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

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Abstract—An efficient Method of Moments formulation using curved segmentation (MoM-CS) to model curl and helical antenna structures is implemented and compared to straight wire segmentation code. This integral equation solver is then employed in conjunction with genetic algorithm (GA) 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 use 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 the 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 an 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: curved wire segmentations formulation is reported for the analysis of helical structures with its validation results in section II. In section III, GA and the MoM integration is described. In section IV the results of three circular polarized designs using the developed code are illustrated and discussed. Finally, conclusions are derived in section V.

II. CURVED WIRE SEGMENTATIONS

This section shows a novel formulation of MoM for simulation of helical structures with limited number of segments using the newly developed curved segment code. A polynomial basis current function with a Galerkin solution for both curved wire segments is applied and implemented. Helical antenna examples are studied using curved wire segments modeled using a newly implemented formulation and compared to straight wire code results.

A. Helical Antenna Description and Curved-Segment Formulation

The curved wire segment has the advantage of correcting the errors produced from integral current equations and junctions of straight segments. In this section the current distribution is assumed uniform over the wire surface transverse to the axis and therefore the approximated kernel solution is used. Curved wire geometry like the helical antenna is considered, the helical structure and its parameters being shown in Fig. 1. Z_o is the starting height of the helix, b is the helix radius and p is the pitch angle on the helix. Φ is the radial angle for the projection of helix points on the horizontal plane $z = 0$ and Φ_o is the initial radial angle describing the location of the starting point of the helix. The (x_h, y_h, z_h) coordinates of any point on the helix can be given by the following

$$x_h = b \, \cos\left(\Phi + \Phi_o\right),$$

$$y_h = b \, \sin\left(\Phi + \Phi_o\right), \, z_h = \frac{p \, \Phi}{2\pi} + z_o \qquad (1)$$

where $(0 < \Phi_o < 2\pi)$. As shown in Fig. 2 the length of one turn, L, and the pitch angle, α, can be written as $L = 2\pi b'$ and $\alpha = \tan^{-1} \dfrac{p}{2\pi b}$ where b' is the modified helix radius, defined as:

$$b' = \sqrt{b^2 + (\frac{p}{2\pi})^2} \quad . \qquad (2)$$

The vector can describe the helical contour:
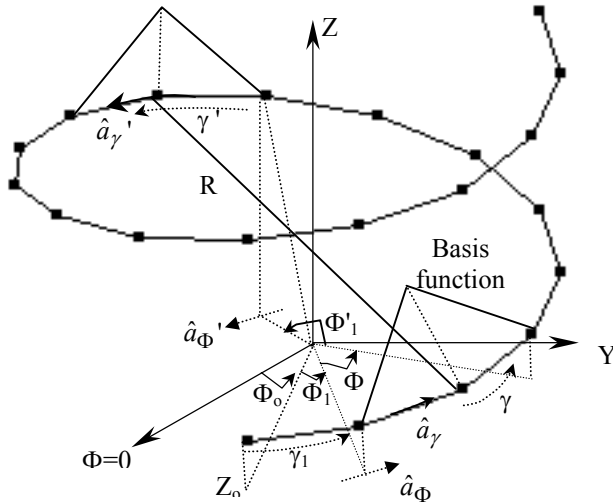
$$\hat{r} = x_h \hat{a}_x + y_h \hat{a}_y + z_h \hat{a}_z \, .$$

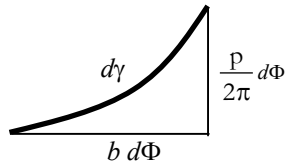Fig. 1. Basis and weighting functions on curved segments of helical antenna.

Fig. 2. Part of one curved segment showing γ and Φ.

