Optimal Helical Antenna with Continuously Varying Radius Using Evolutionary Optimizers

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Abstract— **The size reduction for wire antennas using lumped loading inductors is well known, but introduces significant degradation in efficiency and bandwidth. One of the alternative approaches to solve the problem is the increase of wire length for a fixed height. Various techniques have been investigated to introduce longer wire length, but this paper concentrates on helical windings with continuously varying radii. The continuously varying radii are represented using radial basis functions, which give maximized shape controllability with a minimal number of defining parameters. These parameters that define the shape of the helix are optimized with respect to both bandwidth and efficiency, and matching networks are included in the optimization. The results are obtained from an automated simulation tool (MATNEC) equipped with evolutionary optimizers. Using the proposed strategy, a performance improvement is predicted for an optimized helical winding structure with continuously varying radii.**

Keywords – Electrically Small Antenna, Helical Antennas, NEC2, Evolutionary Optimizers.

I. Introduction

Size reduction is one of the critical and interesting issues in the design of resonant wire antennas, especially for HF and VHF bands. It is well known that the self-resonant frequency of a straight wire monopole is inversely proportional to the wire length. In order to achieve resonance with a shorter antenna, it is necessary to introduce additional complexity such as inductive loading, or a helical structure. Extensive investigations towards loaded linear antennas [1-3] indicate that inductive loadings can effectively achieve the task of shortening resonant length of wire antennas, but at the cost of degradation in both efficiency and bandwidth [4].

This paper first briefly introduces several strategies that have been investigated and applied to effectively introduce self-inductance on the wire antennas, which consequently lower the resonant frequency for a given length [5]. There are conventionally two ways to increase self-inductance on a wire antenna, lumped inductive loading and additional wire length through helical windings. The first method had been investigated previously in [6], and therefore additional wire length will be investigated in this paper.

For this investigation, an automated simulation tool, programmed by the authors is introduced. It is controlled by MATLAB and equipped with evolutionary optimizers. This so-called MATNEC tool is composed with NEC2 (Numerical Electromagnetic Codes) [7] for simulation, and Genetic Algorithm (GA) as well as Particle Swarm Optimization (PSO) to pursue the optimal wire antenna configurations in terms of inductance distributions. Optimal performance is considered with respect to radiation efficiency and bandwidth. The optimal loading distributions for a shortened resonant monopole using lumped inductors has been investigated using MATNEC and the optimized results show significant degradation in efficiency due to component loss [6].

In this paper, a 0.25m structure is considered with the objective to tune it to exhibit a resonant frequency of 100 MHz, maximum bandwidth and efficiency being the performance indicators. The total antenna height corresponds then to one-twelfth of the wavelength. An investigation of helical antennas with continuously varying radii is carried out. The ultimate goal is to find best radius configuration that can be represented by an appropriate set of basis functions. In the investigations, the development of an appropriate cost function is a particular focus due to the fact that it is the critical element in specifying the relevant trade-offs, and determining the optimal solution.

Near-optimal helical configurations are then found by applying evolutionary optimizers. The results of incorporating a single short helix into a wire antenna is first verified by comparing to the optimal loading position of the equivalent lumped inductor found in previous investigations. Then for a continuous distribution of helical windings along antenna, the near-optimal distribution of wingding radius is found with winding radius represented by radial basis function (RBF).

II. Size Reduction Strategy

For electrically small straight wire antennas, the inductance and capacitance at the feeding point are dominantly originating from the self-inductance of the wire and the space from the wires to the ground respectively [5]. To effectively lower the self-resonant frequency, two approached can be taken, explicitly increasing the self-inductance or increasing the self-capacitance. The latter approach can be addressed by adding capacitive loading to the top of the antenna, while the self-inductance of antenna can be increased by either adding wire length, or lumped inductive loads [5]. Lumped inductive loadings on the monopole have been investigated with optimal loading positions, though with significant degradation in efficiency [6]. Therefore, adding wire length to a fixed height antenna through helical windings turns to be the focus and objectives of this investigation. Conventionally, uniform helical antennas with constant radius and pitch have been proposed and studied for many years. Spherical helical antennas where radius is changing at a constant rate have also been investigated [8, 9]. Nevertheless, helical antennas with continuously varying radii have seldom been studied. With modern manufacturing techniques, it is fairly easy to produce antennas with such variations and so this could be a productive avenue of improving the efficiency and bandwidth.

