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NEC2 Based Optimum Design of Circularly Polarized Axial Mode Helical Antenna with Non-linear Pitch Profile Modeled using Catmull–Rom Spline and Particle Swarm Optimization

S. Santhosh Kumar, Monisha Menon A

Abstract*— This paper presents a novel method for design of circularly polarized axial mode helical antenna with maximum directive gain. In this work helical antenna is modeled by eight parameters - helix radius (a), number of turns (N) and nonlinear pitch profile represented by a Catmull-Rom spline curve. This spline curve consists of six pitch angles, α_1, α_2, α_3, α_4, α_5 and α_6 at six equidistant points along the axial length of the helix. For a given number of turns optimum value of radius and pitch profile is determined for maximizing the gain subject to unity axial ratio. The gain and axial ratio are determined using NEC2 (Numerical Electromagnetics Code) simulation and optimization is performed using Particle Swarm Optimization (PSO). The original NEC2++ source code has been modified to incorporate Catmull-Rom spline modeling and PSO to suite the requirement of this work. Simulated and experimental results show that there is significant improvement in gain characteristics compared to design based on Kraus method which uses constant pitch profile.

Index Terms*— Helical Antenna, Axial mode, Catmull-Rom spline, Method of Moments, Particle Swarm Optimization, NEC2.

I. INTRODUCTION

Helical antennas can operate in one of two principal modes: normal (broadside) mode or axial (or end-fire) mode. Axial mode helical antennas are widely used for satellite and WIMAX communications [1]. Design of axial mode helical antenna by Kraus uses constant pitch profile [2]. The design of axial mode helical antennas with nonlinear pitch profile has been also reported which gives better radiation characteristics [3] [4]. In these works the pitch angle is varied nonlinearly to match phase velocity of electromagnetic wave traveling through antenna, with phase velocity of free space wave interfaced with antenna, thereby increasing gain of helical antenna. The design of such axial mode helical antenna is usually done by trial and error method. Starting with a standard geometry, the geometrical parameters of the helix are adjusted until desired characteristics are obtained. Limitation of such a design is that resulting helical geometry cannot be represented by a simplified mathematical expression. In this paper, a helical antenna with nonlinear pitch profile for simultaneously achieving maximum gain and unity axial ratio is presented. NEC2 is used for simulation of antenna parameters and Particle Swarm Optimization is used for optimization. The Numerical Electromagnetics Code (NEC2) is a popular antenna modeling and simulation software package for wire antennas [5]. NEC models can include wires buried in a homogeneous ground, insulated wires and impedance loads. . NEC2++ is a general public license (GPL) C++ code of NEC2 where users are free to modify the code. Particle Swarm Optimization (PSO), was introduced by Kennedy and Eberhart in 1995 [6] for optimization problems. As PSO is easy to implement, it has rapidly progressed in recent years. The aim of the proposed work is to optimize directive gain of axial mode helical antenna with circular polarization. The circular polarization is characterized by unity axial ratio (*AR*). The pitch profile for the entire helix is represented by a Catmull- Rom spline curve using pitch angles at six equal distant points along the axial length of the helix [7]. In this work for a given number of turns '*N*', the optimum values for helix radius '*a*' and six pitch angles α_1, α_2, α_3, α_4, α_5 and α_6 are determined for maximizing gain (*G*) subject to unity axial ratio. Mathematically it can be represented by the following constraint optimization problem.

Minimize

$$f(a, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6) = \frac{1}{G} + \lambda \left| AR - 1 \right| \qquad (1)$$

where λ is the Lagranges multiplier. This optimization problem is solved using PSO. During optimization process, helix pitch profile is dynamically modified until optimum pitch profile is obtained. Simulated and experimental results shows that the helical antenna modeled by our method gives better gain characteristics compared to classical Kraus design. This paper is organized as follows. Section I is introduction. Section II briefly explains Catmull - Rom spline modeling for nonlinear pitch profile. Section III explains proposed method for optimization of gain subject to unity axial ratio. Section IV discusses results and section V is conclusion.

II. CATMULL–ROM SPLINE MODELING OF NONLINEAR PITCH PROFILE

The pitch profile represents variation of pitch angle with respect to number of turns. The basic idea for representing a non linear helix is to represent pitch profile using a few control pitch angles in view of computational complexity. In this work we have chosen Catmull-Rom splines for modeling

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pitch profile because of its computational simplicity. The interpolation between two control values using Catmull –Rom spline curve requires only four consecutive control values as shown in Fig.1.The curve section between control points α_k and α_{k+1} as shown in Fig. 1 and it is represented by $\alpha(u)$. Where $\alpha(0)=\alpha_k$ and $\alpha(1)=\alpha_{k+1}$.

