Using Antenna Modeling Software and an RF Analyzer - A Study for Student Oriented Helical Antenna Projects

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Shane Corbett is currently a senior electrical engineering student at the US Coast Guard Academy. At an early age Shane found himself tinkering with electronics more than he would like to admit. His parents feared buying him new pieces of technology because inevitably they would end in pieces on a work bench next to a kid with a smile on. Once accepted to the USCGA Shane took his curiosity to the classroom and began his studies within the EE major. After an antennas course his junior year he found himself perplexed at the intricacies of this field of study. He then pursued an internship at MIT Lincoln Labs in the radar development group where he worked on helical antennas. Once back at the Academy for his senior year he took up time to dive further into helical design. Shane is looking forward to graduation and service in the Coast Guard aboard a cutter out of Pensacola, Fl.

Abstract

This paper will present a student oriented, experimental approach to learning about the axial mode helical antenna. More specifically, students design, simulate, build, and then test a helical antenna. For simulations, we use software available in the public domain. Students then construct their antennas using readily available materials. Finally, they test their helical using a portable RF analyzer to measure the SWR and radiation pattern. The results show that the measured radiation pattern does indeed match their simulations. In both our empirical testing and simulations, students gain insight on how the three basic helical parameters of circumference, C, pitch angle, α, and number of turns, N, affects the antenna's performance. We also look at how dielectric loading can be employed to electrically lengthen an antenna causing for a drop in frequency with no change in physical size. Students also explore how spatial multiplexing can be achieved with differing polarizations (right hand vs left hand). Our approach allows students the opportunity to gain more insight into the characteristics of helical antennas so they can fully appreciate their capabilities as well as their limitations. Student assessment has shown that our approach greatly enhances understanding of helical antenna systems and has caused significant increase in student enthusiasm for selected topics in antennas.

Introduction

The helical antenna was invented by Dr. John D. Kraus in the 1940s [1]. The unique design has given this type of antenna several advantages over other directional antennas. These advantages include universal polarization, relatively high gain, broad band capability -with respect to both directionality and SWR- greater immunity to multipath interference, as well as having a relatively simple structure and feed system. Helical antennas are widely used in space satellite communication, wireless local area networks and in any other application where broadband operation is required [1,2] because of the latter mentioned advantages. Since helicals have become integral in communication systems, it serves as an important topic for an undergraduate antennas course.

The abstract nature of electromagnetics, and in particular antennas, provides a strong justification for an experiential learning technique with regards to helical antenna design. In our course we first describe the basic operation of the helical, and then proceed to have the students calculate theoretical values, design and simulate the antenna in software, and finally build and test their designs using a set of portable RF analyzers. They then compare their design's empirical results to their simulated and predicted results for understanding of the small uncertainties that are associated with electromagnetic studies. For our purposes in this project we focus primarily on the axial mode of propagation helical antenna. However, we also include the topics of the radial mode propagation helical and dielectric loading of the core. This part of the experiment explores how a material with a higher permittivity than air can electrically lengthen an antenna causing it to operate at a lower frequency than intended by initial design.

In the construction and testing phases of the helical we discuss the many engineering challenges that students have to overcome in order to make their antennas function properly, and enable an accurate characterization of parameters of interest. These include a design at the lowest possible frequency so as to minimize the effects of parasitic inductances and capacitances, the use of readily available construction materials to physically support the relatively large helical antenna dictated by its low frequency of operation, and then suitable dielectrics with sufficient relative permittivity, $\varepsilon_r > 1$ to lower the antennas resonant frequency.

Theory of Helical Antennas

Helical antennas have two operating modes, normal and axial. If the circumference is small, they operate in a normal mode where the propagation pattern looks similar to that of a monopole. A normal mode antenna can also be referred to as a broadside pattern antenna as the propagation is in the orthogonal plane and off the broadside of the main axis. This mode is popular if the application requires a small monopole antenna but it is physically impossible. The helical in normal mode has a "built in" loading coil, and thereby has a lower resonant frequency than its comparable sized monopole counterpart. As we enlarge the circumference, the axial mode propagation emerges as the dominant pattern. We also see this referred to as an end fire pattern meaning the main lobe is in line with the main axis. This mode has a focused main lobe in the direction of the vertical aspect of the antenna. The main physical design parameters of the helical that can affect the operating mode as well as other performance factors are spelled out in the below image.

