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Optimization of Helical Antennas

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Abstract—**Helical antennas have been known for more than half a century, but it seems that the reliable design data for helical antennas do not exist in open literature. This paper points out some inaccurate data about helical antennas and presents a new set of data related to the optimal design of helical antennas. The antenna performance is optimized by varying antenna's geometrical parameters for narrowband and broadband design. Based on these results, a set of diagrams is made to enable simple but accurate design of helical antennas above infinite ground plane. Finally, the results are experimentally verified.**

Index Terms—**Helical antennas.**

I. Introduction

ALTHOUGH helical antennas have been known for a long time [1]–[8], there is a lack of sufficiently reliable formulas and diagrams for their design in the open literature. Furthermore, some frequently used data [1]–[4] are in discrepancy with experimental results [5], [6] and other theoretical results [7], [8]. These differences among results published in the open literature have motivated us to make systematic investigation of helical antenna characteristics.

This paper has a twofold objective. The first goal is to point out some misconceptions about the helical antennas. The second goal is to optimize the antenna performance by varying all geometrical parameters. We have found that, for a given antenna length (L), the optimal pitch angle strongly depends on the wire radius and the desired gain variations within the operating band. The input impedance also depends on the wire radius. The antenna gain depends on the size and shape of the ground plane, but this is beyond the scope of this paper. Based on extensive computations, diagrams are made that enable simple, but accurate, design of helical antennas.

The paper is organized as follows. Section II defines geometrical and electrical parameters of the helical antenna and presents the classical design approach. Section III compares results obtained using theoretical results from [1], experimental results from [5], [6], simulation data from [7], and the design curve from [8] with results obtained from our simulations. Section IV presents diagrams for helical antennas above an infinite ground plane, from which the optimal parameters can be extracted to maximize the antenna gain and bandwidth. Section V presents the design procedure for helical antennas and the experimental verification of the design procedure. Finally, Section VI concludes the paper.

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II. Geometry of Helical Antenna and Classical Design Approach

Fig. 1 shows a typical helical antenna. It consists of a conductor bent in the form of a helix (spiral). Only uniform helices, i.e., helices with a constant pitch (p), are considered in this paper. The number of helix turns is N. The diameter of the imagined cylinder over which the axis of the helical conductor is wrapped is $D = 2a$, where a is the corresponding radius. The helix conductor can be a wire, tube, or a ribbon. In this paper, we shall consider only conductors with a circular cross section, whose radius is r.

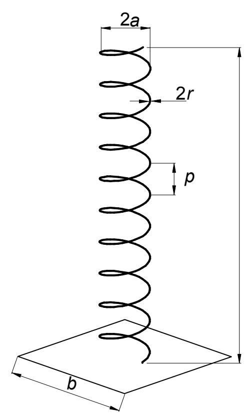


Fig. 1. Sketch of helical antenna.

The helical antenna is often located above a conducting ground plane. The plane can be very large (theoretically infinite) or be on the order of one wavelength (finite dimensions). Only the first case is considered in this paper. We assume that the helix is located in a vacuum. Helical antennas are analyzed using programs from References [9] and [10].

The antenna is fed by a generator connected at the antenna base, between the antenna and the ground plane. The feed is located on the periphery of the cylinder over which the axis of the helical conductor is wrapped, though it can be located elsewhere. In the numerical model, the antenna starts with a short vertical wire segment (whose length is $3r$). Its radius is chosen to be 10 times smaller than the radius of the helix wire, because the radius of this vertical segment impacts the antenna input impedance for thicker wire radii in both practice and computations. The feed is located at the base of this segment. In this paper, we assume that the antenna operates only in the axial mode.

Table I summarizes the basic geometrical parameters that define a helical antenna. It also presents some additional quantities (derived from the basic parameters) that are needed for our analysis.

TABLE I
GEOMETRICAL PARAMETERS OF HELICAL ANTENNA.