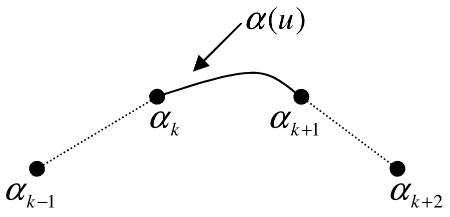

Fig. 1. Catmull- Rom spline curve

where interpolating function $\alpha(u)$ is given by

$$\alpha(u)=\sum_{j=-1}^{2}\alpha_{k+j}\phi_j(u),\ u\in[0,1] \tag{2}$$

where $\phi_j(u)$ is the Catmull-Rom basis functions represented by following equations.

$$\phi_{-1}(u)=(-u^3+2u^2-u) \tag{3}$$

$$\phi_0(u)=(u^3-2u^2+1) \tag{4}$$

$$\phi_1(u)=(-u^3+u^2+u) \tag{5}$$

$$\phi_2(u)=(u^3-u^2) \tag{6}$$

In this work helical antenna is modeled using helix radius (*a*), number of turns (*N*) and nonlinear pitch angles. The pitch profile for the entire helix is obtained by fitting a Catmull -Rom spline curve using pitch angles at six equal distant points along the axial length of the helix as shown in Fig. 2. By six control pitch angles we can cover almost all type of non- linear pitch variations. The geometry of the matrix is given by these pitch angles α_1, α_2, α_3, α_4, α_5 and α_6.

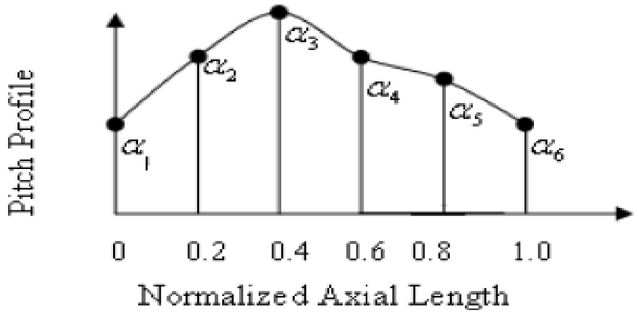

Fig. 2. Pitch Profile using six control values

Helix Design Algorithm is used to determine the geometry of helix. The algorithm has two steps:

1. Pitch Interpolation
2. Evaluation of helix co-ordinates

Aim of the pitch interpolation is to evaluate pitch angles S[i] for each turn of the helix given six pitch control values (α_1, α_2, α_3, α_4, α_5, α_6), number of turns(*N*) and helix radius(*a*).the pitch interpolation is done using Catmull-Rom spline interpolation. In NEC2 Helical antenna is approximately represented by connected wire segments. The coordinated of wire segments are evaluated using following algorithm

```
for each turn  i=1 to N
      z=2π *tan(S[i]));
      • for t=0 to 2π
        x( i*t)=a*cos(i*t)
        y(i*t)=a*sin(i*t)
        z(i*t)=zi-1+2πz*t
       t =t+dt
     end for
end for
• Output coordinate arrays x( ), y( )and z( ).
```

III. PROPOSED METHOD FOR OPTIMIZATION

In this work, the original NEC2++ source code (version 1.3.0) is modified to incorporate Catmull–Rom spline modeling of pitch profile and PSO [6]. The gain, axial ratio, voltage standing wave ratio (VSWR) and input impedance of helix are estimated using NEC2. Particle Swarm Optimization (PSO) is a stochastic, population based computer algorithm for solving optimization problems. It is a kind of swarm intelligence that is based on social-psychological principles and provides insights into social behavior, as well as contributing to engineering applications. The classical Particle Swarm Optimization is summarized below. Let $f: R^m \rightarrow R$ is the fitness or cost function which must be minimized. Let there be *n* particles each with positions $x_i \in R^m$ and velocities $v_i \in R^m$. Let $x_{\min}$ and $x_{\max}$ represents the minimum and maximum value of *x* for the solution region. Let $\hat{x}_i$ be the current best of the *i*' th particle and $\hat{g}$ the global best.