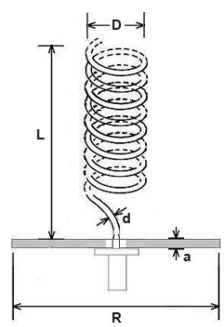

Figure 1. Helical antenna design parameters

The three parameters we will focus on in this study are circumference of the loop, the number of turns, and the pitch angle. From these three parameters we can calculate any of the other design parameters. For instance, the circumference can be found from the diameter, the spacing between turns can be found using the circumference and the pitch angle, and ultimately the spacing between turns and number of turns can give us the height. Let us take a closer look into the three aforementioned design parameters.

In the extremes, the helical can be viewed as either a loop or a dipole antenna. At one extreme when the circumference goes to zero you have a dipole or monopole, and the other extreme, when circumference goes to infinity you will have a loop-like antenna. The parameter of pitch angle acts in a similar way. If the pitch of the antenna approaches zero, you will end up with a loop antenna, and if the pitch approaches 90 degrees you will have designed a dipole. These two parameters directly affect the kind of propagation pattern you can expect in your final design.

The last parameter that has an effect on the antenna's performance is the number of turns. The number of turns is pivotal in determining the height of the antenna, which can cause the Voltage Standing Wave Ratio (VSWR) and bandwidth of the antenna to vary.

We care about both the VSWR and the bandwidth because they tell us how our antenna will perform in the RF spectrum. VSWR is a measure of the reflected power from the antenna back to the hardware. The value is typically represented as a ratio of the max voltage in the line to the minimum voltage. Ideally, you would want a VSWR of 1, but any value below or around 2 is perfectly acceptable. When the VSWR becomes too high, on the order of 5 or so, the mismatch is too great to transmit signals over the antenna at that frequency.

From the three design parameters we can calculate most characteristics of the antenna and provide insight into the type of propagation pattern, as well as performance characterization, at different frequencies. We now move to the equations that relate the physical parameters and the electromagnetic properties.

The basic theory of helical antennas is covered in Stutzman and Thiel [2]. The following is a brief recap of the pertinent theory. To start, when operating in the axial mode, the range of the antennas circumference should follow the equation below.

$$\frac{3}{4}\lambda \le C \le \frac{4}{3}\lambda .$$

Recalling that $C = \pi d$, we can derive the following equation $\pi d \ge \frac{3}{4}\lambda$. For practical student designs where we want to use the lowest possible frequency, the helix coil in this example is supported by a commonly available cardboard tube whose diameter is 10 inches or 25 cm. Thus the minimum wavelength would be $\lambda \le \frac{4}{3} \times \pi(d = 0.25m) \Rightarrow \lambda < 1\ m.$ and therefore the minimum frequency is approximately 300 MHz. At the other extreme, the maximum frequency is calculated to be $\lambda \ge \frac{3}{4} \times \pi(d = 0.25m) \Rightarrow \lambda > 0.59\ m \Rightarrow f \ge 509$ MHz. Thus, if we build a helical antenna using a 10 inch tube for support, the frequency range is, again approximately, from 300 to 550 MHz.

We can lower the operating frequency of a given sized helical by incorporating dielectric loading [3-6]. The following equation that relates the helical's operating frequency to the dielectric constant has been derived by Ezanuddin et al. [4,6] and is given as

$$f_{0\_GHZ} = \frac{8.553}{\sqrt{\varepsilon_r}\left(\frac{\pi}{4} D_r^2 L_r\right)^{1/3}}$$ Where ε_r is the relative permitivity of the dielectric,

D_r is the helical diameter in inches and L_r is the helical length in inches. Thus if we have an antenna supported by a 48 inch long cardboard tube whose diameter is 10 inches, and an air core, we have an operating frequency of

$$f = \frac{8.553}{\sqrt{1}\left(\frac{\pi}{4} \times 10^2 \times 48\right)^{1/3}} = 0.55 \text{ GHz} = 550 \text{ MHz}.$$

If we incorporate a dielectric with $\varepsilon_r = 2$ our operating frequency becomes 388 MHz. Even a modest increase in $\varepsilon_r = 1 \rightarrow 1.2$ gives us a reduction in operating frequency from $550 \rightarrow 502$ MHz. Thus, even a modest increase in dielectric permittivity will enable us to implement a helical at frequencies and physical dimensions otherwise not possible.

