Toroidal Coil Wire Length Calculations

It can be very worrisome when setting up a build project and it comes time to determine how much wire is needed to wind a toroidal coil. It stands to reason that it can be calculated, but who knows how to do so? It gets worse when we realize that toroidal cores are manufactured with two different cross-sectional areas, either a rectangular cross-section or a circular cross-section. Obviously, differing lengths of wire would be needed in these two different situations. In this informative article, we are going to look at three things:

- how to calculate the minimum length of wire to wind a specified number of turns of a given diameter wire on a toroidal core having a rectangular cross section (a *toroid)*;
- how to calculate the minimum length of wire to wind a specified number of turns of a given diameter wire on a toroidal core having a circular cross section (a *torus*); and
- how to determine the maximum number of turns of a given wire size that can be installed in a single layer on a toroidal core of a given size.

The information that we need to perform the wire length calculations is relatively easy to obtain, either by direct measurement of the materials on hand, or by looking for the information online. Either way, what we need to know includes:

1. the cross-sectional shape of the core;
2. the height of the core if it is of a rectangular cross-section;
3. the inner radius of the core;
4. the outer radius of the core;
5. the radius of the wire; and
6. the number of turns to be installed.

Bear in mind that in every case above, we need to use the *radius,* but dimensions measured or listed online are usually the *diameters* of the various factors. Remember that the radius is always one-half of the diameter.

Two different equations are used, depending upon the cross-sectional shape. For a toroid having a rectangular cross-sectional shape, the equation to be used is:

$$\sqrt{\left(n(4r + 2H + 2B - 2A)\right)^2 \; + \; \left(\pi(A + B)\right)^2}$$

where:

n is the number of turns of wire to be wound,
r is the radius of the wire to be used,
H is the height of the toroid,
A is the inner radius of the toroid, and
B is the outer radius of the toroid.

For a torus having a circular cross-sectional shape, the equation to be used is:

$$\pi\, n\sqrt{(2r + B - A)^2 \;+\; \left((A + B)/n\right)^2}$$

where:

- n is the number of turns of wire to be wound,
- r is the radius of the wire to be used,
- A is the inner radius of the torus, and
- B is the outer radius of the torus.

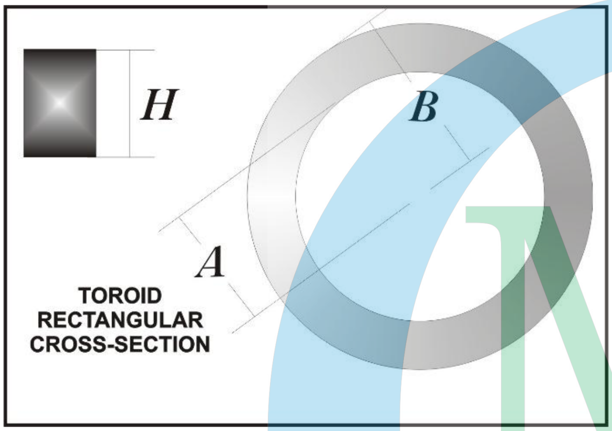

Figure 1 - Rectangular cross-section toroid references

Let's take a quick look at an example of each of these two equations as applied to real-world situations. Suppose you know that you need to wind 30 turns of 26AWG enamel-coated magnet wire on a rectangular cross-sectional T50-43 toroidal core. The following is a listing of the equation variables (Figure 1):

1. the height of the toroid (H) – 0.187";
2. the inner radius of the toroid (A) – 0.140";
3. the outer radius of the toroid (B) – 0.250";
4. the radius of the wire (r) – 0.0085"; and
5. the number of turns to be installed (n) – 30.

Now, we plug those values into the rectangular toroid equation as follows:

$$\sqrt{\left(30(0.0340 + 0.372 + 0.500 - 0.280)\right)^2 \;+\; \left(\pi(0.140 + 0.250)\right)^2} =$$

$$\sqrt{\left(30(0.626)\right)^2 \;+\; \left(\pi(0.390)\right)^2} =$$

$$\sqrt{(18.78)^2 \;+\; (1.225)^2} =$$

$$\sqrt{(352.688) + \;(1.500)} =$$

$$\sqrt{354.188} =$$

$$18.82''.$$

This would indicate that the minimum length of wire needed to wind 30 turns of 22AWG magnet wire into a T50-43 toroidal core is nineteen inches. Do not forget that some additional wire length is needed for handling and for making the connections into the circuit. I tend to add an additional foot (twelve inches) of wire length just to be comfortable and to have sufficient wire to handle the job, pulling the wire snug as I wind it. Some wire length is needed for that handling, and the wire is, in the overall scheme of things, relatively inexpensive.