- Initialization step

Initialize with random values for $x_i \in [x_{\min}, x_{\max}]$ and $v_i = 0$, $\hat{x}_i = \hat{x}$ and $\hat{g} = \arg\min_{x_i} f(x_i)$, *i*=1,….,*N*.

  - Initialize cognitive and social components c_1 and c_2 nearly equal to two.
  - Initialize inertial constant ω slightly less than 1.

- While not converged
  - For each particle $1 \le i \le N$
    - Create random vectors $r_1, r_2 \in R^m$ and $r_{1j}, r_{1j} \in U[0,1], 1 \le j \le m$.
    - Update particle positions $x_i = x_i + v_i$
    - Update particle velocities $v_i = \omega v_i + c_1 r_1.(\hat{x}_i - x_i) + c_2 r_2.(\hat{g} - x_i)$
    - Update local bests $\hat{x}_i = x_i$, if $f(x_i) \le f(\hat{x}_i)$.
    - Update global best $\hat{g} = x_i$, If $f(x_i) \le f(\hat{g})$
- $\hat{g}$ is the optimal solution with fitness $f(\hat{g})$.

where '.' denotes vector dot product. Convergence conditions include reaching a certain fitness value or reaching

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a maximum number of iterations. Fig.3 shows the block diagram for the helical antenna design using Particle Swarm Optimization [8]. In this work, each particle is represented by six pitch angles α_1, α_2, α_3, α_4, α_5, α_6. Using Catmull-Rom spline modeling as described in section II, pitch control values(α_1, α_2, α_3, α_4, α_5, α_6), a and N are converted to antenna configuration that can be read by NEC2. The gain and axial ratio of these helical antennas are computed using NEC2. Using this gain (G) and axial ratio (AR), fitness value of the particle is evaluated based on (1) and it is feedback to PSO for computing new particle positions. This procedure is iterated until PSO converges to an optimum solution.

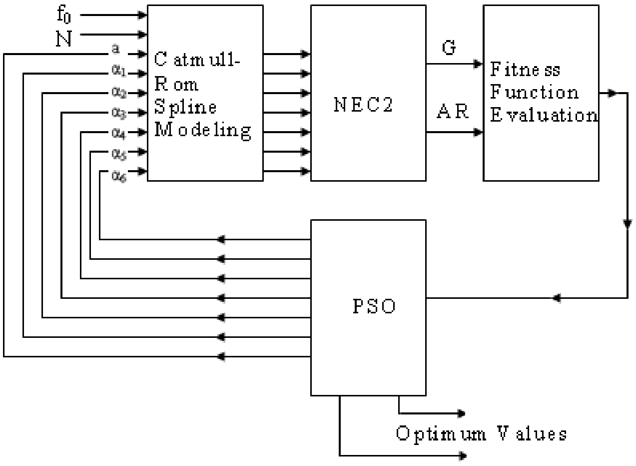

Fig. 3. Helical antenna design using Particle Swarm Optimization.

IV. SIMULATED AND EXPERIMENTAL RESULTS

For simulation, windows based software has been developed to incorporate Catmull-Rom spline modeling and Particle Swarm Optimization. Additional capabilities like visualization of 2D and 3D radiation patterns are also provided by using OpenGL library [9]. Graphical User Interface (GUI) has been developed for simulation of helix and PSO using GLUI (OpenGL User Interface Library). Using this GUI, the pitch control values can be entered using mouse and structure of the antenna can be saved in .nec format. Also using the GUI, the required parameters like number of turns, minimum and maximum value of radius and control pitch angles of the helix, the operating frequency, number of particles and maximum iteration for Particle Swarm Optimization can be entered manually. For comparison of our work with classical Kraus design, we have simulated the gain characteristics of classical Kraus design for different number of turns. For Kraus design, the range of circumference $C\lambda$ (in wavelength) is $\frac{3}{4} \le C\lambda \le \frac{4}{3}$ and pitch angle is $12^o \le \alpha \le 14^o$. In this work we have chosen $C\lambda = 1.10$ and $\alpha = 12.5^o$ for Kraus design. Infinite ground plane has been assumed for simulation. Then PSO is done to find the optimum values of helix radius (a) and six pitch control angles α_1, α_2, α_3, α_4, α_5, and α_6 for N number of turns. For PSO we have chosen the following ranges for radius and pitch angles: $0.15 \le a_\lambda \le 0.25, \quad 10^0 \le \alpha_i \le 15^0 \ i = 1,,6$. Using these pitch angles, helical antenna structures are modeled and simulated. Fig.4 shows directive gain characteristics obtained by classical Kraus method and based on proposed method. From the graph, it is clear that the directive gain from proposed method is 2dB more compared to classical Kraus design. It is also observed that difference in gain increases with increase in number of turns.