Another consideration during most antenna designs is polarization. The two most common are horizontal and vertically polarized antennas. With polarization, think of sunglasses, how they are designed to accept only certain rays of light. Similarly, vertically designed antennas cannot accept horizontally polarized signals and vice versa. This discrimination allows for spatial multiplexing and making it theoretically possible to transmit two different signals simultaneously at the same frequency without interference. Note however, this often does not occur in practice due to multipath. In the case of circularly polarized helical antennas, spatial multiplexing is achieved using right hand and left hand polarization rather than conventional vertical and horizontal. Circular polarization does have the advantage of being universally accepted by both horizontally and vertically polarized receivers.

Circular polarization can also be employed to reduce multipath interference as well. For example, if a right hand polarized signal gets reflected off a surface, it creates a left hand polarized signal and vice versa, hence, a reduced likelihood of multipath interference as the receiver, regardless of horizontal or vertical, can accept the circularly polarized signal. This is why FM broadcasters use circularly polarized antennas [7].

Procedure

Preliminary considerations: Before the students start the design process, we provide them with the basic theory from Stutzman and Thiel [2] for both types of helical antennas, the normal and axial modes. We also supply the relevant equations that relate dimensions to operating frequency, bandwidth, beam width and gain. We show that the helical is in the middle of two extremes – from fully stretched out being the dipole or monopole, versus the compacted version being the loop. We also point out, using some short lab demonstrations, how excess lead lengths can introduce stray, or parasitic, reactance which in turn can affect operating frequency, and impedance matching. These considerations as well as equipment limitations preclude antenna construction in excess of 1 GHz. From previous labs, students will have observed how nearby metallic objects will affect an antenna's SWR and radiation pattern and of course the higher the frequency the easier it is to obtain the far field radiation pattern. In any case, given our equipment, as well as practical construction constraints and materials, we decided to implement a helical whose operating frequency is 435 MHz.

The experimental work of Niow, Ezanuddin and others [3-6] greatly reduce the physical dimensions of their helicals by using such materials such as Teflon with $\varepsilon_r = 2.1$ or Barium Strontium Titanate (BST) with $\varepsilon_r > 100$. In our case, we did not have access to these materials. Even if we did, the physical dimensions of our helical inhibits us from using such a material. Therefore, we had to choose a dielectric that would be relatively lightweight, inexpensive, and readily available. In our case we chose fiberglass wool, which meets the criteria and is obtainable at a local hardware store.

Simulations: To help with calculations and guide a more self taught process a MATLAB script was written to explain each parameter and run the calculations for the theoretical design. This allowed for students to see where the numbers were coming from instead of google-ing a design calculator to do the work for them. For this project we set the frequency to 435MHz. This frequency is a usable HAM frequency that allows us to openly test our antenna. Note however, the RF analyzer source is extremely low power and thus should not interfere with other band users. In any case, from MATLAB we derived the following theoretical design parameters:

Parameter	**Value**
Wavelength	.6892 meters
Circumference (radius)	.5169 meters (.0823m)
Pitch	4.7°
Number of Turns	8
Height	.3446 meters

Table 1: Theoretical design parameters

Using the output from MATLAB we turn to the simulation software of choice, ***4Nec2*** radio frequency design suite. This software is easy to download and readily available for public use. The simulation software gives a thorough analysis of the model as shown in figure 2 below.