Quantity	Symbol	Relation to basic quantities
Helix radius	a	~
Helix diameter	D	$D = 2a$
Circumference	C	$C = 2\pi a$
Pitch	p	~
Pitch angle	α	$\alpha = \arctan\left(p/C\right)$
Number of turns	N	~
Antenna length	L	$L = Np$
Wire radius	r	~
Square ground plane side	b	~

To evaluate the electrical characteristics of a helical antenna, besides the geometrical parameters, we need to know the operating frequency (f) or the frequency band (B). The lower edge of the operating frequency band is f_{min} and the upper edge is f_{max}. The central frequency is defined as $f_{\mathrm{c}} = \left(f_{\mathrm{min}} + f_{\mathrm{max}}\right)/2$. The corresponding wavelength is $\lambda_{\mathrm{c}} = c/f_{\mathrm{c}}$. The frequency at which the maximal (peak) gain occurs is denoted as f_{p}. The corresponding wavelength is $\lambda_{\mathrm{p}} = c/f_{\mathrm{p}}$. The frequency at which $C = \lambda$ is denoted as f_0. The corresponding wavelength is $\lambda_0 = c/f_0$.

According to the classical design data [2], the helical antenna operates in the axial mode in the frequency band where $3/4 < C/\lambda < 4/3$ ($0.8 < C/\lambda < 1.2$ in [3]). The wire diameter has practically no influence on the antenna characteristics [4] in a wide range $0.005 < d/\lambda < 0.05$. Based mostly on experimental research, the optimal pitch angle was established to be in a relatively narrow range $12° < \alpha < 14°$ ($12° < \alpha < 15°$ in [2]). Within the operating frequency band, the antenna gain varies with frequency. The maximal antenna gain occurs near the upper edge of the operating frequency band (i.e., $f_{\mathrm{c}} < f_{\mathrm{p}} < f_{\mathrm{max}}$), when $C/\lambda_{\mathrm{p}} \approx 1.1 - 1.2$ [4]. The minimum number of turns is about $N = 4$. The size and shape of the ground plane are not critical. Typically, square or circular flat plates are used. The minimal size of the square plate (or the minimal circle diameter) is $b/\lambda_{\mathrm{c}} = 0.75$ [2] ($b/\lambda_{\mathrm{c}} = 0.5$ in [3]).

An empirical relation between the antenna gain and the axial length is [1]

$$g_{[\mathrm{dBi}]} = 10\log\left(15\left(\frac{C}{\lambda}\right)^2 \frac{L}{\lambda}\right). \tag{1}$$

Equation (1) holds for constant-pitch helices with $12° < \alpha < 15°$, $3/4 < C/\lambda < 4/3$, and $N > 3$. However, experimental data [5], [6] indicate that the numerical factor in (1) can be significantly lower than 15, i.e., between 4.2 and 7.7. Equation (1) is often used for the design of helical antennas and built into various antenna design programs.

Another relation between the antenna maximal gain and the axial length is [7]

$$g_{[\mathrm{dBi}]} = 10.25 + 1.22\frac{L}{\lambda_{\mathrm{p}}} - 0.0726\left(\frac{L}{\lambda_{\mathrm{p}}}\right)^2, \tag{2}$$

which is valid for $2 < L/\lambda_{\mathrm{p}} < 7$ and $p/\lambda_{\mathrm{p}} = 0.24$. The corresponding optimal radius of the helix is given by $a/\lambda_{\mathrm{p}} = 0.2025 - 0.0079\,L/\lambda_{\mathrm{p}} + 0.000515\,(L/\lambda_{\mathrm{p}})^2$. These formulas are result of extensive numerical modeling using program NEC [11]. In [7], the experimental data from [5] are compared with Equation (2). For $L/\lambda_{\mathrm{p}} = 2$, good agreement between measurements and Equation (2) is obtained. However, as the length of the antenna increases, Equation (2) underestimates the gain up to 2 dB. On the other hand, it is established in [5] that Equation (1) overestimates the antenna gain even for 4–5 dB. Hence, Equations (1) and (2) have opposite prediction of the actual antenna gain with respect to experiments.

These differences among results published in the open literature have motivated us to make systematic investigation of helical antenna characteristics.

III. NEW DESIGN VERSUS CLASSICAL DESIGN

In this section, we compare results obtained using Equation (1), experimental results from [5], [6], simulation data from [7], and the design curve from [8] with results obtained from our simulations, assuming an infinite ground plane.