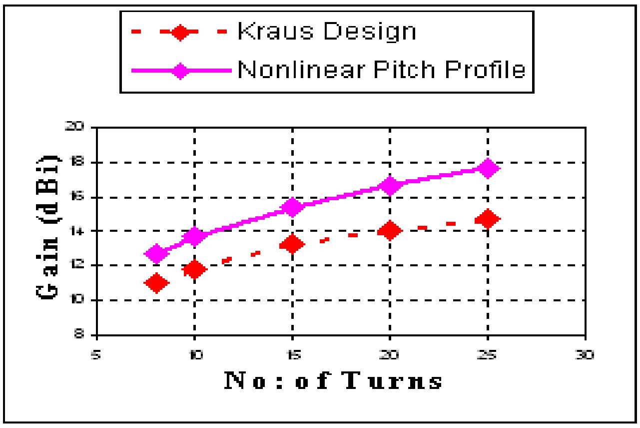

Fig. 4. Directive gain versus number of turns for Kraus design and Proposed method.

Fig. 5 shows variation of a_λ with number of turns based on our approach. Fig. 6 shows optimum nonlinear pitch profiles for different number of turns based on our method. From the figure, it is clear that the pitch angle is smaller for initial turns and increases towards middle and then remains almost constant towards end of the helix.

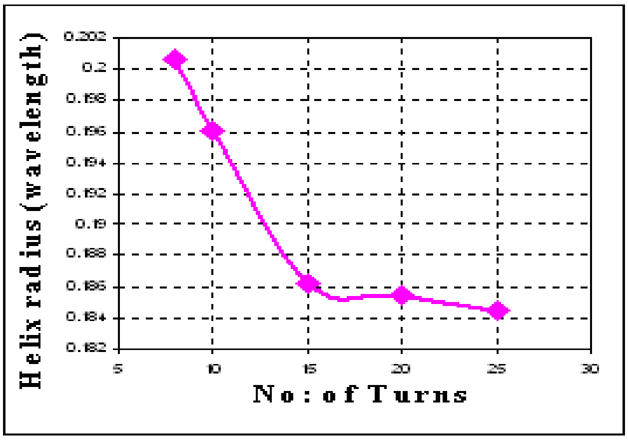

Fig. 5. Helix radius a_λ versus number of turns

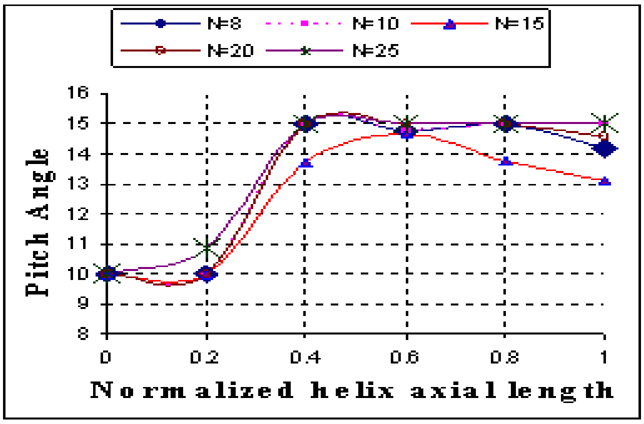

Fig. 6. Optimum nonlinear pitch profile

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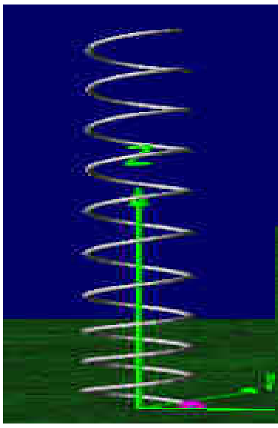

Fig. 7a. Helix structure   Fig. 7b. 3D Radiation Pattern.

Fig. 7a and Fig. 7b shows NEC2 simulated helix structure and 3D radiation pattern for number of turns N=10. Fig. 7c shows NEC2 simulated vertical pattern of E_θ and E_φ for N=10. Table. I shows optimized helix radius a_λ and six control pitch angles in degrees for different number of turns N. The helix geometry is optimized for maximizing the gain subject to unity axial ratio. The simulated values for directive gain in dB and input impedance for different number of turns N. It can be noted that input impedance is nearly resistive with value around 200 ohms.