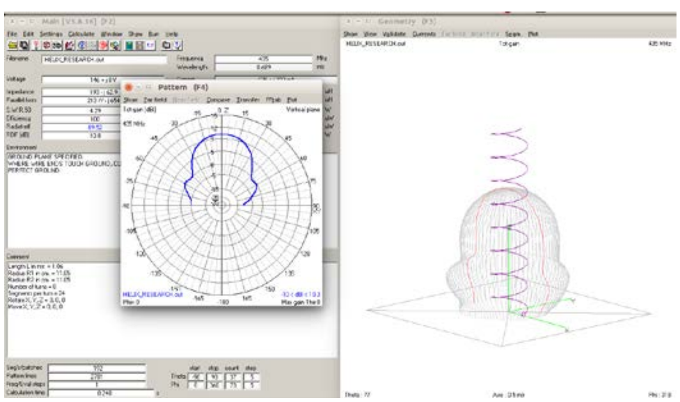

Figure 2: 4nec2 model output

As seen in the above model displayed in Figure 2, the helix is operating in an axial mode at 435MHz. This model however does not perfectly match the parameters outlined from MATLAB. The MATLAB results gave a baseline, the software allowed for fine tuning of the design. The final parameter design is listed in Table 2 below.

Parameter	Value
Wavelength	.6892 meters
Circumference (radius)	.6939 meters (.1105m)
Pitch	10.8º
Number of Turns	8
Height	1.06 meters

Table 2: Simulation design parameters

The biggest change between the theoretical and the simulation is the pitch. The design increased pitch by two times. In theory the pitch should fall between ten and fifteen degrees. The main reason for the change in pitch was the height was increased by a factor of three yet the number of turns remained at eight. The results of the simulated design are shown below in the third table.

Parameter	Value
VSWR	4.2
Propagation	Axial
Radiation Efficiency	89.52%

Table 3: Results of simulation

The simulation results above were based off the optimal design found through multiple trials. The simulated antenna gave us the desired propagation pattern. We obtained a VSWR of 4.2in the majority of simulations, not the best, but a workable number. Using the results, we constructed the antenna.

Building and testing: One of the main purposes of this build is to utilize every day, readily accessible materials. Therefore, the antenna build used a ten inch cardboard hollow cylinder used for concrete pouring for the core, 1/8 inch single strand copper wire for the conductor, an aluminum sheet for the ground plane, as well as zip ties and other fasteners to hold the antenna together. Our constructed antenna is shown below in Figure 3. Practical considerations required us to modify some of the design parameters and these are given in Table 4 below.

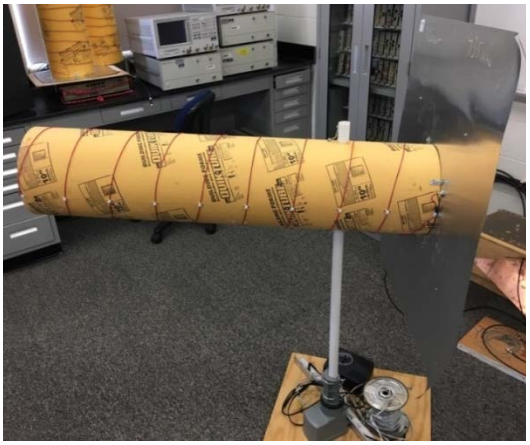

Figure 3: Final helical build

Parameter	Value
Wavelength	.6892 meters
Circumference (radius)	.8478 meters (.135m)
Pitch	8.9º
Number of Turns	9
Height	1.2 meters

Table 4: Final design parameters

Results and Discussion

For our tests, we want to make sure that at 435 MHz, the antenna is indeed operating in the axial mode with a radiation pattern similar to the simulations. We tested the antenna on an open field using the Keysight 9912A RF analyzer feeding into our helical as the signal source. We used a second 9912A with a vertical whip acting as a spectrum analyzer to measure the signal intensity. As shown in Figure 1, the helical was then mounted on a mechanical rotator 20 yards away from the receiver.

Using the mechanical rotator we transmitted a signal then recorded its intensity in increments of 12.5° of rotation. We recorded the VSWR at each angle and then normalized the data to create the pattern shown in Figure 4.

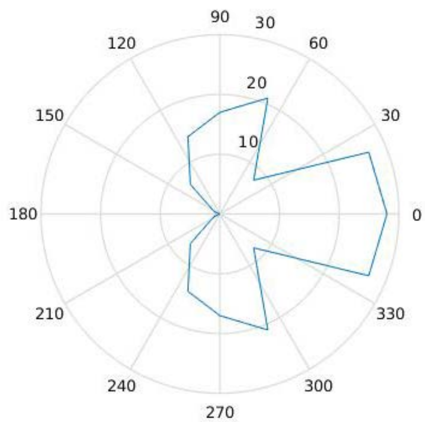

Figure 4: Propagation of the antenna

As seen above, the pattern of the antenna is the greatest in the direction of the main axis, angle 0 in the plot. This is the main lobe of our antenna. There are also two side lobes, which are expected as the ground plane is not a perfect infinite plane. Overall the pattern matches the prediction of an axial mode helical antenna fairly closely. The front the back gain of this particular propagation test is 28dB.