The unit vector, $\hat{a}_\gamma$, which describes the contour of the helix is defined by

$$\hat{a}_\gamma = \frac{\partial}{\partial \Phi} \hat{r} \, / \, \left| \frac{\partial}{\partial \Phi} \hat{r} \right| . \qquad (3)$$

Then it may be written as:

$$\hat{a}_\gamma = -\cos\alpha \sin(\Phi + \Phi_o) \, \hat{a}_x$$
$$+ \cos\alpha \cos(\Phi + \Phi_o) \, \hat{a}_y + \sin\alpha \, \hat{a}_z \, .$$

The current is obtained on this general helical antenna geometry by using Galerkin type moment method for the electric field integral equation (EFIE). The surface current $J_s(r')$ is approximated as a line current given by $I(\gamma')\hat{a}_{\gamma'}$, where $\hat{a}_{\gamma'}$ is defined at the source point and follows the contour of the helix. Then, for Galerkin type functions the typical input impedance term can be written as:

$$Z_{ms} = j\omega\mu \iint_{\gamma' \, \gamma} \left[\begin{array}{c} f_m\left(\gamma\right) f_s\left(\gamma'\right)\left(\hat{a}_\gamma \cdot \hat{a}_{\gamma'}\right) \\ -\dfrac{1}{k^2}\nabla_\gamma.f_m\left(\gamma\right)\nabla_{\gamma'} \cdot f_s\left(\gamma'\right) \end{array} \right] g\left(R\right) d\gamma \, d\gamma' .$$

This integral depends only on γ and γ', the lengths of the wire contours for the source and the observation points and their corresponding $\hat{a}_\gamma$ and $\hat{a}_{\gamma'}$. The basis and weighting functions for the helical antenna problem are chosen as two segments with first order polynomial (linear) functions, as shown in Fig. 1, can be given by:

$$f_s(\gamma') = \begin{cases} \dfrac{\gamma'}{\gamma'_{s1}} & \gamma' < \gamma'_{s1} \\ 1 - \dfrac{\gamma'}{\gamma'_{s2}} & \gamma' < \gamma'_{s2} \end{cases}, \quad f_m(\gamma) = \begin{cases} \dfrac{\gamma}{\gamma_{m1}} & \gamma < \gamma_{m1} \\ 1 - \dfrac{\gamma}{\gamma_{m2}} & \gamma < \gamma_{m2} \end{cases} \quad (4)$$

where γ_{m1} and γ_{m2} are the lengths of the two segments of the weighting function and γ'_{s1} and γ'_{s2} are the lengths of the two segments of the basis function.

B. Computation of the Integral Used in the Impedance Matrix Elements for Curved Segments

For 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:

$$V_{factor} = f_m\left(b'_m\Phi\right) f_s\left(b'_s\Phi'\right)\left(\hat{a}_\gamma.\hat{a}_{\gamma'}\right)$$

$$-\frac{1}{k^2} f'_m\left(\gamma\right)\Big|_{b'_m\Phi} f'_s\left(\gamma'\right)\Big|_{b'_s\Phi'}$$

$$Z_{ms} = j\omega\mu \int_{\Phi'} \int_{\Phi} \left[V_{factor}\right] g\left(R\right) b'_s \, b'_m d\Phi d\Phi' \quad (5)$$

where $\gamma' = b'_s \, \Phi'$ and $\gamma = b'_m \, \Phi$ as shown from Fig. 2 while b'_m and b'_s are defined in equation (1), and

$$f_s'(\gamma')\Big|_{b',\Phi'} = \frac{\pm 1}{b_s'\Phi_s'} \text{ and } f_m'(\gamma)\Big|_{b_m'\Phi} = \frac{\pm 1}{b_m'\Phi_m} \qquad (6)$$

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, assuming the use of curved segments with equal lengths. Before equation (3) can be implemented, the dot product $\left(\hat{a}_\gamma \cdot \hat{a}_{\gamma'}\right)$ 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:

$$\hat{a}_\gamma \cdot \hat{a}_{\gamma'} = \cos^2(\alpha)\sin(\Phi + \Phi_1 + \Phi_o)\sin(\Phi' + \Phi_1' + \Phi_o)$$
$$+ \cos^2(\alpha)\cos(\Phi + \Phi_1 + \Phi_o)\cos(\Phi' + \Phi_1' + \Phi_o) \quad (7)$$
$$+ \sin^2(\alpha).$$

