Understanding the Behavior of Baluns

The inductance of a toroid can be calculated as:

$$\text{(1)}\ L = 2\mu N^2 2.54H \ln\frac{OD}{ID} x10^{-9}\ Henries$$

where OD, ID and H are the core dimensions in inches, μ is the material permeability and N is the number of turns.

The inductance of any core shape can be calculated as:

$$\text{(2)}\ L = \frac{.4\Pi\mu N^2 A_e}{\lambda_e} x10^{-8}\ Henries$$

where A_e and l_e are the effective cross sectional area and magnetic path length, respectively.

It can be seen from Equation 1 that inductance is proportional to the OD/ID ratio and height of the core. Equation 2 shows that the inductance of any core form is proportional to its A_e/l_e ratio. In cores where the magnetic path intersects varying cross sectional areas, inductance is calculated by using the summation of the A_e/l_e segments.

In a toroid, where the cross sectional area is consistent throughout the magnetic path, the A_e and l_e are calculated as:

$$\text{(3)}\ A_e = \frac{.5H \ln^2 OD/ID}{\frac{1}{ID} - \frac{1}{OD}}\ \text{cm}^2 \quad \text{(x } 2.54^2 \text{ when using in.)}$$

and

$$\text{(4)}\ \lambda_e = \frac{\Pi \ln OD/ID}{\frac{1}{ID} - \frac{1}{OD}}\ \text{cm} \quad \text{(x 2.54 when using in.}$$

A typical balun form is depicted in Figure 1. In this form, T is the outer diameter of two imaginary toroids whose outer edges overlap in the balun's center. C_L is the distance between the hole centers and determines the extent to which the imaginary toroids overlap one another. A line is drawn between the intersection points of the imaginary toroids, forming a flattened portion of both. An angle, α, is formed by the horizontal core centerline and a line drawn from one hole center to one intersection of the imaginary toroids.

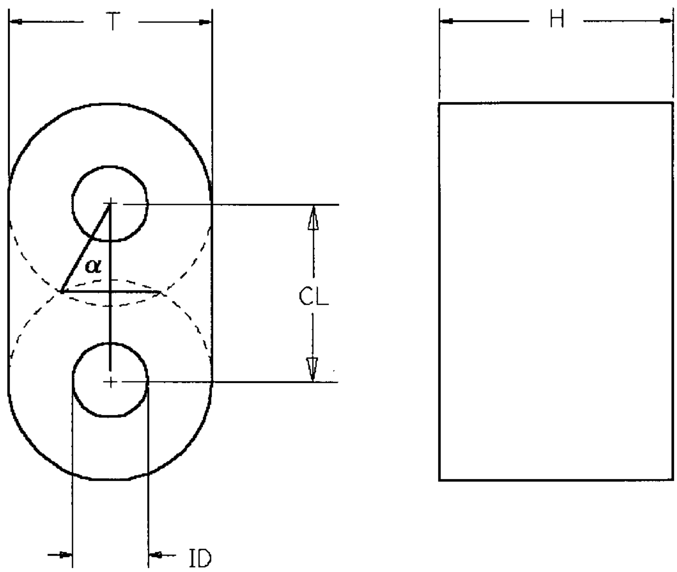


Figure 1

In order to accurately predict the A_L for balun cores with a single wire passed through both holes, Ferronics has traditionally used the following formulas, which have been verified with over thirty years of performance data:

(5) Intersection angle: $$\alpha = \cos^{-1}\frac{C_L}{T}$$

(6) Path length to Area: $$\sum\frac{\lambda}{\mathrm{A}} = \frac{\Pi}{H}\left[\frac{\alpha/360}{\ln\frac{C_L}{ID}} + \frac{(360-\alpha)/360}{\ln\frac{T}{ID}}\right]cm^{-1}$$

(7) Inductance: $$L_o = \frac{4H}{\frac{\alpha/360}{\ln\frac{C_L}{ID}} + \frac{(360-\alpha)/360}{\ln\frac{T}{ID}}}x10^{-9}\,Henries$$ (dimensions in cm)

The A_e/l_e ratio in the nonintersecting regions of the imaginary toroids is equivalent to that of a discreet toroid having an OD equal to T and the same ID. In the intersecting regions, the OD is assumed to be C_L, (OD radius being $C_L/2$). When the core outer diameter is flattened, the cross sectional area is reduced to a greater extent than the magnetic path length and as a result, its A_e/l_e ratio is reduced. Therefore, the extent to which the balun A_L is reduced when compared to the A_L of two discreet toroids with OD = T and the same ID and height placed side by side, is determined by the amount of overlap in the imaginary toroid sections.