The usual design goal is to obtain an antenna that has the best performance and minimal overall size. The key parameter that defines the size of helical antenna working in the axial mode is the length of the antenna axis (*L*). Hence, our primary target will be to maximize the antenna gain for given *L*, keeping under control the axial ratio and matching.

In an attempt to optimize the antenna parameters to obtain the maximal gain, we have observed that the maximal gain depends on the type of application (narrowband or broadband). For the narrowband application, the antenna parameters are optimized at a single frequency, by maximizing the gain. The gain of the narrowband antenna, as a function of frequency, has one well-defined maximum at the design frequency (f_{c}). Hence, $f_{\mathrm{c}} = f_{\mathrm{p}}$. We refer to the narrowband antenna design as the NB design. On the other hand, for broadband applications, the antenna properties are optimized for a range of frequencies. The goal is to maximize this range for a prescribed variation of antenna gain, given the maximal voltage standing-wave ratio (*VSWR*) and the axial ratio. Alternatively, for a given band, the goal is to maximize the gain, and to minimize *VSWR* and the axial ratio. We have arbitrarily adopted the total gain variations (Δg) of 1 dB, 2 dB, and 3 dB. We denote these three cases as the WB1, WB2, and WB3 design, respectively.

To compare results available in the literature with results obtained from our simulations for narrowband and wideband designs, we plot in Fig. 2 the maximal gain of the helical antenna as a function of the normalized axial length. For the data obtained using Equation (1) and for the data from [8], we have assumed that the normalizing wavelength is λ_p.[3]

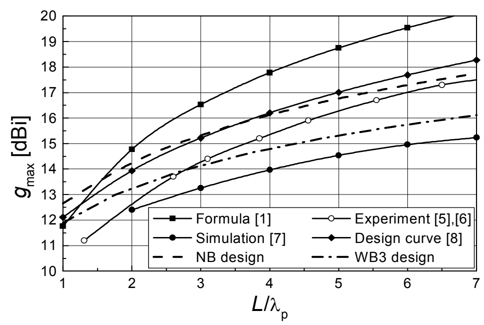


Fig. 2. Antenna gain versus normalized antenna length. Comparison of results obtained by: theoretical formula [1], experiment [5], [6], simulation [7], design curve [8], and our computations for narrowband design (NB) and 3 dB wideband design (WB3).

Fig. 2 shows that there are indeed large discrepancies in the predicted gain. Compared to our results for the NB design, Equation (1) gives an overestimated gain (for more than 2.5 dB for long helical antennas) and steeper gain increase with the antenna length (about 3 dB/octave). The simulation results from [7] underestimate the maximal gain. The results from the design curve given in [8] are similar to our curve for the NB design.

Comparison with the experimental results in [5], [6] is not straightforward. Our computer simulations of the antennas presented in [5], [6], assuming an infinite ground plane, lead to results for the gain that practically coincide with the curve from [7]. There are two reasons for such a large discrepancy. First, in the experimental model, the antenna has a cup (circular "cavity") instead of a large flat ground plane. This cup suppresses back radiation and increases the forward gain [12]. Second, the experiments in [5], [6] are performed at several ranges. There is a discrepancy in data in [5] and [6] about the length of the first range: 59 ft versus 10 ft. The second range is declared to be 30–40 ft. For the antennas measured at both ranges, there is a difference in measured gain of 0.25 dB for $L/\lambda_p = 4.6$, which decreases with reducing the antenna length. This difference can be attributed to improper calculation of the distance between the transmitting and the receiving antennas. In [5], it is explained that the distance is taken from the phase center of the helical antenna, which is assumed to be located at $L/4$ from the antenna feed point. However, our numerical simulations show that a more appropriate position is near the centroid of the antenna, i.e., close to $L/2$ from the feed point.

Although the experimental results [5], [6] have a boost, our estimated maximal gain for the NB design is still greater than the maximal gain obtained by the experiments. Also, our maximal gain is about 2 dB greater than the gain from [7]. These differences are due to different pitch angles used in [5]–[7] and in our simulations. In [5], [6], classical pitch angles are used ($12.5° - 14.5°$). The range of angles in [7] is also restricted to larger values. In contrast, our simulations use optimized pitch angles, which depend on the wire radius and on the antenna length.