The distance R can be written as

$$R = \sqrt{\begin{array}{l}\left(b\cos\left(\Phi + \Phi_1 + \Phi_o\right) - b\cos\left(\Phi' + \Phi_1' + \Phi_o\right)\right)^2 \\ + \left(b\sin\left(\Phi + \Phi_1 + \Phi_o\right) - b\sin\left(\Phi' + \Phi_1' + \Phi_o\right)\right)^2 \\ + \left(\frac{p\Phi}{2\pi} - \frac{p\Phi'}{2\pi}\right)^2 + a^2\end{array}} \quad (8)$$

where Φ_1 and Φ_1' are the starting radial angles for the source and observation curved segments, as shown in Fig. 1. Substituting equations (6), (7) and (8) into equation (5), makes the integral a function of Φ and Φ' only. 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, the approximated kernel is used, thus pseudo-singular integrals are considered.

The mathematical analysis and numerical solutions given in this section were simulated by the (MoM-CS) computer program. The results obtained from this MoM-CS code are compared with equivalent ones from the 'Numerical Electromagnetics Code' (NEC). It should be stated that NEC has different basis and weighting functions for its solution from those used in (MoM-CS). Also, unlike (MoM-CS), NEC uses straight wire approximations to model curved wire antennas. An investigation of the current distribution in wire antennas and especially normal-mode helical antennas (NMHA) will be demonstrated. The input resistance is particularly used to test (MoM-CS)

subroutines discussed earlier. Considering a center-fed normal mode helical antenna in free space with the following parameters; helix radius $b = 0.0273\ m$; pitch $p = 0.03646\ m$; number of turns $n = 10$; and wire radius $a = 0.001\ m$. The helix is oriented along the z-axis and it starts from the x-axis ($\Phi = 0$).

Figure 3 shows the convergence plots of input resistance of the specified helix. It is seen that significantly fewer segments are needed when the curved segments of (MoM-CS) are used versus NEC straight wire segments representing the curved helix geometry. For straight wire segments, the accuracy of the thin-wire approximation for a wire of radius a and segment length Δ is acceptable, within 1% error, for the following condition; $8a < \Delta < 0.1\lambda$, while if the extended thin-wire kernel is used $2a < \Delta$ could be used [5]. NEC results are fairly well converged at 401 segments or 40 segments per turn. The (MoM-CS) models with curved segments are stable for numbers of 21 curved segments or 2 segments per turn, so it can be said that the number of segments is reduced by 20 times which means more efficiency in terms of unknowns and computer memory for modeling curved structures. Also one should be careful when modeling curved geometries using straight wire segments to avoid the unstable region when modeling the helix with small numbers of segments (51 segments in this example).

For testing (MoM-CS) over a wide band, the response of the input impedance of the previous ten-turn NMHA is presented in Fig. 4 for input reactance versus the frequency for various pitch distances. The results of 21 segmentations with (MoM-CS) agree well with those calculated using 401 segments with NEC. Three different pitch distances of 0.036, 0.045, and 0.054 m are used with fixed axial length for the helix, which means that the number of turns and the total length of the wire are changed. From the obtained results it can be concluded that MoM-CS routines performs well and the use of curved segments allows accurate modeling especially for normal mode helical antenna.
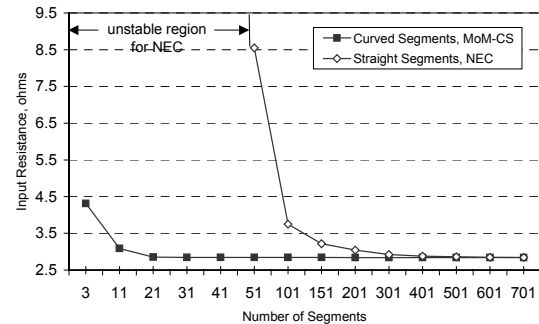

Fig 3. Normal mode center fed helix input resistance convergence versus number of segments.
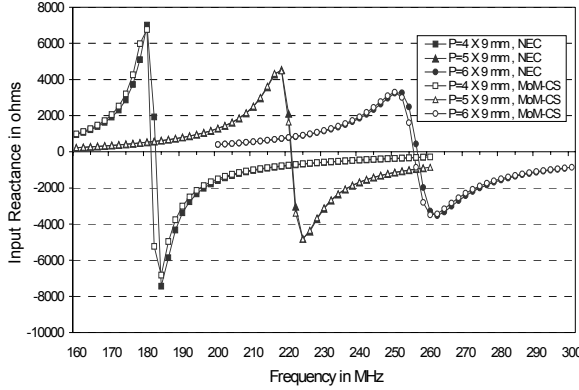
Fig. 4. The input reactance of a ten-turn NMHA for various pitch distances using MoM-CS and NEC.

