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DESIGN OF CIRCULAR POLARIZED ANTENNAS USING GENETIC ALGORITHM BASED ON CURVED WIRE ANALYSIS

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Abstract—An efficient Genetic Algorithm / Method of Moments formulation using curved segmentation (GA/MoM-CS) to optimize the curl and helical antenna structures is implemented and employed to design and optimize complex helical wire antennas such as Tapered Single Helical Antenna (TSHA), Single Elliptical Curl Antenna (SECA) and Tapered Quadrifilar Antenna (TQFA) mounted over infinite ground plane. An optimum gain, VSWR and circular polarization properties that make these antennas suitable to be used in satellite communications systems are obtained. The numerical results show that the hybrid GA/ MoM-CS produces superior antenna designs for such complex geometries with reduced computation time compared to codes that uses straight wire segmentations.

Keywords- Method of Moments, curved segmentation, genetic algorithm, circular polarization.

I. INTRODUCTION

Many satellite and wireless communications systems require high efficiency, lightweight and low cost circularly polarized (CP) antennas. Due to the resonant characteristics, circular microstrip antennas have narrow bandwidth. However, the tapered helical, curl and quadrifilar are nonresonant antennas that radiate circularly polarized waves and they have wider bandwidth. Designing these kind of complex geometrical antennas is typically a slow haphazard process. Consequently, a numerical model and a numerical optimization of that model are important for developing realistic designs. Most of previous work for GA / MoM formulation consider straight wires for fitness function calculations [1] and [2]. In this paper an efficient MoM algorithm is described using curved segmentation [3] to model the curved geometrical antennas, which is then run under a GA optimization routine to design antenna with specific performance attributes similar to [4]. The use of curved segment keeps the computational time manageable throughout the many runs required in this evolutionary procedure. The requirement of fewer segments gives the curved segment model a speed advantage therefore important when the MoM is combined with GA for optimization problems. The organization of the paper is as follows: In section II, GA and the MoM integration is descried. In section III the results of three circular polarized designs using the developed code are illustrated and discussed. Finally, conclusions are derived in section IV.

II. GA AND THE MOM-CS INTEGRATION

The GA/MoM-CS integration program is developed to utilize the numerically calculations for the fitness function of the GA program by curved wire segmentation formula [3].

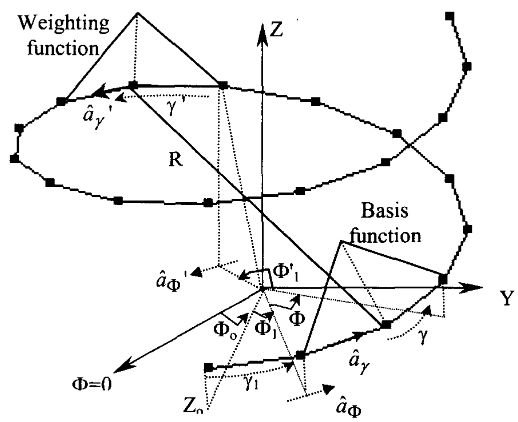

Fig. 1. Basis and Weighting functions on curved segments of helical antenna

The solution for the current on general antenna geometry begins with the electric field integral equation (EFIE) is obtained by computing the impedance matrix elements it can be expressed in terms of the radial horizontal angle Φ instead of the contour length γ as follows:

$$Z_{ms} = j\omega\mu\Big(\int_{\Phi'}\int_{\Phi}[f_m(b'_m\,\Phi)f_s(b'_s\,\Phi')(\hat{a}_{\gamma}\cdot\hat{a}_{\gamma'}) - \frac{1}{k^2}f_m'(\gamma)\big|_{b'_m\Phi}\,f_s'(\gamma')\big|_{b'_s\Phi'}]\,g(R)b_s'b_m'\,d\Phi\,d\Phi' \qquad (1)$$