In the following sections, we present a systematic revision of the data used for the design of helical antennas.

IV. OPTIMIZATION OF HELICAL ANTENNA PARAMETERS

In this section, we optimize antenna parameters to maximize the antenna gain and bandwidth. The optimization of the antenna parameters (e.g., C, α, and r) for the maximal gain depends on the type of application (narrowband or broadband). As mentioned earlier, we define the "maximal" gain in two ways. The first one is for narrowband applications, when we find the absolute maximum at a single frequency or in a narrow frequency band. The second one is for broadband applications, when we try to find the optimal gain in a wide band, where the gain has some prescribed variations. As a result of the optimization, we generate design curves that enable prediction of the antenna gain and bandwidth with respect to axial length, pitch angle, antenna circumference, and conductor radius.

The antenna analysis is much simpler and more efficient (due to the image theory) if the ground plane is taken to be infinite. Hence, we assume an infinite ground plane. In our models, we have included conductor losses as for copper at 300 MHz. We have found the effect of losses to be negligibly small even for thinnest wire considered[4], which agrees with the conclusions from [7]. We also neglect the influence of the dielectric or metallic support of the antenna and of the wire insulation.

To make results applicable to various frequency bands, we normalize the linear geometrical dimensions by the helix circumference (C). Within the operating band of the antenna, C is close to one wavelength. It becomes exactly $C = \lambda$ at the frequency f_0 that is usually within the operating band (for wideband designs) or very near it (for narrowband designs).

The normalized wire radius (r/C) is taken as a parameter, with a discrete set of values 0.00015, 0.0015, and 0.015. The last value is at the edge of validity of the thin-wire approximation. Thicker wires are not considered, as they require precise definition of the shape of the excitation region. For each wire radius, the antenna is swept over frequencies, for the number of turns (N) in the range 3–250, and for the

[3] If $\lambda_0 = C$ is taken instead, steeper curves would be obtained.

[4] Losses in the thinnest wire reduce the gain by 0.1–0.2 dB.

pitch angle (α) in the range 3°–20°. The results of the numerous simulations are collected in a considerably large database. From this database, we have extracted the information relevant for the antenna design.

A. Maximal Gain

From a practical point of view, the antenna length (*L*) is an important design parameter. Hence, we set the goal to maximize the gain (*g*) for the given normalized length (L/C). In the optimization, we set requests for the axial ratio and *VSWR* to be lower than 2, as these values are considered to be acceptable in practice [2].

Additionally, for the WB design, we define the edges of the operating band ($f_{\min}$ and $f_{\max}$) under the constraints that the gain is within the prescribed limit (Δg) below the maximal value. We evaluate the product of the numerical gain and the relative bandwidth ($G \cdot B$).

We search for antennas in the database whose gain (for the NB design) or gain-bandwidth product (for the WB design) is among the highest for a given normalized length. We have formed an ensemble of these antennas. We summarize their properties in the following graphs. The curves are obtained by averaging data over the corresponding ensemble.

For shorter antennas, the axial ratio is the limiting factor in many cases. For longer antennas, the variations of the gain determine the bandwidth. We note that numerical values for the axial ratio and *VSWR* are, in most cases, very close to each other.

The gain of the optimal helical antenna as a function of the antenna normalized length is presented in Fig. 3, for the NB and WB designs. The maximal deviation of results from the curves is ± 0.25 dB . Fig. 3 shows that the maximal gain (in dBi) increases with the normalized antenna length at a rate of about 1.5 dB/octave. It also shows that the maximal gain is sacrificed for the broadband applications. For example, it is 1−1.5 dB lower in the WB3 case than in the NB case.

Our computations show that for narrower bands and longer antennas the peak gain occurs when $C/\lambda_{p} < 1$, which does not fit into the well-established results [7].

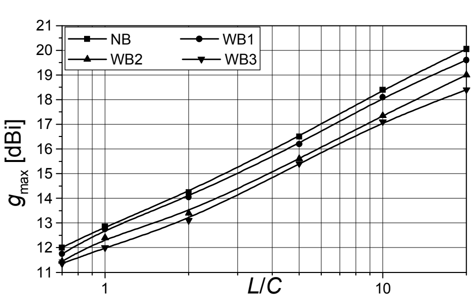


Fig. 3. Maximal antenna gain versus normalized antenna length.