The following table illustrates this point:

Table 1

Part Number	α (Degrees)	Balun A_L (nH/N^2)	Toroid A_L* (nH/N^2)*	Ratio (Bal/Tor)	T (in.)	ID (in.)	C_L (in.)
12-315-B	43.82	3700	3983	.929	.079	.034	.057
12-322-B	30.29	5639	5714	.987	.120	.047	.105
12-340-B	44.05	4575	4983	.918	.160	.073	.115

*Toroid A_L is the inductance of two discreet toroids with OD = T, ID = ID and H = H with a single turn through each.

From the table it can be seen that α is proportional to the extent of overlap of the balun imaginary toroids. In the 12-315 B and 12-340-B, A_L is reduced to a greater extent than in the 12-322-B, where there is minimal overlap.

The preceding discussion assumes that a balun will behave as if it were two discreet toroids shaped as in Figure 2, placed flat side to flat side and wound hole-to-hole. It also assumes that flux lines will be evenly distributed throughout the cross-sectional area they intersect, i.e., if there is flux present in each half of the core, the flux paths of each half will be confined to the area shown in Figure 2. Conversely, if a winding exists through one hole only, wound hole-to-outside, the available cross-sectional area in the core center will be increased to a greater extent than the path length, resulting in a higher A_e/l_e ratio in the overlapping section.

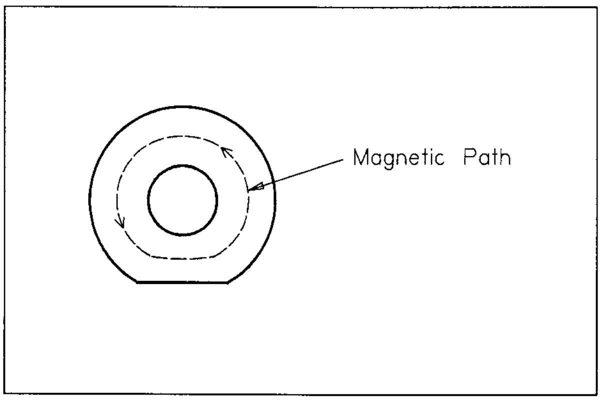


Figure 2

In applications where AC and DC excitation are low, significant overlap of the imaginary toroids results in only a reduction of inductance per turn. However, in high AC flux density and/or high DC field applications, the reduction of cross sectional area can cause significant performance degradation. When the balun is wound hole-to-hole, the flux travels in circular paths around the hole in each half of the core, clockwise in one half and counterclockwise in the other. The amount of flux present in the section between the holes is twice that of the outer core portions. If the available cross-sectional area between the holes is reduced by way of significant overlap, flux density, (B), will be greater than in the non-overlapping sections. In high DC field or high AC excitation applications, the center of the core will saturate before the non-overlapping sections, causing premature inductance roll-off..

Thus, expectations are:

1. Balun cores wound hole-to-hole will exhibit lower inductance than discreet toroids having the same dimensions as the balun imaginary toroids. The amount of reduction is proportional to the extent of overlap of the imaginary toroids.

2. Balun cores wound through one hole only and wound hole-to-outside will exhibit inductance that is greater than half the inductance produced by the same core wound hole-to-hole. The increased inductance will be proportional to the distance between holes.

3. As DC Field, (H) and/or as AC Flux Density, (B), is increased, permeability of balun cores wound hole-to-hole will decrease at a faster rate than their discreet toroid counterparts. The rate of deterioration in permeability is proportional to the amount of overlap of the imaginary toroids.