where g(R) is the Green's Function, $\gamma' = b'_s\,\Phi'$ and $\gamma = b'_m\,\Phi$ as shown from Fig. 1. basis and test functions are

$$f_s'(\gamma')\big|_{b'_s\Phi'} = \frac{\pm 1}{b'_s\Phi'_s} \text{ and } f_m'(\gamma)\big|_{b'_m\Phi} = \frac{\pm 1}{b'_m\Phi_m} \qquad (2)$$

where Φ'_s and Φ_m are the radial horizontal angles covering the segments lengths over the basis and test functions, γ_s and γ_m respectively, assume using equal segment lengths. The dot product $(\hat{a}_{\gamma}\cdot\hat{a}_{\gamma'})$ and the distance R between the source and the observation points on curved segments in terms of Φ and Φ' must be defined. The dot product term is given by:

$$\hat{a}_{\gamma}\cdot\hat{a}_{\gamma'} = \cos^2(\alpha)\sin(\Phi+\Phi_1+\Phi_o)\sin(\Phi'+\Phi'_1+\Phi_o) + \cos^2(\alpha)\cos(\Phi+\Phi_1+\Phi_o)\cos(\Phi'+\Phi'_1+\Phi_o) + \sin^2(\alpha) \qquad (3)$$

The distance R can be written as

$$R = \sqrt{\begin{matrix}(b\cos(\Phi + \Phi_1 + \Phi_o) - b\cos(\Phi' + \Phi'_1 + \Phi_o))^2 \\ + (b\sin(\Phi + \Phi_1 + \Phi_o) - b\sin(\Phi' + \Phi'_1 + \Phi_o))^2 \\ + (\frac{p\Phi}{2\pi} - \frac{p\Phi'}{2\pi})^2 + a^2\end{matrix}} \quad (4)$$

where Φ_1 and Φ'_1 are the starting radial angles for the source and observation curved segments, as shown in Fig. 2. Substituting Equations (2), (3) and (4) in Equation (1), thus the integral will be a function of only Φ and Φ'. A Fortran computer subroutine was written to solve this integral by dividing it into real and imaginary parts of the Green's function. The integral with respect to Φ' is solved numerically by using a Gaussian-Legendre Formula for 8-16 points, while two integrals over Φ for both real and imaginary parts are also solved numerically, that solves singular or pseudo-singular integral adaptively within 10^{-6} relative error. In this case, approximated kernel is used, thus pseudo-singular integrals are considered.

Using this MoM-CS significantly reduces the computational cost in the optimization process compared to previously reported GA/MoM approaches. In any optimization problem, candidate solutions are evaluated according to a fitness function. For antennas used in satellite systems, the optimization criteria targeted is a good CP main lobe at a specific angle with respect to the antenna axis with good gain and low VSWR (good matching). The objective (fitness) function for one iteration (chromosome) involves solving an electric field integral equation with the previously described curved segment formulation. The GA code initializes a random sample of individuals with different parameters that maps the antenna geometrical parameters that are optimized by evolution via survival of the fittest. That is calculated using the numerical technique of MoM-CS. The selection scheme used is tournament selection with a shuffling technique for choosing random pairs for mating. The routine includes binary coding for the individuals, jump mutation, creep mutation, and uniform crossover. Mutation caused small random changes in chromosomes so that the search doesn't trap in a local optimum. The process is repeated till the algorithm converges.

III. SIMULATIONS AND NUMERICAL RESULTS

Our numerical examples to illustrate the efficiency of the hybrid GA/MoM-CS code are designing three different complex helical structures to obtain circular polarization properties with a high gain and minimum VSWR values at the same time. The antennas are Tapered Single Helical Antenna (TSHA), Single Elliptical Curl Antenna (SECA) and Tapered Quadrifilar Antenna (TQFA) mounted over infinite ground plane. For these antennas, the GA/MoM-CS is allowed to search for the optimum configuration that will produce the desired properties. The fitness function of GA linked with MoM-CS to evaluate the gain, axial ratio and VSWR in terms of the optimization parameters is given as:

$$\frac{1}{NM}\sum_f\left(\sum_\theta A\times \mathrm{gain}(f,\theta)+\sum_\theta B\times \mathrm{Axia}(f,\theta)\right)+\frac{N\times C}{\sum_f \mathrm{VSWR}(f)}$$

where A, B and C are constants chosen by user, N is the number of frequency steps, f is the frequency. M is the number of elevation angle steps, θ is the elevation angle. We chose to weight the axial ratio and the gain more heavily than the VSWR as it is possible to enhance the VSWR by using a matching technique. This fitness Function is used with a constrain states that the average VSWR(f) lies between 1 and 10 and if it is not satisfied the fitness function resets to zero and the population is discarded. In this examples, 1.8 GHz was used here as a convenient operating frequency because it falls close to the transmitting and receiving bands (L and S band) of the LEO personal satellite systems. However, dual band optimization could be performed.

A. Tapered Single Helical Antenna (TSHA):

Fig. 2 defines the basic geometric parameters of the TSHA over the ground plane on elevation and side view angles. The helix has overall length h_l and tapers from a radius of r_o at the base to r_l at the top, at a taper angle β and a pitch p. The wire has a radius r and a tilted wire feeds the helix over the ground with a height h_2. The six parameters p, h_l, r_o, r_l, r and h_2 are encoded each into 6 bit genes. The parameters of the GA are number of population = 8, discard rate = 0.5 and mutation rate =0.1, number of generations = 500. That means that for each run the GA routine require 4000 evaluations of the fitness function obtained by the numerical MoM-CS technique. The gain and axial ratio are samples every 30-degree in elevation. From θ =-90 to 90 for azimuth angle ϕ = 0 at frequency 1800 MHz. It is found that 30-degree increments yield better circular polarization performance than 5, 10 and 20-degree sampling steps. Then the gain and AR is averaged over the angles and frequencies for dual and tri band designs. The six optimization parameters are as shown in the table I

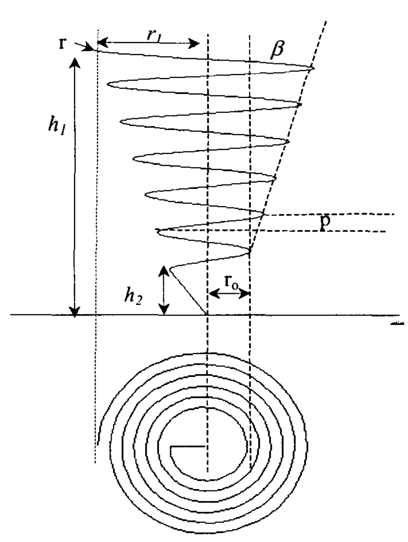

Fig. 2. Tapered Single Helical Antenna (TSHA) configuration and optimization parameters

The genes used along with their permitted range variations are shown in Table I. The highest ranked chromosome has characteristics determined by the genes in the right hand column of the table.

TABLE I
TSHA optimization Genes and optimum results

Genes	Range		Optimum
	From	To	
Pitch	0.001	0.05	0.028222
Total length	0.001	0.05	0.049222
Base radius	0.001	0.05	0.025111
Top radius	0.001	0.05	0.028222
Wire radius	0.001	0.005	0.001063
Feeder height	0.01	0.05	0.013174
Av. gain =2.05	Av. AR=0.57		VSWR=3.25

The optimized average gain, average axial ratio from –90 to 90 and VSWR over the operating band for the best chromosome are illustrated in the last row in Table I. Clearly these values are acceptable and show good circular polarization properties. Other ranked individual chromosomes may have higher values for one of these three-design parameters gain; but the chose one has the highest fitness function for the three-scaled values combined together.