B. Optimal Circumference

Fig. 4 shows the normalized helix circumference at the central design frequency (C/λ_{c}) as a function of the antenna normalized length (L/C). The curves for various designs almost coincide. The dispersion of values of C/λ_{c} about the curves is ± 0.05 .

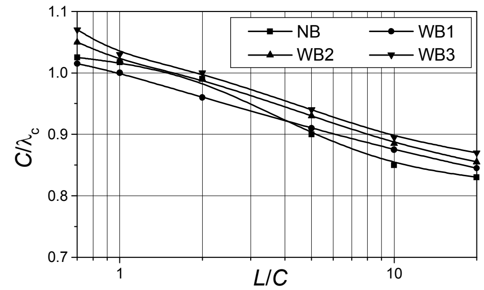


Fig. 4. Normalized circumference at central frequency (f_{c}) versus normalized antenna length.

C. Axial Ratio

Fig. 5 shows the axial ratio (in the direction along the antenna axis) at the frequency where the gain has the maximum (f_{p}) for the narrowband design.

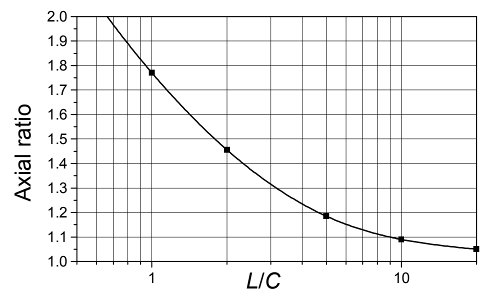
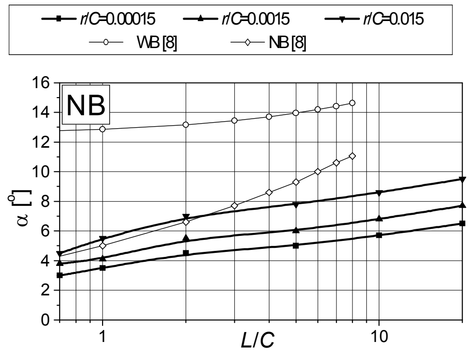
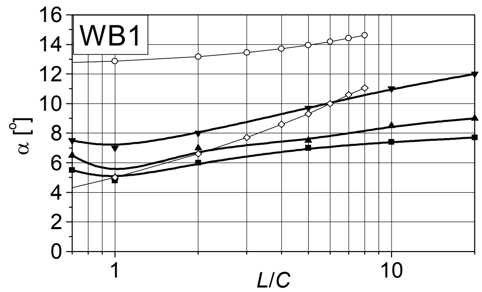


Fig. 5. Axial ratio at frequency of maximal gain (f_{p}) versus normalized antenna length.

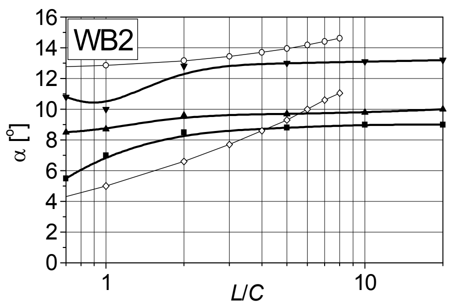
For the wideband design, the axial ratio increases going towards the edges of the frequency band. It sharply deteriorates near the lower edge ($f_{\min}$). For some antennas in the ensemble, the upper limit for the axial ratio ($A = 2$) defines the band edges, in particular for shorter antennas ($L/C < 1$). Only very few antennas in the ensemble for $L/C < 0.7$ satisfy the adopted request for the axial ratio ($A < 2$). Even if the request is satisfied, it happens only in a narrow bandwidth. Consequently, the resulting optimal antenna parameters and characteristics have large dispersion. This is the reason why we present our results only for $L/C > 0.7$ and why some curves for $0.7 < L/C < 1$ exhibit a different behavior than for $L/C > 1$. Consequently, for some antennas in the WB design, the axial ratio within the band can be as high as 2. However, the average value of the axial ratio decreases with increasing L/C practically following the curve in Fig. 5.