Moving on to the circular cross-sectional toroidal cores, we will look at an example of one of those coils as well. However, it should be understood that the rectangular cross-section is the more desired form for toroidal cores. This is based on several good reasons. First, the rectangular cross-section core is easier to manufacture. These cores start as a powder that is formed into a solid under pressure in a form, and it is simpler to exert that pressure in straight lines. That is a simplification, but it gets the point across. In addition, a rectangular core will have a more uniform pattern of magnetic flux density than will a circular core, which also makes the rectangle the preferred shape. Finally, there is the fact that for a given outside diameter core, a squared or rectangular cross-section will have a larger inside diameter dimension than will a circular core. As a result of that difference, the rectangular core of a given outside diameter will offer more space for the installation of wire turns inside that core than will a torus.

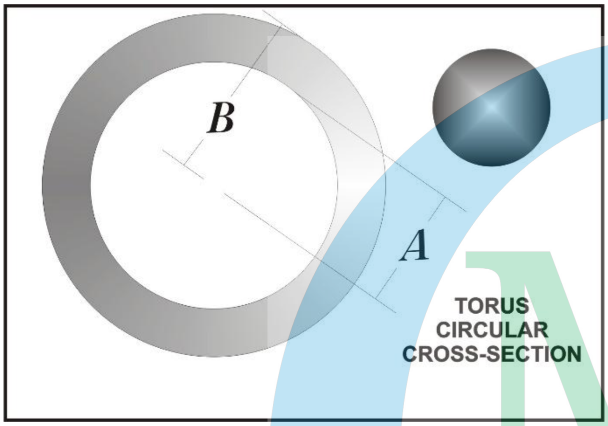

Figure 2 - Circular cross-section torus references

Let's consider a torus having an outside diameter of 1.125" and an inside diameter of 0.6". We are going to wind this core with 25 turns of 36AWG wire. How much wire is needed, as a minimum (Figure 2)?

Our variables for this equation are as follows:

1. the inner radius of the torus (A) – 0.300";
2. the outer radius of the torus (B) – 0.5625";
3. the radius of the wire (r) – 0.0028"; and
4. the number of turns to be installed (n) – 25.

As a reminder, the equation is provided on the first line below, followed by our values plugged in where they belong:

$$\pi\, n\sqrt{(2r + B - A)^2 \; + \; \left((A + B)/n\right)^2} \; =$$

$$\pi\, 25\sqrt{(0.0056 + 0.5625 - 0.300)^2 \; + \; \left((0.5625 + 0.300)/25\right)^2} \; =$$

$$\pi\, 25\sqrt{(0.2681)^2 \; + \; (0.0345)^2} \; =$$

$$\pi\, 25\sqrt{0.07187761 + \; 0.00119025} \; =$$

$$\pi\, 25\sqrt{0.07306786} \; =$$

$$\pi\, 25 \; x \; 0.270310673 \; =$$

$$\pi\, 6.757766828 \; =$$

$$21.23015062" \; or \; 22".$$

Thus, in this case, we would need at least twenty-two inches of 36AWG wire, plus any allowance for tails and handling. While, when compared to the previous example this may seem like an incorrect length of wire, it must be remembered that this torus is more than twice the outer diameter of the previous toroid. The numbers do not lie, though fat fingers and running the calculator too quickly can introduce some errors, so work slowly and check your calculations to make sure that they are correct.

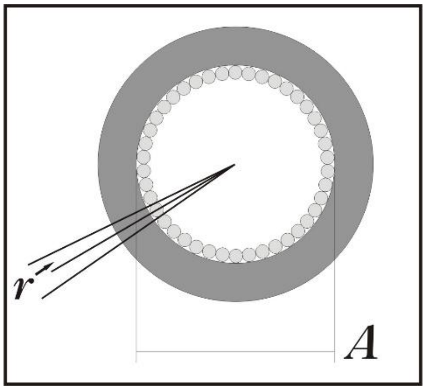

Figure 3 - Single-layer turns references

OK – so far, we have seen how to calculate the minimum length of wire needed for a given number of turns of a given size wire on a given size core. What if, instead, we simply want to know how many turns we can fit in a single layer on a specific core, using a given wire gauge? Of course, that too can be calculated. In electronics, there is an equation for just about anything and everything. The necessary equation for this calculation is as follows (Figure 3):

$$n = \pi \,/\, sin^{-1}\,\left(r \,/\, (A - r)\right)$$

where:

- n is the maximum number of turns that will fit in a single layer,
- r is the radius of the wire to be used, and
- A is the inner radius of the toroidal core.

