perfect circularly symmetric pattern (i.e., identical E- and H-plane patterns), with zero or low cross-polarization, and at the same time achieves a specified beamwidth and a low return loss at the design frequency range. A parametric study of the corrugated horns, however, shows that the objective function relating the pattern shape, beamwidth and return loss is a nonlinear function of the corrugation dimensions and has many local optima. As a result one has to resort to global optimization techniques, such as Evolutionary Algorithms (EA) or Genetic Algorithms (GA), for a successful design of these antennas.

Here an evolutionary programming (EP) algorithm is used to optimize the pattern of a corrugated circular horn subject to various constraints on return loss, antenna beamwidth, pattern circularity, and low cross-polarization. EP algorithms with different mutation operators including Gaussian, Cauchy and hybrid are applied and the results are compared. Also a hybrid EP-GA algorithm is used for comparison. The EP algorithm is inherently suited for parallelization on a Massively Parallel Computer (MPP), which increases the computation speed by orders of magnitude. Examples of design synthesis for a few corrugated horns are presented. The results show excellent and efficient optimization of the desired horn parameters.

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1. INTRODUCTION

Corrugated horn antennas are frequently used as the feed elements in ground-based reflector antennas for satellite and deep space communications. In particular, for the latter application, it is desirable to design a horn that has a nearly perfect circularly symmetric pattern (i.e., identical E- and H-plane patterns), with zero or low cross-polarization, and at the same time achieves a specified beamwidth and a low return loss at the design frequency range. A parametric study of the corrugated horns, however, shows that the objective function relating the pattern shape, beamwidth and return loss is a nonlinear function of the corrugation dimensions and has many local optima. As a result one has to resort to a global optimization technique such as Evolutionary Algorithms for a successful design of these antennas.

Using these techniques, extremely fast and efficient design and synthesis procedures can be implemented, sometimes resulting in highly unusual designs which would otherwise be extremely difficult, if not impossible, to achieve. Among the difficulties encountered in non-automated design by analysis only are that a single input parameter simultaneously affects several output characteristics (pleiotropy) while a single output characteristic is determined by the simultaneous interaction of many input parameters (polygeny).

Corrugated horn antennas are frequently used as the feed elements in ground-based reflector antennas for satellite and deep space communications. In particular, for the latter application, it is desirable to design a horn that has a nearly perfect circularly symmetric pattern (i.e., identical E- and H-plane patterns), with zero or low cross-polarization, and at the same time achieves a specified beamwidth and a low return loss at the design frequencies. A parametric study of the corrugated horns, however, shows that the objective function relating the pattern shape, beamwidth and input return loss is a nonlinear function of the corrugation dimensions and has many local optima. As a result one has to resort to a global optimization technique such as Evolutionary Algorithms for a successful design of these antennas.

Evolutionary algorithms differ substantially from more
traditional search and optimization methods. The most significant differences are:

i) They search a population of points in parallel, not a single point.

ii) They do not require derivative information or other auxiliary knowledge; only the objective function and corresponding fitness levels influence the directions of search.

iii) They use probabilistic transition rules, not deterministic ones.

iv) They are generally more straightforward to apply.

v) They can provide a number of potential solutions to a given problem. The final choice is left to the user. Thus, in cases where the particular problem does not have one individual solution, as in the case of multi-objective optimization and scheduling problems, the evolutionary algorithm is ideally suited for identifying these alternative solutions simultaneously. And finally,

vi) Due to their inherently parallel nature, evolutionary algorithms can be developed to speed up the computation by harnessing the power of massively parallel processing computers.

The Evolutionary Algorithms (EAs) are in general multi-agent stochastic search methods that rely on a set of variation operators to generate new offspring population. A selection scheme is then used to probabilistically advance better solutions to the next generation and eliminate less-fit solution according to the objective function being optimized. Among the three paradigms of EAs, namely, Genetic Algorithms (GA), Evolutionary Programming (EP) and Evolution Strategies (ES), GA and EP have been successfully applied to the design and optimization of various antenna and microwave structures [1,2,3,4].

The variation operator used in GA is a combination of crossover and mutation with the former being the main mechanism of change. The selection of the crossover and mutation probabilities is rather arbitrary and they are not adapted during evolution. EP, however, models the evolution at the species level, thus its variation operator is entirely based on mutation where adaptive and/or self-adaptive techniques exist for adapting the parameters of mutation operator during the evolution process. Mutation-based reproduction process in EP, coupled with the fact that unlike the conventional GA, EP works directly with continuous parameters, provides a versatile tool in design of the problem specific variation operators for multi-parameter antenna optimization, and easy integration with available apriori knowledge about the problem.