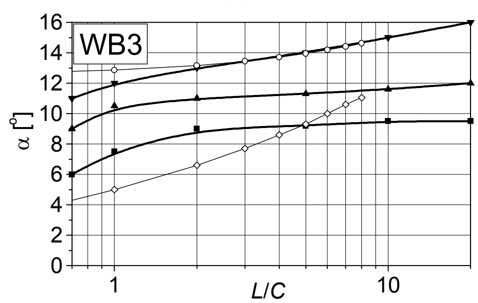
(a)



(b)



(c)



(d)

Fig. 6. Optimal pitch angle versus normalized antenna length with normalized wire radius as parameter for (a) NB, (b) WB1, (c) WB2, and (d) WB3 design.

D. Optimal Pitch Angle

Fig. 6 shows the optimal pitch angle versus the normalized antenna length, with the wire radius as the parameter, for the NB and WB designs. The deviations from the curves are on average $\pm 0.5°$. The results show that the optimal pitch angle increases with increasing the wire radius.

The maximal gain in the WB designs is achieved for larger pitch angles than in the NB design. Larger pitch angles correspond to larger allowed gain variations. Larger pitch angles also broaden the curve for the gain at the expense of lowering the peak gain for given L/C, as shown in Fig. 3.

Fig. 6 shows that the optimal pitch angle strongly depends on the wire radius and the desired gain variations within the operating band (which does not fit into the well-established results). The optimal pitch angles are in the range $3° < \alpha < 16°$. This is significantly wider than the classical range ($12° < \alpha < 14°$). The classical range is optimal practically only for the wideband design (in particular, the WB3 design) for antennas wound by thick wires.

Fig. 6 also shows two sets of optimal pitch angles presented in [8]. We interpret these two sets as the results for the NB and WB designs, respectively, although there is ambiguity in [8] about their meaning. These two sets are close to our results for the NB and WB3 design, respectively, for the thickest wires.

E. Relative Bandwidth, Input Impedance, and Other Issues

Fig. 7 shows the relative bandwidth for the WB1, WB2, and WB3 designs for various normalized wire radii (r/C). The deviation of the relative bandwidth from the curves is about $\pm 5\%$.

Generally, antennas with thicker conductors yield better broadband performance for the same antenna length. Up to 25% difference in the bandwidth is observed between the antennas with two extreme values of the wire radii in the BW3 design. The bandwidth decreases as the antenna length increases. Our results are in fair agreement with the results interpreted from [8].

The input impedance of a helical antenna depends on various parameters: wire radius, location of the feeding point, number of turns, helix radius and pitch, frequency, shape of the conductor in the feeding region, influence of the antenna mechanical support, etc. We compiled data for the input impedance for various antennas with the request that $VSWR < 2$ in the widest possible frequency range. $VSWR$ is obtained with respect to the optimal nominal impedance (Z_c), which is shown in Fig. 8 as the function of the pitch angle (α), with the normalized wire radius (r/C) as the parameter. The nominal impedance can be significantly different than 140 Ω declared by the classical design approach. It varies between 90 Ω and 270 Ω, what is inconsistent with the claims in [3]. Fig. 9 shows the reactance of the optimal series compensating element required for matching. The results shown in Figs. 8 and 9 are dispersive and the deviations are even $\pm 20\ \Omega$.

Fig. 10 presents a simple way to match the antenna to a 50 Ω feeder, by soldering an appropriately shaped metallic plate to the first turn of the helix conductor. This plate and the ground plane constitute a transformer. This technique is particularly convenient for helices made of relatively thick conductors, as the conductor shape does not need be modified. This technique is similar to the one presented in [13], where the matching plate is soldered upwards. Our geometry is better, because the metallic plate is soldered downwards and does not significantly produce parasitic radiation. It is also convenient for broadband matching.