B. Single Elliptical Curl Antenna (SECA)

The type of curl antenna investigated here is elliptical spiral antenna with a single arm fed by a 5 cm prob against infinite ground plane. The general configuration of the SECA is shown in Fig. 3 It is made of a thin wire of radius r and is bent and curled above the ground plane. The antenna is composed of a straight vertical and horizontal and a curled horizontal section. Generally, the curled section can take the shape as shown in Fig 2.

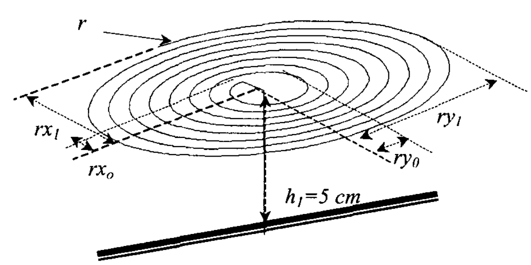

Fig. 3. General Configuration of Elliptical curl antenna and top view with optimization parameters

The curved equation of the curled section is: $x = a\,\phi\cos(\phi)$, $y = a\,\phi\sin(\phi)$, where a and b are constants if a=b this antenna will be a circular curl antenna. ϕ is the winding angle starting at ϕ_o, and ending at $\phi_l=\phi_o+2\pi\times$ (number of turns). A range of parameters is assigned to find the design that gives the optimum characteristics. These parameters are as shown in the figure N: number of turns, rx_0: inner radius in x-axis: rx_l: outer radius in x-axis, ry_0: inner radius in y-axis, ry_l: outer radius in y-axis and r: wire radius. The GA/MoM-CS described earlier is used to optimize the values. Different segments were tested to evaluate the stability of the results. The constraints on the designed parameters are given in table II. The maximum antenna dimension is chosen to be 10 cm in radius this value can be changed depending on the required volume. The program initializations and the chromosomes structures are similar to the previous TSHA runs. Also, the same fitness function is applied to obtain the minimum VSWR, maximum average axial ratio and maximum average gain over the ±90 angular angles from the zenith in the x-z elevation plane sampled each 30-degree at 1800 MHz. The results of GA/MoM-CS for the optimum design configuration and best fitness functions values are illustrated at the left column and bottom row of Table II. Good circular polarization properties with nearly similar values of gain, AR and VSWR to previous antenna are obtained. It is found that the best design has the same value for the outer radius in x and y-axis. It means that optimizing the elliptical curl geometry yield to a circular structure antenna.

TABLE II
SECA optimization Genes and optimum results

Genes	Range		Optimum
	From	To	
Number of turns	1	10	4
Inner radius: x-axis	0.001	0.01	0.001143
Outer radius: x-axis	0.015	0.1	0.098651
Inner radius: y-axis	0.001	0.01	0.001429
Outer radius: y-axis	0.015	0.1	0.098651
Wire radius	0.001	0.005	0.003731
Av. Gain =6.2	Av. AR=0.55		VSWR=7.4

C. Tapered Quadrifilar Antenna (TQFA):

One of the best candidates for the satellite applications is the quadrifilar antenna. Thus, Tapered Quadrifilar Antenna (TQFA) with nonuniform radius is chosen to be optimized by the developed GA/MoM-CS code. The TQFA of Fig. 4 has the following geometrical parameters: r_o, r_l, r, p and h_2 respectively for base radius, top radius, wire radius, pitch and total length.

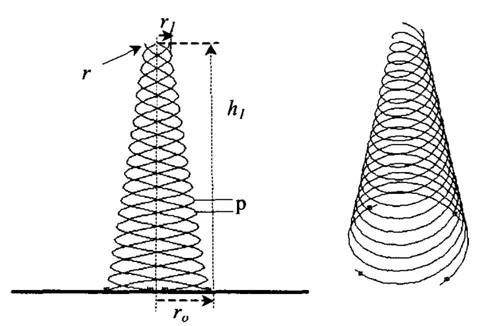

Fig. 4. Tapered quadrifilar helical antenna 3D and side view with optimization parameters.

