Evolutionary Optimization of Zig-Zag Antennas Using Gaussian and Multiquadric Radial Basis Functions

Shifu Zhao [1], Christophe Fumeaux [2], Chris Coleman [3]
School of Electrical and Electronic Engineering, the University of Adelaide
Australia
[1]shifu@eleceng.adelaide.edu.au
[2]cfumeaux@eleceng.adelaide.edu.au
[3]ccoleman@eleceng.adelaide.edu.au

***Abstract* - Zig-Zag monopole antennas are frequently used and are of great importance in HF and VHF communications. Their shapes provide addition of wire length and thus contribute to inductive loading. Structural variations of the zig-zag shape are explored in this paper to change the distribution of inductance along the monopole height and thus improve the antenna performance. These variations are represented using radial basis functions to lower the number of variables in the optimization process. Evolutionary optimizers are applied to obtain the optimal shape variations based on electromagnetic simulations. The performance is considered with respect to bandwidth and radiation efficiency with a matching network tuned at the target frequency. Prototypes of the optimized zig-zag antennas are fabricated, measured and compared to a uniform zig-zag monopole. Experiments indicate a good agreement to the optimal simulation results.**

***Index Terms* - Zig-zag antenna, radial basis function, multiquadric, MATNEC, evolutionary optimizations.**

I. Introduction

Size reduction strategies are a topic of great importance in the design process of HF and VHF antennas, and have been investigated extensively for decades. It is well known that lumped inductive loadings can successfully shorten the resonant length of wire antennas, but at the costs of efficiency and bandwidth [1, 2]. Inductive loadings can, however, be distributed along the antenna. For example, lumped inductive loadings on monopole and optimized helical structures had been previously investigated in order to achieve size reduction in [3] and [4] respectively. The zig-zag antenna is another structure that can also add distributed inductance, but contrarily to the helix, its geometry remains in one plane. This advantage comes at the cost of slight performance degradation compared to the helical structure [5].

This paper first briefly describes the traditional uniform zig-zag antennas introduced several decades ago and used frequently since then [6-9]. It investigates optimized modifications of the original uniform zig-zag structure towards an effective improvement of radiation performance. Variations on the zig-zag structure can be made through changes in the pitch angle along the length, as well as in the number, and length, of zig-zag wire segments.

In a straightforward approach, the structural variations of zig-zag antennas can be defined for each segment individually. This strategy, however, can lead to a large number of optimization parameters, and thus a great complexity in the design process. Alternatively, the variations of qualities such as pitch along the zig-zag can be expanded in terms of radial basis functions (RBF). If selected appropriately, these can provide effective description of parameter variations with only a few variables. Two types of radial basis functions, explicitly Gaussian (G) and multiquadric (MQ) RBFs, are employed in the present investigation. Those RBFs are used in an automated simulation tool equipped with evolutionary optimizers [3]. This so-called MATNEC tool is based on NEC2 (Numerical Electromagnetic Codes) for electromagnetic simulation and a genetic optimization algorithm performed in Matlab.

In this paper, the optimization of a zig-zag antenna with a fixed height of 0.25 m and resonant frequency of 100 MHz is the goal. Maximized bandwidth and efficiency are considered as the performance indicators. A fixed pitch angle of 30° is applied in the zig-zag structure, while the number of segments and their individual length are the variable parameters. Simulations and optimizations towards the optimal performances are carried out with the ultimate goal of finding the best zig-zag antenna configuration, i.e. the geometry which exhibits the widest bandwidth and highest efficiency at 100 MHz. In this process, bandwidth is defined as the frequency range with a VSWR less than 2.0 using an L-type matching network.

Near-optimal zig-zag configurations are found by applying evolutionary optimizer. The optimized results, obtained using G-RBF and MQ-RBF, are compared to a uniform helix resonant at 100 MHz to verify the performance improvements. To validate the findings, prototypes of the optimal zig-zag antennas were fabricated and measured. The consistency in the comparison supports the effectiveness and accuracy of the methodology proposed in this investigation.