III. SIMULATION TOOL WITH EVOLUTIONARY OPTIMIZERS

A. MATNEC

MATNEC is an automated program combining NEC2 and optimization through MATLAB. NEC2 is a simulation tool for numerical electromagnetic computation based on the method of moments. MATLAB functions as the control of MATNEC. As can be seen from the flow diagram in Fig. 1, MATNEC controls the execution of NEC2 once the parameters of a set of trials antennas are known. After simulation, all antennas are tested and their performances are assessed. If the best performance has not reach satisfactory level, another step of the optimization procedure is implemented and a new set of trial antennas is simulated. This process is then continued until convergence to a near optimal antenna geometry is achieved. The output of MATNEC is directly the optimized antenna parameters and the associated optimal performances.

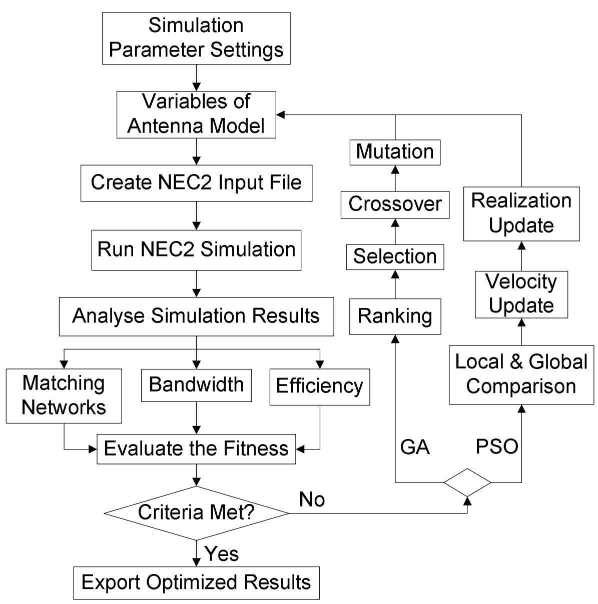


Fig. 1. Flow chart of MATNEC with GA & PSO

B. GA & PSO

The GA was initially invented based on the natural process of evolution and genetic recombination, and this makes it a robust stochastic search method [10, 11]. PSO is based on the exploration of the problem space according to given rules inspired by the food search behavior of living organism swarms [12]. GA and PSO are both global search methods, and are effective in finding an approximate global optimum in a high-dimension space.

C. Fitness/Cost Function

The selection of an appropriate cost function is of critical importance to the success of the optimization. In this investigation, the cost function is composed of three factors, two meriting terms, the efficiency and bandwidth; as well as one penalizing term, the so-called frequency shift. Each factor is assigned with an individual weighting, and the resulting fitness function can be written as

$$Fitness = w_1 \bullet Efficiency + w_2 \bullet Bandwidth + w_3 \bullet f_{shift} \quad (1)$$

The efficiency (expressed in %) includes the radiation efficiency at the target frequency, and the efficiency of the matching network. The bandwidth is defined as the operating bandwidth with a VSWR less than 2.0. The frequency shift (f_{shift}) is the distance from the target frequency to the center of the band with a VSWR < 2.0, as illustrated in Fig. 2.

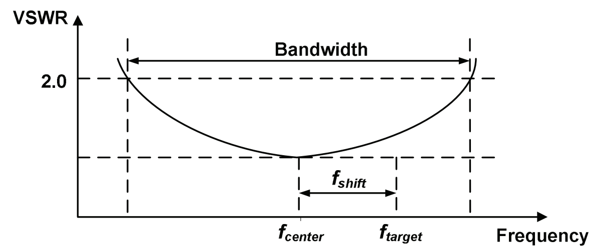


Fig. 2. Relationships of target frequency, center frequency, frequency shift and bandwidth

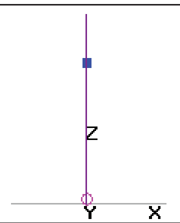
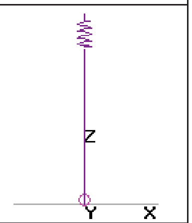
The employment of an appropriate fitness function, defined specifically through the weighting values for each factor, is a particular focus in the investigation. It is important that the correct balance between the weightings of factors be achieved.