The above five parameters are optimized using GA/MoM-CS employing 30 bit chromosomes, 8 population and 500 generation. The rest of the GA parameters are the same as the previous two cases. The Quadrifilar structure with its four helices required many basis functions to represent the vector direction of the current along the meandering wire. That means more computationally time and memory is required for this structure. However, the results of the best design shown in Table III left column and last row indicates that this antenna has high average axial ratio = 0.71 for the zenith coverage and it better than the previous two designs. The average computational run time is about 1 h on a Pentium IV processor.

TABLE II
TQFA optimization Genes and optimum results

Genes	Range		Optimum
	From	To	
Pitch	0.01	0.02	0.018095238
Total length	0.02	0.05	0.044761905
Base radius	0.001	0.05	0.029777778
Top radius	0.001	0.05	0.008777778
Wire radius	0.001	0.005	0.004936508
Av. Gain =2.11	Av. AR=0.71		VSWR=4.63

Finally, the best three designs for the previous case studies are compared together. Fig. 5 shows the axial ratio verse the elevation angle theta for the three antennas mounted on infinite ground plane at 1800 MHZ and at phi=0. Generally, true circular polarization is achieved for wide angular coverage. The polarization purity is acceptable for the axial ratio under 3 dB level. Thus TSHA has good circular polarization characteristics for the θ in the range between -37° and 65°. However, this range is between -45° and 55° for SECA. The best result is found to be for the TQHA that provides low axial ratio in the symmetric range ±77°.

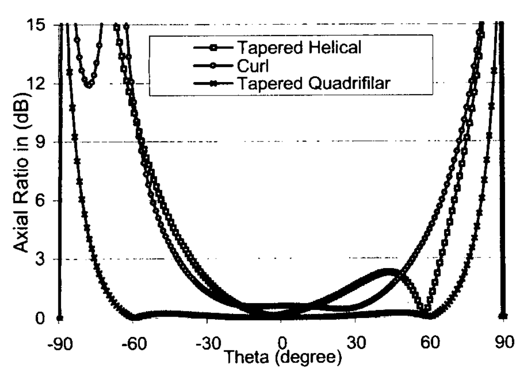

Fig. 5. Computed axial ratio verse the elevation angle theta for the three antennas mounted on infinite ground plane at 1800 MHZ and at phi=0.

Fig. 6 illustrates the power gain pattern for the elevation cut corresponding to azimuth angle of 0°. We note that for the three cases the coverage is excellent over most of the ±90° zenith range. The previous result indicates that TQHA gives the best circular polarization and that the developed GA/MoM-CS performs well in designing such antennas.

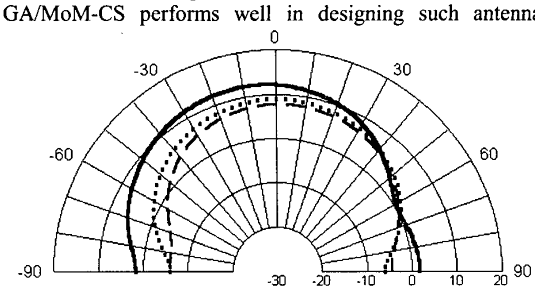

Fig. 6. Power gain in the xz plane for the three antennas at 1800 MHz. (—— SECA, …… TSHA, - - - TQHA)

VI. CONCLUSION

Method of Moments using curved segmentation running under genetic algorithm is successfully used to optimize three different Tapered Single Helical Antenna (TSHA), Single Elliptical Curl Antenna (SECA) and Tapered Quadrifilar Antenna (TQFA) mounted over infinite ground plane. Obtaining good circular polarization suitable for satellite applications in a wide zenith band with a high gain and minimum VSWR was the fitness function that is evaluated numerically. Such combination of antenna characteristics would be difficult to achieve through extensive runs for MoM alone especially for complex helical and curl structures. It is concluded that the efficient GA/MoM-CS holds much promise in the development of new designs for satellite antenna applications with its circular polarization requirements.

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