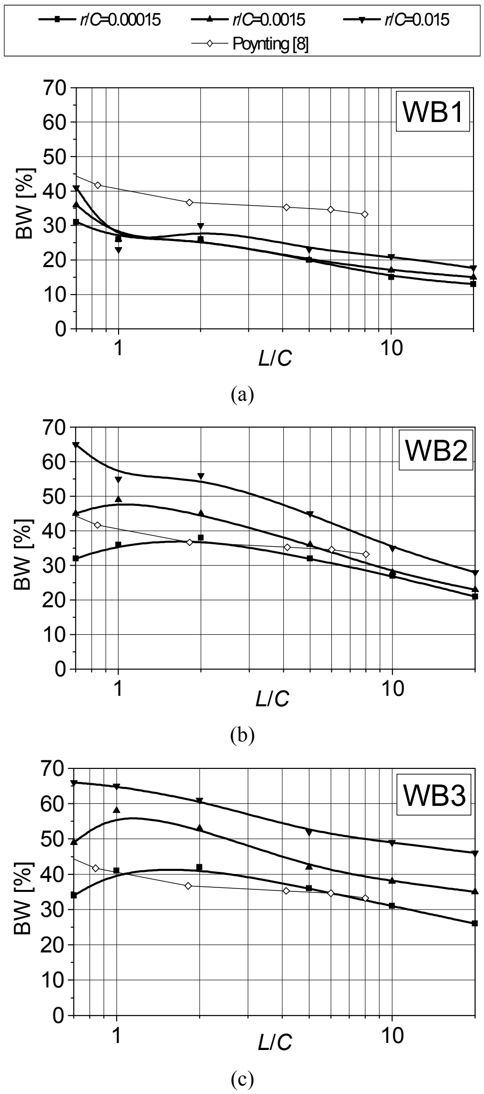


Fig. 7. Relative bandwidth versus normalized antenna length with normalized wire radius as parameter for (a) WB1, (b) WB2, and (c) WB3 design.

We have observed that the size and shape of the ground conductor of helical antennas have significant impact on the antenna gain. By shaping the ground conductor, we have increased the gain of a helical antenna for as much as 4 dB. Some details of this work are presented in [12].

V. Design Procedure and Experimental Verification

In this section, we present a design procedure and experimental results obtained using this procedure.

A. Design Procedure

Required input information to start the design procedure consists of: the frequency range and the central frequency f_c, required maximal antenna gain, allowed variations of the gain, axial ratio, and the required relative bandwidth.

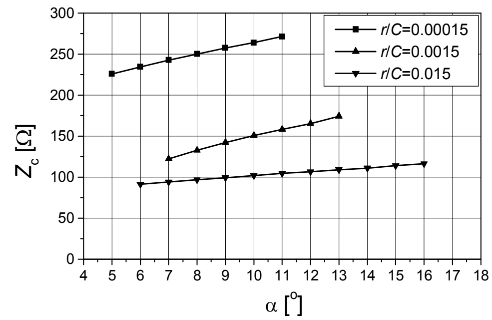


Fig. 8. Optimal nominal impedance versus pitch angle, with normalized wire radius as parameter.

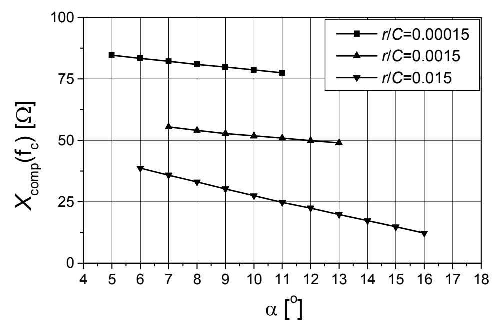


Fig. 9. Optimal reactance of series compensating element versus pitch angle, with normalized wire radius as parameter.

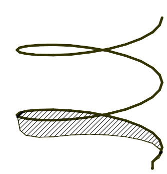


Fig. 10. Vertical profiled metallic plate as matching device.

The first step in the design procedure is to inspect Figs. 3, 5, and 7 to verify that specifications are achievable. The second step in the design procedure is to extract from Fig. 3 the information about the required antenna normalized length L/C, for the required maximal antenna gain. The third step in the design is to use Fig. 4 to obtain the normalized circumference C/λ_c for the required antenna normalized length L/C. Knowing the normalized circumference C/λ_c and the normalized length L/C, the denormalized values for the circumference C, the helix diameter D (using formula in Table I), and the antenna axial length L (using the antenna normalized length L/C) can be obtained.