Experiments

Three balun cores having different dimensions were produced using the same raw material powder and firing. Note that different firing profiles are used for different core sizes since small cores with higher surface area to volume characteristics react more sensitively to firing conditions. Therefore, in the same firing, smaller cores will be higher in permeability than larger cores. In investigating Expectations 1 and 2, one core in each size was wound with three 5-turn windings. One winding was made hole-to-hole. Additionally, a 5-turn winding was placed on each hole, wound hole-to-outside. Each winding was tested for inductance at 100KHz, B = 5 Gauss.

The 5-turn hole-to-hole winding was used to calculate core permeability, using the following formula:

$$\mu = \frac{5000 * N^2 L}{A_L}$$

where L is the measurement in Henries and A_L is the published core A_L in nH.

Permeability results for the three parts are summarized in Table 2.

Table 2

Part Number	Permeability (μ)
12-315-B	5335
12-322-B	4328
12-340-B	4521

In Table 3, Column 1 lists the average of the two Hole-To-Outside windings. Column 2 lists the Hole-To-Hole winding inductance.

Table 3

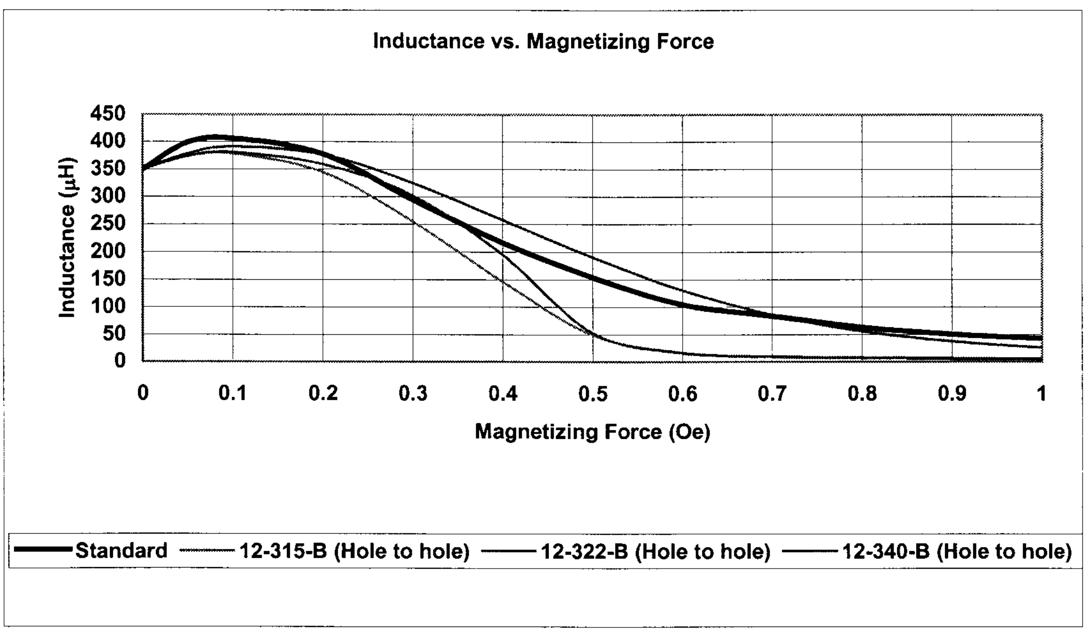
Part Number	(1) LS_{AVG} (μH) Hole-to-Outside	(2) L_s (μH) Hole-to-Hole	(3) LS_{NOM} (μH)[1] Imaginary Toroid Hole-to-Outside	(4) LS_{NOM} (μH)[2] Imaginary Toroid Hole-to-Hole
12-315-B	58.65	98.69	53.12	106.24
12-322-B	66.90	122.03	61.83	123.64
12-340-B	62.90	103.41	56.32	112.64

1. Inductance for a single core with imaginary core dimensions wound with 5 turns and having the actual measured permeability.
2. Inductance for a two cores with imaginary core dimensions placed side by side, wound with 5 turns hole-to-hole and having the actual measured permeability.