III. GA AND THE METHOD OF MOMENTS INTEGRATION

The GA/MoM-CS integration program is developed to utilize the numerical calculations for the fitness function of the GA program by curved wire segmentation formula. That significantly reduces the computational cost of the optimization process compared to the MoM approach that uses linear segmentations. Fewer curved basis functions are required for an accurate representation of the spiral or curved contour and current distribution. Moreover, the speeds up of the matrix inversion process for the MoM technique, leading to a reduction in the cpu time and the used memory becomes increasingly important when the code is linked with the GA optimization procedures that need to run the MoM code many times.

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.

IV. SIMULATIONS AND NUMERICAL RESULTS

The efficiency of the developed hybrid GA/MoM-CS code is illustrated by using it to design three different complex helical structures for mobile satellite applications. These antennas are optimized to have good circular polarization properties with a high gain and minimum VSWR values. 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 is obtained by MoM-CS to evaluate the average gain over the elevation angles (Av-gain), average axial ratio over the elevation angles (AR) and average voltage standing wave ratio over the operating frequencies (VSWR) in terms of the optimization parameters is given as:

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

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 constrained such that the average VSWR lies between 1 and 10 and if it is not satisfied the fitness function resets to zero and the population is discarded. For the following examples, 1.8 GHz is selected 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):

Figure 5 defines the basic geometric parameters of the TSHA over the ground plane on elevation and side view angles. The helix has overall length h_1 and tapers from a radius of r_o at the base to r_1 at the top, 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_1, r_o, r_1, 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 requires 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 operating frequency of 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 1
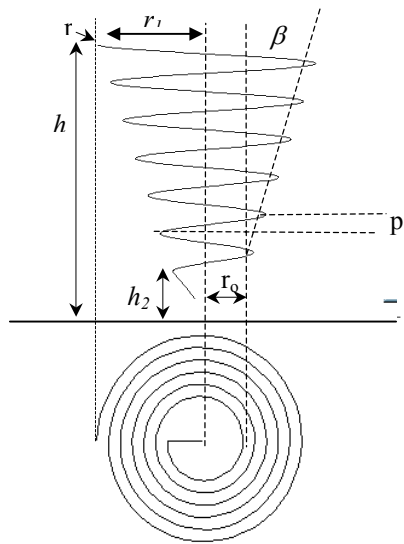

Fig. 5. Tapered Single Helical Antenna (TSHA) configuration and optimization parameters.

The genes used along with their permitted range variations are shown in Table 1. The highest ranked chromosome has characteristics determined by the genes in the right hand column of the table.

Table 1. 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 1. Clearly these values are acceptable and show good circular polarization properties. Other ranked individual chromosomes may have higher values for one of the three-design parameters; but the chosen 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 an elliptical spiral antenna with a single arm fed by a 5 cm prob against infinite perfectly conducting ground plane. The general configuration of the SECA is shown in Fig. 6. 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 6.
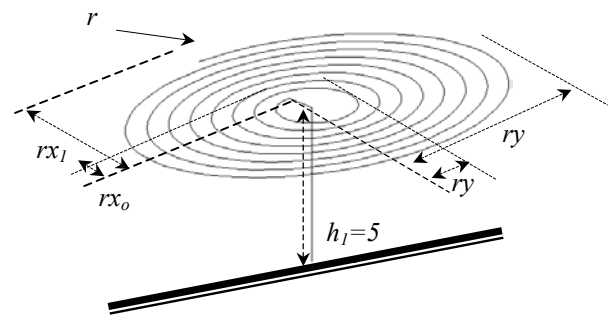

Fig. 6. General Configuration of Elliptical curl antenna and top view with optimization parameters.