II. Zig-zag Antenna & Structural Variations

A zig-zag antenna was first reported in 1955 [6], and had been studied extensively in the following decades [7-9]. Zig-zag antennas are of great importance in HF and VHF communications. This kind of antenna is strongly related to the helical antenna [7], but importantly, the planar nature of

the zig-zag wire structure makes it easier and faster to fabricate than the helix. Thus, the zig-zag antenna is a very convenient geometry to verify the small antenna design procedure that is proposed in this paper.

One of the configurations of zig-zag antennas that has been frequently investigated, and extensively used, is the uniform zig-zag monopole antenna [8]. The pitch angle (α) which defines the angle between two zig-zag segments, and the segment length (L), are the two essential parameters that fully characterize the structure, as shown in Fig. 1.

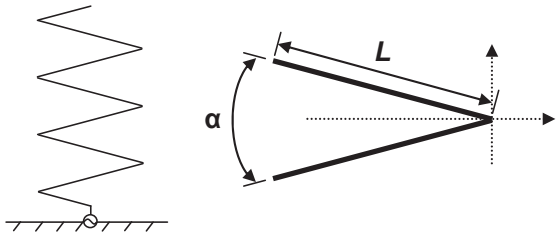


Fig. 1. Illustration of a uniform zig-zag antenna & pitch angle (α).

Our optimization strategy is based on the fact that the segments in the zig-zag antenna do not necessarily have to be all the same length. This will bring a great amount of possible variations to the structure, and thus change the performance correspondingly. Considering the length of each segment in the zig-zag antenna as variable can, however, significantly increase the complexity of optimization if defined individually. The alternative is to use curves that constrain the end points of the zig-zag and then expand these curves in terms of a limited number of basis functions (radial type in our case). Length variations are then described in terms of a small number of variables.

III. Methodology & Radial Basis Function

For optimal antenna design, electromagnetic simulation and evolutionary optimization are the two major processes. Electromagnetic simulation with NEC provides fast estimation of antenna performance for given optimization variables, and evolutionary optimization guides these variables to their optimal values.

A radial basis function is a real-valued function whose value depends only on the distance from the origin, that is $f(x) = (\|x\|)$ [10], 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:

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

where N is the number of RBFs, f_i are the radial functions, c_i are the control points, and ω_i are scalar weightings.

In this work, one of the tasks in the investigation is to achieve sufficient shape variations for zig-zag antenna, by using the minimum numbers of optimization variables. Conventionally, a ten-segment zig-zag requires ten variables to describe the shape; whereas in this case, only a total number of five RBF variables are used. Importantly, increasing the number of zig-zag segments does not require increasing the number of required RBFs.

In the current investigation, the G-RBF and MQ-RBF are used to represent the variations in zig-zag structure. They can be written as:

$$f_{G-RBF}(x) = \sum_{i=1}^{N} \omega_i \cdot e^{-R(x-c_i)^2} \qquad (2)$$

$$f_{MQ-RBF}(x) = \sum_{i=1}^{N} \omega_i \cdot (1 + \varepsilon^2 (x - c_i)^2)^{\beta} \qquad (3)$$

The practical implementation of the design optimization algorithm with these basis functions is achieved within MATNEC, an in-house developed program combining NEC with optimization through MATLAB. NEC is a simulation tool for numerical electromagnetic computation based on the method of moments [11]. MATLAB uses an evolutionary optimizer that is based on a genetic algorithm (GA) and uses NEC in the calculation of costs functions. The cost functions consider both efficiency and bandwidth, and are discussed in [4]. The output of MATNEC are the optimized antenna parameters and the associated optimal performances [3].

IV. Optimization Results

A. Structure Implementation

The shape of zig-zag is varied by altering the weightings ω_i in (1) while fixing the centre heights c_i in (2) or (3). Fixing the number of segments (M), the length of each segment (L_i) is obtained from the RBF expansion, based on a fixed pitch angle (α = 30°). The accumulated zig-zag height is derived and then scaled to the physical height limitation (H_{max} = 0.25 m). The scaling factor is then applied to the RBF expansion to obtain an antenna that satisfies the length constraint. This process is carried out at each stage of the optimization in order to implement the length constraint. Fig. 2 illustrates how the zig-zag is constrained within the sum of G-RBFs.