As expected, baluns wound with a single winding through one hole exhibit inductance significantly higher than half the hole-to-hole winding on the same core. The 12-315-B and 12-340-B showed increases of 10.8% and 11.7% respectively, while the 12-322-B showed an increase of 8.2%.

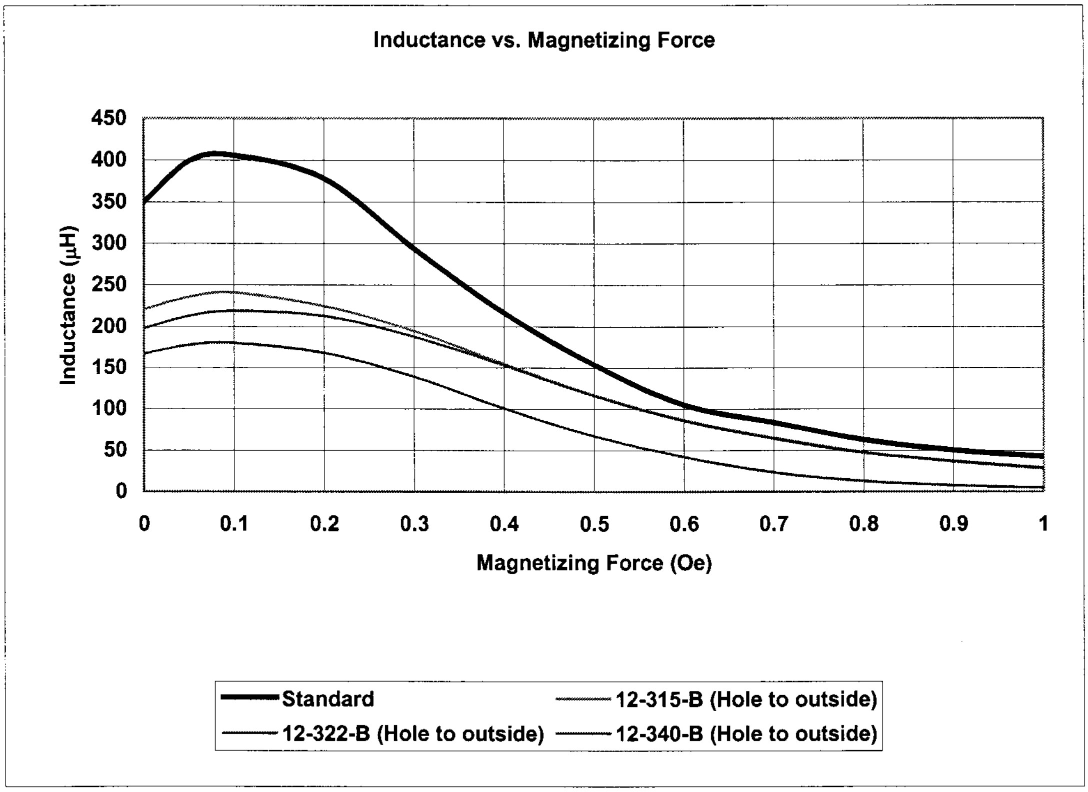
The three core sizes were then tested for Inductance vs. Magnetizing Force with a hole-to-hole winding and then with a single winding hole-to-outside. Each core type was tested with the number of turns being determined by calculating the number of turns necessary to reach 350μH with nominal A_L. For each H point measurement, DC current was calculated using each balun's imaginary toroid l_e. Graph 1 displays results of the hole-to-hole winding test compared to a standard performance curve for B Material, normalized to 350μH. Note the rapid fall of the 12-315-B and 12-340-B and the better 12-322-B performance.

Graph 1



Graph 2 depicts the single winding measurements. In this case all parts seem to exhibit normal inductance drop with increasing H field.

Graph2



In the preceding measurements, hole-to-hole windings produced flux that traveled in the same direction in the area between the holes. In this configuration, if the cross sectional area between the holes is less than twice the area of the outer portions of the imaginary toroids, the center of the core will saturate before the outer portions. If the winding were placed with half the turns in one hole and the remaining half in the other hole as depicted in Figure 3, the flux paths will be clockwise around each hole. Fields created by high DC current will cancel one another between the holes and saturation will occur in the outer portions of the core.