D. MATNEC & Helical Windings Validation

In previous investigations [6], near-optimal distributions of ideal lumped inductors on a 0.25 m monopole were found using MATNEC and a cost function (1) with finely selected weighting factors. In this investigation, the same antenna with realistic inductors consist of short helical windings is simulated and optimized, in order to verify the effectiveness of helical windings in adding self-inductance to a wire antenna. This coil has a fixed pitch, while other geometrical parameters involving in the optimizations are the radius, the position, the length as well as the number of turns of the coil. All four parameters are limited within certain ranges, so that the computation load is bounded and convergence can be achieved in a fairly short time. The LC components in the L-type matching network are also included in the optimization to maximize bandwidth.

The comparison in Table I illustrates the equivalence of ideal inductors and realistic inductors using copper windings. It can be seen that both ideal and realistic inductors on the wire antenna achieve reasonably wide bandwidth at the lowered frequency of 100 MHz. Further, the realistic inductor of helical windings improves the radiation efficiency significantly.

Table I. Shortened monopole using inductive loadings

Parameter	Ideal Inductor	Realistic Inductor
Wire Radius	1 mm	
Position	≈ 0.063λ	≈ 0.067λ ~ 0.08λ
Inductance	2.25 μH	20 nH
Radius	Infinitesimal	10.6 mm
Height	Infinitesimal	0.205 m
Length	Infinitesimal	0.345 m
No. of Turns	Not Applicable	4
L in Matching	289 nH	610 nH
C in Matching	40 pF	93.8 pF
Efficiency	36.7 %	96.4 %
Bandwidth	1.01 MHz	1.11 MHz
f_{center}	100.09 MHz	100.08 MHz
Configurations		

IV. Helical Wire Antennas

The helical antenna was first proposed in [13], and has been known and developed successfully for a long time, both theoretically and experimentally [8, 14, 15]. Nevertheless, apart from the spherical helical antennas [16-18], most of the researches have been focused on the uniform helices with constant pitch and constant radius. This section will first briefly describe the uniform helix, and then propose a new method to represent radius-varying helix.

A. Basic Cylindrical Structure

A basic uniform helix with constant radius can be defined uniquely with the dimension parameters shown in Fig. 3, where D is the center-to-center diameter of helix, S is the spacing between turns, N is the number of turns, A is the axial length, and d is the diameter of the wire.

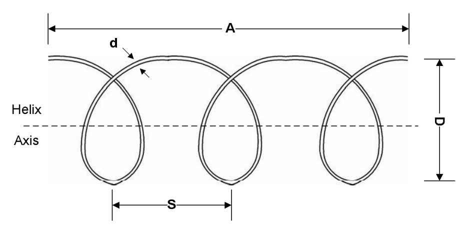


Fig. 3. Parameters of helix dimensions

B. Continuous Radius-Varying Helical Structure

The radius of the helix can be made to vary from turn to turn, which may effectively change the current distribution and thus the corresponding performance in terms of efficiency and bandwidth. Therefore, helical windings with optimally varying radius are proposed to provide an effective method to tune the resonance of the antenna.

The radius of the helical windings can be in principle described explicitly from turn to turn. This however introduces a large and variable number of defining parameters which complicates the optimization. Alternatively, the varying radius can be defined continuously using basis functions. Several types of basis functions, including polynomial basis function, spline basis function, and radial basis function, have been compared. It is determined that radial basis functions are the most appropriate candidates in this case because of their high controllability with a minimal numbers of parameters required.

C. Radial Basis Function Representation

A radial basis function (RBF) is a real-valued function whose value depends only on the distance from the origin that is $f(x) = (\|x\|)$ [19], or on the distance from a certain point c that is $f(x,c) = (\|x-c\|)$. Linear combinations of RBFs are typically used to build up approximations of the form:

$$y(x) \approx \sum_{i=1}^{N} \omega_i f_i(\|x - c_i\|) \qquad (2)$$

where N is the number of RBFs, f_i are the radial functions, and c_i are the control points, ω_i are scalar weighting parameters (describing the radius of f_i with units of mm).