The fourth step in the design procedure is to choose the optimal r–α pair from Fig. 6. In making the choice, one should note that a thicker conductor yields slightly higher gain. It also yields somewhat more wideband antenna properties and a lower input resistance than a thinner conductor does. Hence, a thicker conductor is recommended wherever its application is possible. Using the selected pitch angle and the formulas in Table I, the antenna pitch and the number of antenna turns can be calculated. Finally, the last step in the design procedure is to extract information about the optimal nominal impedance from Fig. 8 and information about the series compensating reactance from Fig. 9.

B. Experimental Verification

To illustrate the design procedure, we design a narrowband (NB) and a wideband (WB3) helical antenna. Designed antennas are simulated and measured. In both designs, a square metal plate with side $b = 600$ mm is used as the ground plane.

For the NB design, a helical antenna with gain 15.5 dBi at the frequency $f_c = f_p = 1.6$ GHz is chosen. The corresponding operating wavelength is $\lambda_c = \lambda_p = 187$ mm. The acceptable axial ratio is <1.5.

From Fig. 3 we extract the information about the required antenna normalized length. For the given gain, using the curve for the narrowband design (NB), we choose $L/C = 3.3$. From Fig. 5 we confirm that the expected axial ratio is 1.28 <1.5. From Fig. 4, we obtain the normalized circumference $C/\lambda_c = 0.94$. Then, the circumference is $C \approx 176$ mm, the corresponding helix diameter is $D = C/\pi \approx 56$ mm, and the antenna axial length is $L = 3.3\,C \approx 580.8$ mm. We select a wire with radius $r = 0.3$ mm, i.e., $r/C \approx 0.0017$. From the diagram for the narrowband design in Fig. 6, by interpolating between the curves for $r/C = 0.0015$ and $r/C = 0.015$, we estimate $\alpha = 5.8°$. The pitch is $p = C\tan\alpha = 17.88$ mm and the number of turns is $N = (L/C)/\tan\alpha \approx 32.5$. The required total wire length is $L/\sin\alpha \approx 5.75$ m.

For the WB3 design, a helical antenna for the frequency range 1.3–2 GHz, with the gain in the range (13 ± 1.5) dBi is chosen. The central frequency is $f_c = 1.65$ GHz, the corresponding wavelength is $\lambda_c = 182$ mm, and the relative bandwidth is 45%. The axial ratio is <1.5.

By inspecting Figs. 3, 5, and 7, we verify that our specifications are achievable. From Fig. 3, using the curve for the wideband design with 3 dB variations in gain (WB3) and the maximal gain $g_{max} = 14.5$ dBi, we choose the normalized antenna length $L/C = 3.46$. The circumference of the helix is $C = 176$ mm, the helix diameter is $D = C/\pi \approx 56$ mm, and the helix axial length is $L = 609$ mm. The wire radius is $r = 0.3$ mm, i.e., $r/C \approx 0.0017$, the optimal pitch angle is $\alpha = 11.2°$, the helix pitch is $p = 34.8$ mm, the number of turns is $N = 17.5$, and the total wire length is 3.135 m.

Fig. 11 compares simulated and measured results for the NB and WB3 helical antennas described above. Results show good agreement between measured and simulated results.

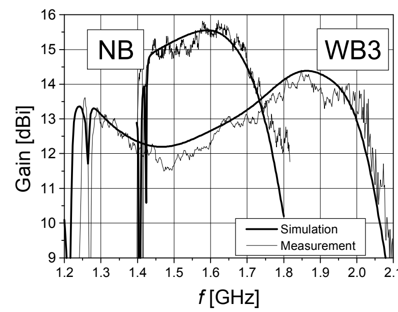


Fig. 11. Simulated and measured RHC gain for NB and WB3 design.

VI. CONCLUSIONS

The paper points out some inaccurate data about helical antennas that persist in the literature. We present a new set of data related to the optimal design of helical antennas (located above a large ground plane) with respect to the maximal gain, the axial ratio, the operating bandwidth, and the input impedance. The optimization is achieved based on computations of a large number of antennas, by varying many parameters. Diagrams are made and rules are established that enable simple but accurate design of helical antennas. The results are experimentally verified.

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