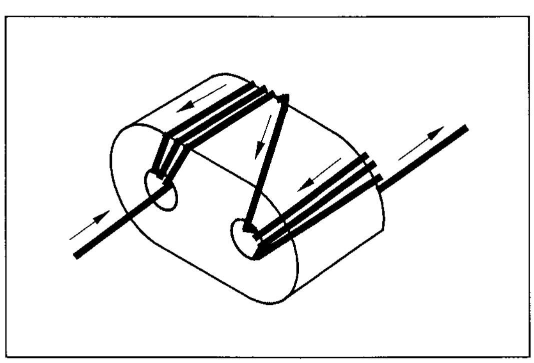
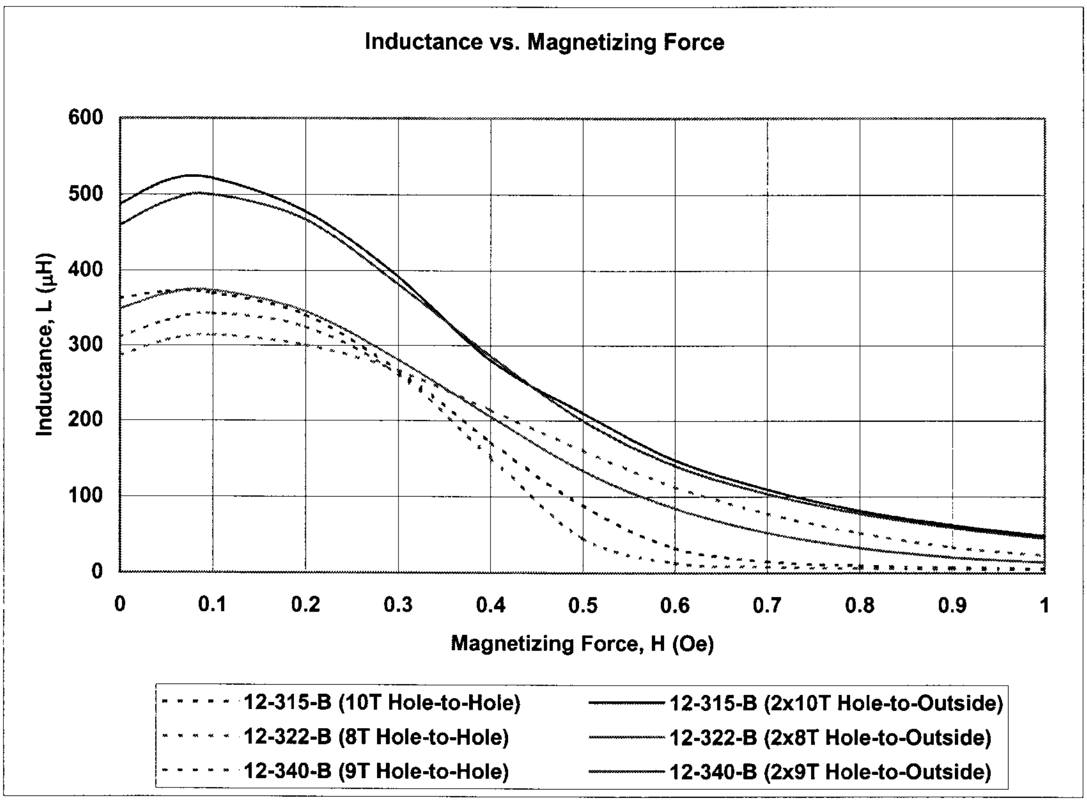