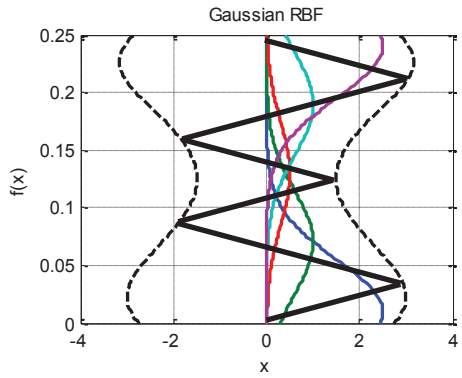


Fig. 2. Illustration of G-RBF constraining the zig-zag. The individual RBFs are represented in color, their sum as black dashed line, and the resulting zig-zag antenna as solid black line.

B. Optimization Results

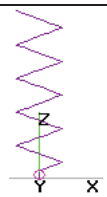
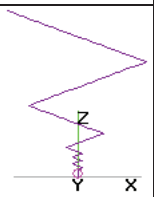
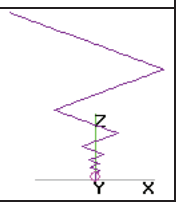
First, a 10-segment uniform zig-zag antenna with a fixed pitch angel of 30° is simulated. This uniform structure, and its resulting performance, is used as the reference for the comparison of optimized zig-zag antennas with variable segment lengths.

In the current simulations, the shape variations for the 10-piece zig-zag antenna with a fixed pitch angle (α = 30°) are described by five (N = 5) uniformly spaced RBF's. Thus, these five weighting factors (ω_i) become the optimizing variables. For both G-RBF (R = 250) and MQ-RBF (β = -3/2), the variable optimizing ranges for the weightings ω_i are set to be the same, and the corresponding shapes are then normalized to the physical requirements. Limiting the number of variables and their optimizing range will ensure that the computational burden associated with optimization is bounded. After optimization, an L-type LC matching network is employed to provide the perfect matching at 100 MHz.

The optimized uniform zig-zag antenna and the optimized piece-length-varying zig-zag antennas using two types of radial basis functions are compared in TABLE I.

TABLE I

COMPARISONS OF OPTIMIZED UNIFORM & SEGMENT-LENGTH-VARYING ZIG-ZAG ANTENNAS

10-Segment	Uniform	G-RBF	MQ-RBF
Segment Length	97.6 mm	N/A	N/A
ω_1	N/A	0.733	0.049
ω_2		1.056	0.352
ω_3		0.020	0.029
ω_4		0.244	0
ω_5		19.18	19.64
L in Matching	245 nH	137 nH	138 nH
C in Matching	112 pF	98.5 pF	97.5 pF
Efficiency with Matching	81.2%	88.2%	88.3%
Bandwidth with Matching	1.40 MHz	1.75 MHz	1.75 MHz
Configurations			

It can be seen that both RBF-defining zig-zag antennas exhibit greater efficiency and wider bandwidth than the uniform one. The optimized zig-zag geometries have comparatively longer segments near the top. Besides, both G-RBF and MQ-RBF yield a very similar general shape and overall performance. It is also essential to point out that, different values for R and β in (2) and (3) respectively also affect the accuracy and reached optimum of the results. The values that have been used in the investigation are finely selected, so that the radial basis functions reach a balance of local impact and possible overall dynamic range. The radiation patterns for the three zig-zag antennas are very much similar to a small monopole antenna.

In Fig. 3, the convergences of the optimizations for the two RBFs are compared with respect to the best individual and overall performances at the same optimization settings. For the present optimization case, G-RBF appears to converge faster than MQ-RBF in terms of total number of simulation runs, while MQ-RBF achieves a slightly higher total fitness.