For those who may be wondering, sin^{-1} is another way of writing or expressing the value $arcsin$. I use the sin^{-1} expression here because that is what will be found on a scientific calculator, and I wanted it to be crystal clear to the reader.

For this example, we will suppose that we are back with our T50-43 toroid, having an inside radius of 0.140", and we will be winding 22AWG magnet wire having a radius of 0.014". So… how many turns will fit in a single layer? If we plug these values into the equation, we get:

$$n = \pi \,/\, sin^{-1}\,\left(0.014 \,/\, (0.140 - 0.014)\right) =$$

$$n = \pi \,/\, sin^{-1}\,\left(0.014 \,/\, (0.126)\right) =$$

$$n = \pi \,/\, sin^{-1}(0.111111) =$$

$$n = \pi \,/\, 0.111340903 =$$

$n = 28.21597977$ or $n = 28$ turns maximum.

It is critical to note that this equation is worked using radians rather than degrees. Be sure to set your scientific calculator to *radians* mode to get this equation to work out. If you would rather work in degrees, place the scientific calculator in *degrees* mode and replace π with 180. The equation below uses the same variables, but is worked in degrees instead of in radians:

$$n = 180 \,/\, sin^{-1}\,\left(0.014 \,/\, (0.140 - 0.014)\right) =$$

$$n = 180 \,/\, sin^{-1}\,\left(0.014 \,/\, (0.126)\right) =$$

$$n = 180 \,/\, sin^{-1}(0.111111) =$$

$$n = 180 \,/\, 6.379363803 =$$

$n = 28.21597977$ or $n = 28$ turns maximum.

In another article about the build of a -30dB RF sampler, I make note of the fact that I wound 32 turns of 22AWG wire onto an FT50-43 toroid. In that article, it was not stated that all of those turns were in a single layer, as from the above it is obvious that 32 turns simply will not fit in a single layer on that toroid. However, in order for that pickup coil to work at the power ratio desired, a total of 32 turns were required, so I wound that number of turns, and they overlapped slightly over the last few turns. Magnetically, it is the number of turns that matters more than the actual positioning of those turns. The magnetic operation is dependent upon the permeability of the core, the number of turns, and the current flowing in the wire.

This article was intended to help the reader to understand the calculations involved in ensuring that sufficient wire length is on hand when winding toroidal coils. While these equations are geometrically accurate, the manner in which the wire is wound on the core has a great effect on how well the maximum number of turns will actually fit on the core. Install each turn directly in place against the preceding wrap of wire when initially winding the coil. The turns can be spread apart afterwards if necessary for tuning.

As I have mentioned in other places in various other articles, it is always a good idea to kill the sharp edges of the toroidal core. This is done so that the enamel is not inadvertently scraped off the wire as the wire is pulled through and/or wrapped around the core. The edge corners can be rounded over using a knife edge, using a file, using a countersink bit (when the core is small enough), or using abrasive cloth or paper. It does not take much work to round these corners, but it pays some worthwhile benefits. I typically use my Dremel tool with an abrasive drum in the chuck to do this job.

If the finished coil is one on which the wire tends to loosen and slip, the coil can be wrapped with a strip of glass cloth tape such as 3M #69 tape, made specifically for use on transformers and electromagnetic devices. This tape or its equivalent is readily available from companies such as Amidon and other firms that specialize in materials for electromagnetic components and supplies.

When a toroidal coil is being wound, each pass of the wire through the center of the toroidal core is counted as a turn. Thus, a single wire simply passing through a core is considered to be a one-turn coil. In the other article referenced above, I described the construction of an inductive attenuating RF sampler in which a 32-turn toroidal coil is placed onto a short length of coaxial cable that is pulled taut between a pair of SO-239 panel-mount connectors. Although the toroidal coil is described in detail, mention is barely made of the fact that this construction is actually a transformer having a primary winding with only a single turn.

It is apparent that some of this information has little or nothing at all to do with the main subject of *this* article, but it is nonetheless pertinent to toroidal coil design and assembly. As such, it is appropriately included in this article. Much of the time, it is the incidental information that makes the biggest difference in the ultimate achievement of success.