Now that we can confirm our antenna is propagating the way we want it to the second important parameter is the VSWR. For this test we use a 9912A signal analyzer on the SWR mode and swept from 1MHz to 1GHz and then again from 400MHz to 500MHz. The results of the initial unloaded sweep can be seen below in Figures 5 and 6 respectively.

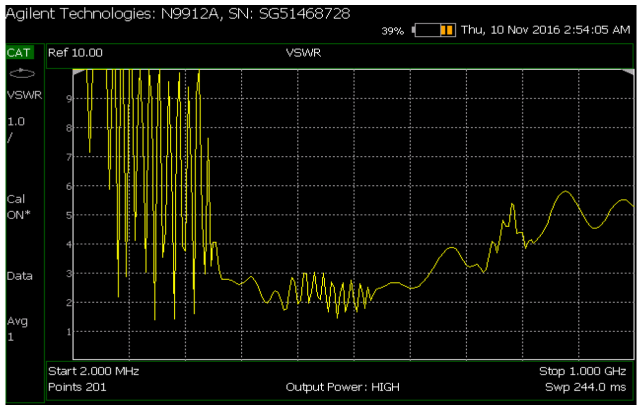

Figure 6: Full spectrum sweep

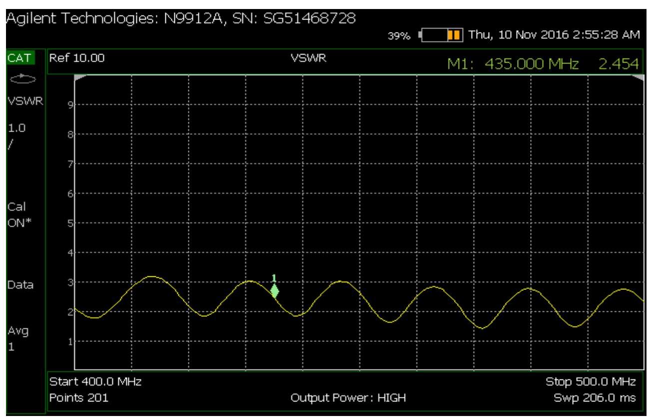

Figure 7: Zoomed in sweep (400MHz to 500MHz)

To note the specific frequency of interest, 435MHz, the VSWR of the antenna showed a 2.45. This is nearly half the predicted 4.2, which further shows the difference between theoretical, simulation, and real world measurements. Another important note is how broadband the antenna is. It is observed from Fig 6, that the VSWR is below 3 from 300 to 600 MHz. If we added a relatively simple matching network, we could observe a further reduction in SWR.

Loaded testing: The initial testing was done with an air core for the antenna (relative permittivity of 1). Dielectric loading offers a way of electrically lengthening the antenna without physically making the antenna larger. This is useful for applications that require a small antenna with a lower frequency. With keeping to the idea of readily available materials and the fact that our antenna is larger and cannot support heavy materials, we choose to test with commonly used fiberglass insulation in the helical core. .

With fiberglass loading, we get a VSWR sweep similar to one in Figure 7 except that the minimum SWR has shifted to a slightly lower frequency.

To get a more precise picture of the differences in SWR for the unloaded versus the loaded versions, we replotted the SWR data in 1 MHz increments at Figure 8. Note in the overlay, the approximate leftward shift in frequency, about 1MHz, for the loaded case. Thus, we