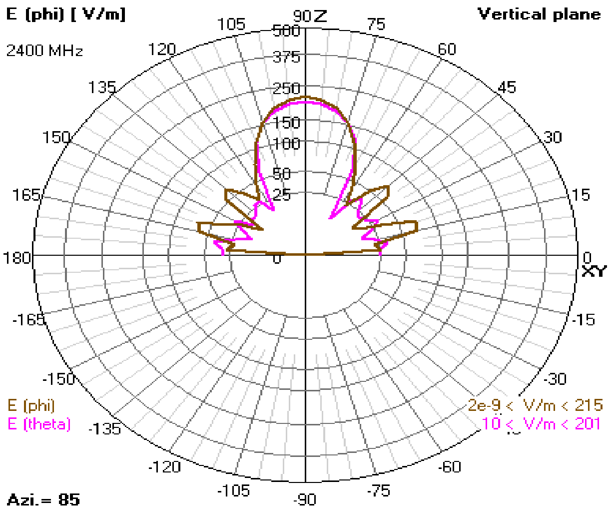

Fig. 7c. Vertical pattern of E_θ and E_φ

Table 1. Optimum helix parameters

N	α_1	α_2	α_3	α_4	α_5	α_6	a_λ	G(dB)	Zin
8	10	10	15	14.76	15	14.21	0.2007	14.08	244.87-j46.56
10	10	10	15	14.74	15	15	0.1961	14.6	220.39-j19.24
15	10	10	13.72	14.65	13.78	13.08	0.1862	15.45	231.49-j11.76
20	10	10	15	15	15	14.57	0.1855	16.59	206.60-j9.69
25	10	10.87	15	15	15	15	0.1845	17.2	221.51-j8.47

Fig. 8 shows the experimental set up. Antenna is constructed by winding a copper wire around a PVC pipe and using aluminum circular plate as the ground plane. By using a standard dipole antenna as the receiver, received power is measured along the axial direction. This is done for both Kraus method and Proposed method. HP8481A microwave sensor together with $\lambda/2$ dipole antenna is used for measuring the received power. Source used is Agilent N9310A RF signal generator with an input power of 10dBm. The difference in received power gives gain enhancement. We have observed gain improvement of 2.5dB over Kraus design.

Fig. 8. Experimental Setup

Fig. 9 shows the obtained VSWR characteristic from 1 GHz to 3 GHz. Rohde & Schwarz ZVL Network Analyzer with frequency range 9 kHz to 3 GHz is used. From the plot, it is clear that the VSWR is low for a wide range of frequency. Fig. 10 shows the measured radiation pattern.

Fig. 9. Measured VSWR characteristics

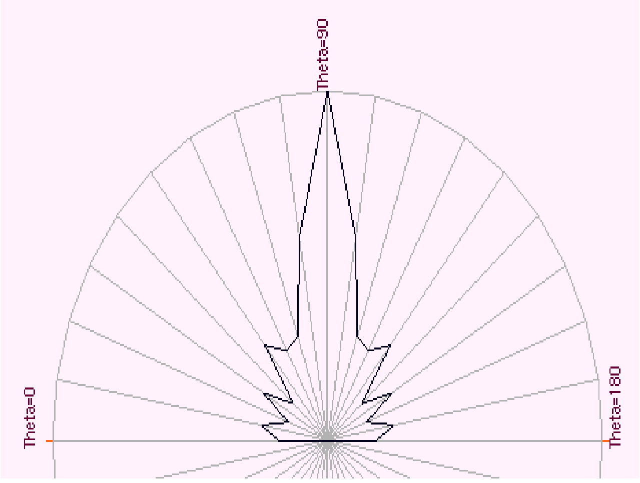

Fig. 10. Measured radiation pattern.

V. CONCLUSION

This paper presents a novel method for design of helical antenna with nonlinear pitch profile for maximizing the gain subject to unity axial ratio based on Catmull-Rom spline modeling and Particle Swarm Optimization. In our work the helix is modeled using six pitch control angles, number of turns and helix radius. Simulated and experimental results show that gain characteristics of helical antenna designed using our approach is better than classical Kraus design. Further work involves finding the optimal helical geometry with modified ground plane such as using conical ground plane.

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