The curved equation of the curled section is: x = a ϕ cos(ϕ), y = a ϕ sin (ϕ), 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 $\phi_1=\phi_o+2\pi \times$. A range of parameters is assigned to find the design that gives the optimum characteristics. These parameters are as shown in Fig. 6, where N: number of turns, rx_0: inner radius in x-axis: rx_1: outer radius in x-axis, ry_0: inner radius in y-axis, ry_1: 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 2. The maximum antenna dimension is chosen to be 10 cm in radius that 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 2. Good circular polarization properties with nearly similar values of gain, AR and VSWR to the previous antenna are obtained. It is found that the best design has the same value for the outer radius in x and y-axis, which produces circular curl geometry.

Table 2. 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. 7 has the following geometrical parameters: r_o, r_1, r, p and h_2 respectively for base radius, top radius, wire radius, pitch and total length.
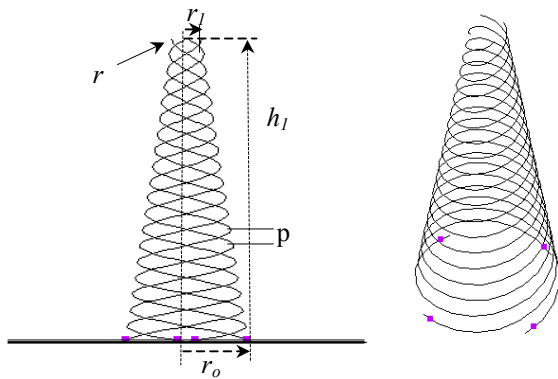

Fig. 7. Tapered quadrifilar helical antenna 3D and side view with optimization parameters.

The above five parameters are optimized using GA/MoM-CS employing 30 bit chromosomes, 8 populations and 500 generations. 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 computational time and memory is required for this structure. However, the results of the optimum designs are shown in the left column and the last row of Table 3.

These results 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 3. TQFA optimization Genes and optimum results

Genes	Range		Optimum
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. Figure 8 shows the axial ratio versus the elevation angle θ for the three antennas mounted on infinite ground plane at 1800 MHz and at φ=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°.
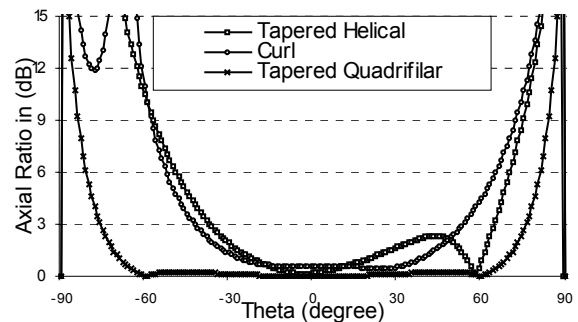

Fig. 8. Computed axial ratio versus the elevation angle. θ for the three antennas mounted on infinite ground plane.

Figure 9 illustrates the power gain pattern for the elevation cut corresponding to azimuth angle of 0°. We note that for these three cases the coverage is excellent over most of the $\pm90^o$ 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.
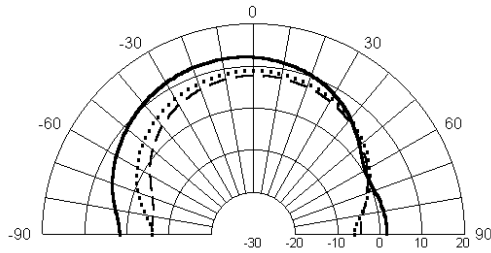

Fig. 9. Power gain in the xz plane for the three antennas at 1800 MHz. (—— SECA, …… TSHA, – – – TQHA).

V. CONCLUSION

Tapered Single Helical Antenna (TSHA), Single Elliptical Curl Antenna (SECA) and Tapered Quadrifilar Antenna (TQFA) mounted over infinite conducting ground plane have been designed using GA with MoM-CS optimization technique. Good circular polarization properties, high zenith gain and minimum VSWR were considered in the evaluation of the numerical fitness function to produce optimum geometrical parameters of these antennas. 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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