In the present investigation, the RBFs are composed of Gaussian functions to represent the helical winding structure in terms of the radius to the height position as

$$r(x) = \sum_{i=1}^{N} \omega_i \cdot e^{-(\frac{x-H_i}{R})^2} \qquad (3)$$

where H_i are positions of each control points, and R is the radius of the Gaussian functions, common to all RBFs.

A number of six control points (N=6) are applied in the present investigation, and variable shapes of helical windings can be formed by altering only the weight ω_i while fixing the heights H_i. Fig. 4 shows a set of six radial basis functions, and an example of achievable resulting radii configuration.

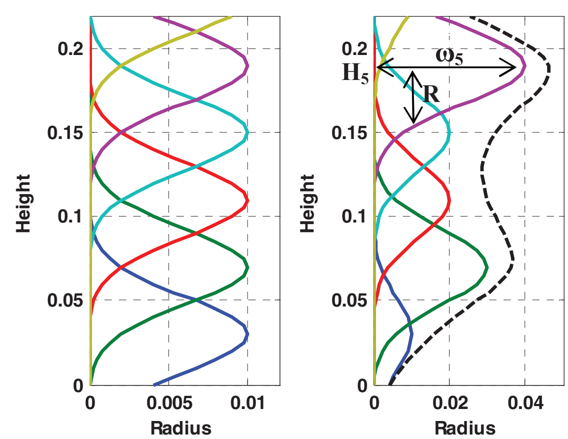


Fig. 4. Example of radial basis functions and a varying radii helix

V. SAMPLE CASE RESULTS

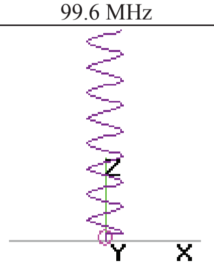
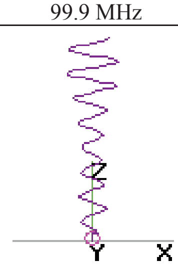
A. Optimized RBF Representing Model

First, a uniform helix with a fixed pitch (S = 30 mm) is first designed and optimized with respect to the radius from 10 to 30 mm, while the matching networks are also involved in the optimization to obtained a maximized bandwidth.

When RBFs are used to introduce radius variations into the helical windings, they are defined using six fixed control points (H_i) and a fixed radius R. This requires only six weighting variables (ω_i) to determine the overall shape of the radii along the wire antenna. In the optimization, the radius weights at the control points (ω_i) range from 10 to 30 mm while the pitch is kept constant at 30 mm. Limiting the number of optimization variables ensures that the computational load associated with optimization is bounded. The LC components of the matching circuit are also included in the optimization to help maximizing bandwidth, within an acceptable frequency shift.

The performances of the two helices are compared, as shown in Table II. It can be seen that the helix with varying radius defined using optimized RBFs exhibits a wider operating bandwidth and a slightly higher total efficiency. This helix has comparatively wider windings near the top.

Table II. Comparison of optimized uniform helix and RBF represented helix with continuously varying radii

Parameter	Uniform Helix	Radii Varying RBF
Pitch	30 mm	
Radius	24.2 mm	N/A
ω_1	N/A	20.7 mm
ω_2		10 mm
ω_3		10 mm
ω_4		15.3 mm
ω_5		30 mm
ω_6		28.7 mm
L in Matching	-75.2 nH* / 33.7 pF	-43nH* / 58.9 pF
C in Matching	62.9 pF	62 pF
Efficiency	91.3 %	92.39 %
Bandwidth	1.21 MHz	1.51 MHz
f_{center}	99.6 MHz	99.9 MHz
Configurations		

*: negative inductors can be realized by capacitors.

VI. CONCLUSION

This paper has investigated strategies that can be applied to effectively lower the resonant frequency by introducing self-inductance to wire antennas. Adding wire length by helical windings with varying radii is a particular focus. An automated tool has been programmed that combines simulation and evolutionary optimization. A 0.25 m fixed-height wire antenna is designed with the goal to achieve a resonance frequency of 100 MHz with optimized helical windings. Radius variations on the helical windings represented using radial basis functions may effectively change the self-inductance of the antenna. The optimal results with greater bandwidth indicate a success of the investigation method, and a potential improvement when more variations, i.e. changing pitch, are made to the wire antennas.

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