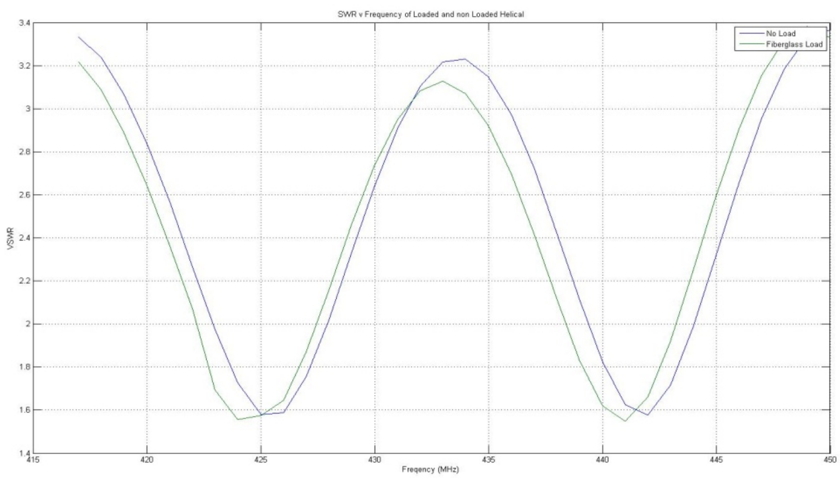

Figure 8: Overlay of no load and fiberglass load

can readily observe that the fiberglass loading does indeed electrically lengthen the antenna.

CONCLUSION

The study started as a comparison of theoretical, simulated, and empirical results. We found the theoretical values using helical antenna theory to drive us into the ball park for our design parameters. When plugged into the simulation software we found that the parameters could be manipulated slightly in order to yield better results. Ultimately we calculated a VSWR of 4.2 and an axial mode propagation pattern.

From our simulated data we strived to build a helical as close to the parameters derived in simulation. Due to common material sizes we came close but our final parameters were slightly off. However, this did not impact the overall design too much as we found a VSWR of 2.45 at 435MHz for our control and an axial propagation pattern.

Finally we explored dielectric loading with the common material of fiber glass. We found the fiber glass to have minimal effect on the antenna; however this small effect was still a change in the electrical properties of the antenna. The change constituted a frequency shift of 1MHz to the left.

This project allows for students to see the differences in the design process as well as appreciate the small factors that can affect an electromagnetic design. These small factors can be the dielectric example, multipath off of a nearby object in the testing field, or the difference between what is available and the design parameters. From the theory to the design to the implementation there are always changes to be made and experiential learning to be done.

References

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APPENDIX

MATLAB CODE for Helical Design: Can be used to walk through the calculations of the Helical antenna. User inputs frequency, number of turns, pitch angle, and diameter. Simple program to aid in the design understanding.

```
%%
% Antennas Lab Helical Design for Direction Finding
% 1/c Shane Corbett
%
% Helical operating frequency is based almost entirely off of the
% circumference of the turns.  These antennas can be quite broadband, and
% they can also operate in two modes.  In "End Fire" mode, the prop pattern
% is directional in the direction of the z-axis.  To operate at this mode
% the following equation applies .75*lambda < cir < 1.25*lambda.  This also
% defines the bandwidth of the antenna.
%
% Point being... You are tasked to create a helical with an fo of about
% 435MHz.  So we will just go ahead and start by defining a few things.

%%
% Basic values
f     = 435 * 10^6;       % 435MHz for resonant frequency
c     = 2.998 * 10^8;     % Speed of light
```

```
lambda  = c/f;              % Wavelength of operating freq
% Now you can select the fraction of the frequency the circumference will
% be.  This will be constrained based off of material used for core so
% measure the diameter to calculate circumference (cir).
diam    = input('What is the diameter of your core?'); %make sure to input in meters
cir     = diam*pi;
cir_l   = cir/lambda;         % This is the circumference relative to wavelength
% Again looking for in between .75 and 1.25
%%
% Pitch is another factor for the antenna.  If the angle goes to zero, you
% have a loop antenna, and if the angle approaches 90 you have a dipole.
% generally speaking you want to aim for a pitch of around 10-15 degrees.
% we can also now define how many turns, usually between 6-10 is
% sufficient.  From that we will derive our total height and total length.

pitch   = input('What is the pitch angle you wish to use? ');
pitch   = pitch *pi/180;      % Calculate pitch into radians
spacing = tan(pitch)*cir;     % Spacing between turns
turns   = input('How many turns on your antenna? ');
tot_h   = turns*spacing;      % Total height of the antenna
tot_l   = tot_h + cir * turns;% Total length of wire
```