In this work we have used an EP algorithm with a Gaussian mutation operator to optimize pattern of a corrugated circular horn subject to various constraints on return loss and antenna beamwidth. A software code, based on generalized scattering matrix and mode-matching technique [5], which has been developed and modified at JPL over many years, is used for the analysis of the corrugated horn and the calculation of the radiated far field from the horn. Examples on design synthesis of a 45 section corrugated horn, with a total of 90 optimization parameters, are presented. The initial design for the horn, as shown in Figure 1, is generated using various guidelines in the literature [6,7] and by implementing a simple MATLAB program.

2. APPLICATION OF EP TO HORN DESIGN

For optimization purposes the N-section corrugated horn in Figure 1 is mathematically represented as a vector of length \( n = 2N \):

\[
\bar{X} = [r_1, r_2, \ldots, r_N; d_1, d_2, \ldots, d_N]^T
\]

where \( r_i \) and \( d_i \) are radius and length of the \( i \)-th corrugated segment, respectively. For the minimization of the difference between the E- and the H-plane co-polar patterns, subject to the constraints on the beamwidth and the overall return loss, we construct the fitness function as,

\[
F(\bar{X}) = \frac{1}{M_{\theta}} \sum_{i=1}^{M_{\theta}} \left[ E(\theta, 0^\circ) - E(\theta, 90^\circ) \right] + \alpha_1 \left[ E(\theta_1, 0^\circ) - q_1 \right] + \alpha_2 \left[ q_2 - E(\theta_2, 0^\circ) \right] + \beta \left( S_{11} - S_{\text{opt}} \right)
\]

with

\[
\alpha_1 = \begin{cases} w_1 / M_{\theta} & \text{if } q_1 \leq E(\theta_1, 0^\circ) \\ 0 & \text{otherwise} \end{cases}
\]

\[
\alpha_2 = \begin{cases} w_2 / M_{\theta} & \text{if } E(\theta_2, 0^\circ) \leq q_2 \\ 0 & \text{otherwise} \end{cases}
\]

in which \( E(\theta, \phi) \) is the normalized co-polar pattern in dB obtained by the application of the mode matching code already mentioned.. \( M_{\theta} \) in the first term is the number of elevation angles, \( \theta \), sampled in the interval \([0, \theta_{\text{max}}]\), in which we require a near circularly symmetric pattern. The second and third terms in (2) penalize all the solutions that violate the constraint, \( q_1 \leq E(\theta_1, 0^\circ) \leq q_1 \), on the normalized gain value at \( \theta \), while the last term penalizes those that violate the constraint, \( S_{11} \leq S_{\text{opt}} \), on the return loss. The weighting factors \( w_1, w_2 \) and \( \beta \) are selected such that to prioritize the influence of various constraints on the fitness function.

To optimize vector \( \bar{X} \) in (1), we apply a continuous parameter meta-EP. The process consists of five basic steps: initialization, fitness evaluation, mutation, tournament and selection [8,9]. In particular, an initial population of \( \mu \) individuals is formed through a uniform random or a biased distribution. We consider each individual to be a pair of real-valued vectors, \((\bar{x}, \bar{y})\), \( \forall i \in \{1, \ldots, \mu\} \) where \( \bar{x} = [x_1, x_2, \ldots, x_{\nu}] \) and \( \bar{y} = [y_1, y_2, \ldots, y_{\nu}] \) are the \( n \)-dimensional solution and its corresponding strategy parameter (variance) vectors,
respectively. The variables are initialized based on the user-specified search domains, $\bar{x}_i \in \{x_{\text{min}}, x_{\text{max}}\}$, which may be imposed at this stage. A meta-EP algorithm is now implemented by generating a single offspring $(\bar{x}', \eta')$ from each parent $(\bar{x}, \eta)$ according to:

$$x'_i(j) = x_i(j) + \sqrt{\eta_i(j)} N_j(0,1)$$

$$\eta'_i(j) = \eta_i(j) e^{t_i N(0,\tau) + \tau N(0,\nu)}$$

for $j = 0,1,2,...,n$, where $x(j)$ and $\eta(j)$ are the jth components of the solution vector and the variance vector, respectively. $N(0,1)$ denotes a one-dimensional random variable with a Gaussian distribution of mean zero and standard deviation one. $N_j(0,1)$ indicates that the random variable is generated anew for each value of $j$. The scale factors $\tau$ and $\tau'$ are commonly set to $\sqrt{2n}$ and $\sqrt{2n}$, respectively, where $n$ is the dimension of the search space.