Figure 3

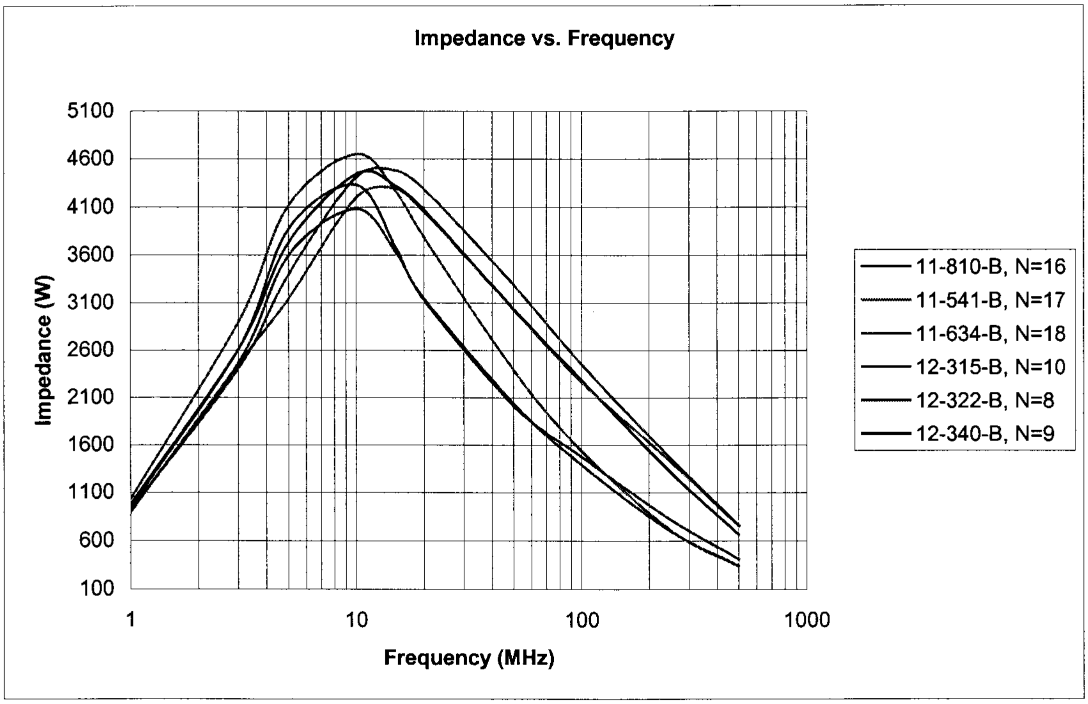
Graph 3 compares the Hole-To-Hole inductance with the inductance for the same cores wound as in Figure 3, as Magnetizing Force is increased. As demonstrated previously, note the large inductance increase for the 12-315-B and 12-340-B because of the larger overlap of the imaginary toroids. Also note that in the 12-322-B, where there was almost no overlap of the imaginary toroids, the initial inductance increase is modest. In the 12-322-B the traditional hole-to-hole winding produced slightly better results at Magnetizing Forces above .4 Oersteds, demonstrating that it saturated in the outer regions before the center regardless of the winding because of the ample area between holes.

Graph 3



In order to properly evaluate a core's potential suitability in high frequency analog applications or in rectangular waveform applications with fast pulse rise and fall times, its impedance characteristic should be investigated. Graph 4 depicts Impedance vs. Frequency for the three balun cores and three toroid cores currently used in DC Bias applications. N was calculated as the number of turns needed to produce 350μH using nominal A_L. All balun cores showed lower self-resonant frequency and high frequency impedance than the toroid cores, even though there were significantly fewer turns and total winding wire length. In the toroid cores, turns could be placed adjacent to preceding turns, without overlap. However, in the balun cores, turns became necessarily "bunched" in the holes, which probably increased the distributed capacitance.

Graph 4



Conclusions

When selecting a core of any type for DC Bias applications, the OD, height and OD/ID ratio should be as large as is practical, considering both the available space and degree of difficulty of winding. Maximizing these dimensions will produce higher A_L and fewer turns, which will reduce magnetizing force. Balun cores have traditionally been used in high frequency and/or wideband applications, where number of turns and average length per turn is low. For this reason, their OD/ID ratios are typically larger than toroids, which are normally designed to accept more turns. When using balun cores wound hole-to-hole, care must be taken to ensure that the cross-sectional area between holes is large enough to withstand the additional flux without saturating prematurely. For the balun core sizes examined in this note, deterioration of inductance due to insufficient center cross-sectional area occurred at magnetizing forces over .2 Oersteds.