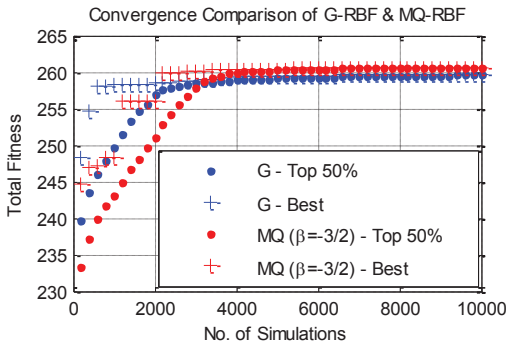


Fig. 3. Convergences of G-RBF (R = 250) & MQ-RBF (β = -3/2).

V. MEASUREMENTS & COMPARISONS

The prototypes of the proposed zig-zag antennas were fabricated according to the optimized parameters in TABLE I, as shown in Fig. 4. The uniform zig-zag antenna has equal segment length of 97.6 mm; the other two optimized zig-zag antennas have varying segment length, ranging from 10 mm to 330 mm, while the three antennas have a common and fixed pitch angle of 30°. The measurements were carried out on top of an aluminum ground plane (2.0 m × 2.0 m), and the results were obtained with Agilent 814ET RF network analyzer. The L-type matching network was connected and finely tuned between the antenna and the network analyzer. It was realized that the available connectors adds an extra 40 mm additional wire length at the bottom of the antennas. Theoretically, the 40 mm additional wire increases the original size (250 mm) by 16%, which should bring a 16% decrease in natural resonant frequency. Taking this into account, the measurements indicate a good agreement, as shown in TABLE II.

TABLE II

COMPARISONS OF NATURAL RESONANCE

Natural Resonance	Uniform	G-RBF	MQ-RBF
Original Simulation	139 MHz	118 MHz	118 MHz
Prototype Measurement	114 MHz	100 MHz	100 MHz

New simulations and matching network calculations were performed based on the fabricated prototype geometries. The VSWR from original simulation, prototype measurement, and re-simulation were compared, as shown in Fig. 5; the corresponding bandwidth was also obtained for VSWR ≤2, as shown in TABLE III.

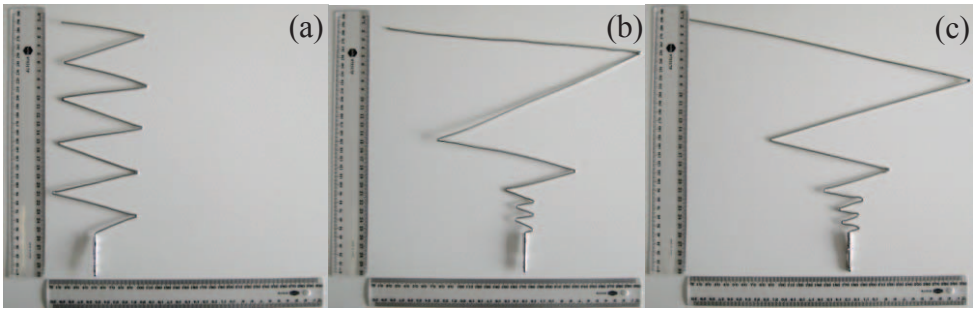


Fig. 4. Prototypes of the proposed zig-zag antennas, (a) uniform, (b) G-RBF, (c) MQ-RBF

In the measurement, the VSWR is not perfectly matched to 1.0 at 100 MHz, due to the lower Q factor of the LC components considered in the simulation compared to the actually available components. The relative efficiency, assuming equal directivity, is also measured by comparing transmitted power at a fixed distance. This value is normalized to one (for the reference uniform zig-zag antenna) for comparison in TABLE III. A general qualitative agreement can still be observed. The measured bandwidth and efficiency are very close to the re-simulation results, which provide strong validation of the optimization strategy.