3. **Numerical Results**

As an example, we have optimized a 45-segment corrugated horn. The geometry of the initial structure, before optimization, is shown in Figure 1. The population size and the number of opponents in the tournament selection of EP were set to $n = 10$ and $q = 4$, respectively. To optimize the X vector in (1), the radii and lengths of the sections were randomly initialized in the search domains $0.95r_0 \leq \eta_i < 1.05r_0$ and $0.7d_0 < d_i < 1.3d_0$, where $r_0$ and $d_0$ are the radius and length of the i-th segment of the initial structure, respectively. The strategy parameters were initialized to $(x_{\text{max}}-x_{\text{min}})/6$ and kept above a lower bound of $10^{-6}$ during the self-adaptations in (4). Two cases are considered here. In each case 200 generations were performed.

In Case I, the optimization was performed subject to the constraint on the return loss ($<-40$ dB) only, i.e. $\alpha = 0$ in (2), and with $M_0 = 60^\circ$, corresponding to a near circular symmetric pattern up to an elevation angle of 60 degrees. The Fitness-value trajectory of the best overall population member for Case I is shown in Figure 2.

The optimization was performed at the frequency $f = 8$ GHz. Figure 3 and 4 show the E- and H-plane far-field patterns and the difference between them, respectively. The corresponding patterns for the initial structure are also included for comparison.

Figure 5 shows the S11 versus frequency for the initial as well as the optimized horn at 8 GHz. As can be seen the optimization has resulted in a return loss of about $-50$ dB and an almost perfect circularly symmetric pattern at the design frequency.

The geometry of the final optimized structure for the 8 GHz case is shown in Figure 6. The narrow band of the optimized design at 8GHz and the "non-smooth" variation of the corrugations can be attributed to the fact that the original design has a better match and bandwidth around 9.5 GHz while optimization is performed around 8 GHz.

A similar optimization was performed at 9.5 GHz, which is closer to the best performance location of the original horn. The result is shown in Figure 7. As can be seen, this optimization results in a much wider bandwidth and is indeed very close to the original non-optimized case, as may be expected, but only smoother. Similarly, a smoother variation of the corrugations occurs which is not shown.

In Case II, the optimization was performed at $f = 9.5$ GHz. In this case the pattern was optimized with $M_0 = 45$, subject to the constraints of $S_{11} < -40$ dB and the normalized field, $-21$ dB $\leq E(\theta_p = 45^\circ, \phi) \leq -19$ dB. Figures 8 shows the E- and H-plane far-field patterns of the optimized horn while Figure 9 shows the frequency variation of $S_{11}$, and Figure 10 presents the geometry of corrugated horn after optimization in this case.
Figure 3. Comparison of horn patterns in two orthogonal planes before & after optimization, Case I.

Figure 6. Geometry of corrugated horn after optimization, at 8GHz, Case I.

Figure 4. Pattern difference in the two planes before & after optimization, Case I.

Figure 7. Input $S_{11}$ as a function of frequency for the horn before and after optimization at 9.5GHz, Case I.

Figure 5. Input $S_{11}$ as a function of frequency for the horn before and after optimization at 8GHz, Case I.

Figure 8. Comparison of horn patterns in two orthogonal planes before & after optimization at 9.5 GHz, Case II.
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4. CONCLUSIONS

In this paper we have shown that the evolutionary programming techniques can be successfully applied to the problem of corrugated horn design. Many additional results will be shown at the conference. The next step already being worked on, is the parallelization of the optimization program on a massively parallel computer such as SGI Origin 2000 at JPL. The present work was performed on the JPL CRAY SV1 and takes many hours of computation, which can be substantially reduced by parallelization. The parallel code will be applied to the design multi-frequency X/Ka feed horns of the JPL/NASA Deep Space Network (DSN) reflector antennas.
Ahmad Hoorfar is an associate professor of electrical engineering at Villanova University, PA. He received M.S. and Ph.D. degrees in electrical engineering from the University of Colorado at Boulder, in 1978 and 1984, respectively. From 1984-1986 he was a post-doctoral research associate in the Electromagnetics Laboratory at the University of Colorado. In 1986 he became a research faculty in the NSF center for Microwave/Millimeter-waves Computer-Aided Design (MIMICAD) in Boulder. Since 1988 he has been with Villanova University where he is now an associate professor of electrical engineering, program director of the ECE graduate program and director of the Villanova's Antenna Research Laboratory. His present research interests include electromagnetic field theory, microwave and millimeter-wave antennas and circuits, numerical methods, and evolutionary computational techniques. He was the chair of the joint Antennas and Propagation/Microwave Theory and Techniques (AP/MTT) Chapter of the IEEE Philadelphia Section from 1993 to 1995, and was the General Chairman of the Twelfth and Thirteenth IEEE Benjamin Franklin Symposiums in Microwave and Antenna Technology held in 1994 and 1995, respectively. He is a senior member of IEEE and a member of the International Union of Radio Science (URSI).

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