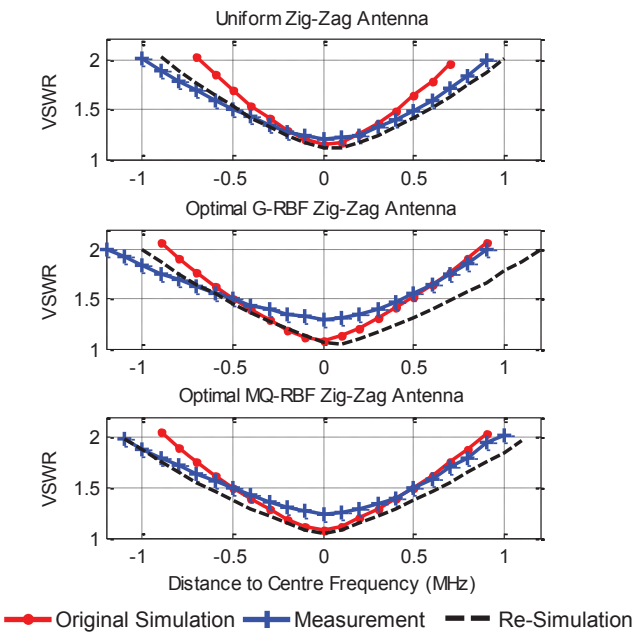


Fig. 5. Comparisons of original-simulated, prototype-measured, and re-simulated VSWR & Bandwidth of three optimal antennas.

TABLE III
COMPARISONS OF BANDWIDTH & EFFICIENCY

Bandwidth	**Uniform**	**G-RBF**	**MQ-RBF**
Original Simulation	1.4 MHz	1.75 MHz	1.75 MHz
Measurement	1.9 MHz	2.15 MHz	2.15 MHz
Re-Simulation	1.9 MHz	2.20 MHz	2.20 MHz
Efficiency	**Uniform**	**G-RBF**	**MQ-RBF**
Original Simulation	81.2%	88.2%	88.3%
Measurement (Norm.)	1	1.17	1.17
Re-Simulation	62.1%	77.0%	77.3%

VI. CONCLUSIONS

This paper has presented an optimization strategy for zig-zag antennas. The additional wire lengths, provided by a non-uniform zig-zag shape, provide an effective way to introduce distributed inductance along a wire antenna to effectively shorten it. By employing radial basis function, sufficient structural variations can be made to the zig-zag antenna with fewer variables than with a fully parameterized geometrical description. Near-optimal zig-zag configurations are found by applying evolutionary optimizer through electromagnetic simulations. The proposed optimal zig-zag antennas are fabricated and measured. Experimental results indicate a fairly good agreement between the simulation and measurement, which validates of the investigation methodology.

REFERENCES

[1] S. R. Best, "A discussion on the properties of electrically small self-resonant wire antennas," IEEE Antennas Propagat. Mag., vol. 46, pp. 9-22, 2004.

[2] H. A. Wheeler, "Fundamental Limitations of Small Antennas," IRE Proc., vol. 35, pp. 1479-1484, 1947.

[3] S. Zhao, et al., "Optimal Positions of Loading for a Shortened Resonant Monopole Using Genetic Algorithm," in International Conference on Electromagnetics in Advanced Applications, Australia, 2010, pp. 705-708.

[4] S. Zhao, et al., "Optimal Helical Antenna with Continuously Varying Radius Using Evolutionary Optimizers," presented at the IEEE APS Symp., USA, 2011.

[5] S. R. Best and D. L. Hanna, "A Performance Comparison of Fundamental Small-Antenna Designs," Antennas and Propagation Magazine, IEEE, vol. 52, pp. 47-70, 2010.

[6] W. Cumming, "A nonresonant endfire array for VHF and UHF," Antennas and Propagation, IRE Transactions on, vol. 3, pp. 52-58, 1955.

[7] D. Sengupta, "The radiation characteristics of a zig-zag antenna," Antennas and Propagation, IRE Transactions on, vol. 6, pp. 191-194, 1958.

[8] L. Sing and K. Mei, "Analysis of zigzag antennas," Antennas and Propagation, IEEE Transactions on, vol. 18, pp. 760-764, 1970.

[9] P. S. Bhatnagar and S. B. L. Sachan, "Analysis of infinite zig-zag antenna," IERE Proceedings -, vol. 14, pp. 44-46, 1976.

[10] M. D. Buhmann, Radial basis functions : theory and implementations vol. 12. New York: Cambridge University Press, 2003.

[11] G. Burke, "Numerical Electromagnetic Code (Nec2) - Method of Moments," Lawrence Livermore National Lab, 1981.