Choosing a Ferrite for the Suppression of EMI

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INTRODUCTION

The mysteries of magnetism have been perplexing investigators for millennia. Naturally occurring magnetite stones, discovered in the district of Magnesia in Asia Minor, first found application in the lodestone of early navigators. Named magnetite because of its source, this weak form of hard ferrite was the precursor of the soft ferrites* we know today, but it was not until the 1930s that this analogous material was successfully synthesized. Applications soon became abundant and varied. Originally manufactured in a few select shapes and sizes, primarily for inductor and antenna applications, soft ferrite has proliferated into countless sizes and shapes for a multitude of uses.

Ferrite cores can be used on component leads or in board level circuitry to prevent parasitic oscillation and attenuate unwanted signal pickup.

Ferrite cores are used predominantly in three types of applications — low level applications, power applications, and as electromagnetic interference (EMI) suppressors (Figure 1). This article will focus on ferrites employed in EMI suppression.

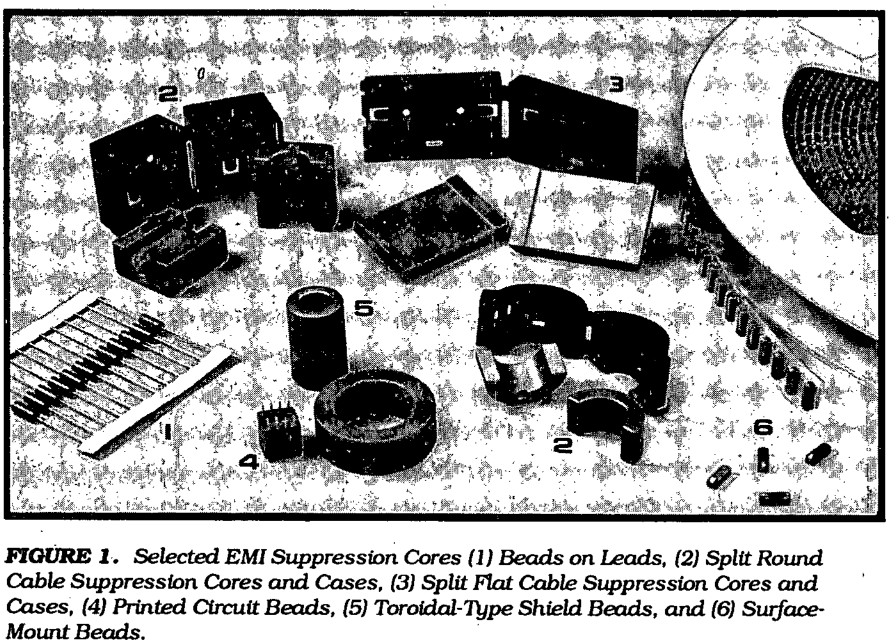

FIGURE 1. Selected EMI Suppression Cores (1) Beads on Leads, (2) Split Round Cable Suppression Cores and Cases, (3) Split Flat Cable Suppression Cores and Cases, (4) Printed Circuit Beads, (5) Toroidal-Type Shield Beads, and (6) Surface-Mount Beads.

There are basically three different ways to use ferrites as suppressors of unwanted signals. The first, and least common, involves the use of a ferrite to isolate a conductor, component or circuit from an environment of stray electromagnetic fields. The second application is in conjunction with a capacitive element to create a lowpass filter that is basically inductance-capacitance (LC) at low frequencies. The third and most common use will be addressed in this article. In this case the cores are used alone on component leads or in board level circuitry either to prevent any parasitic oscillations or to attenuate unwanted signal pickup or transmissions which might travel along component leads or interconnecting wires, traces, or cables.

WHAT IS A FERRITE?

Ferrite is a class of ferromagnetic materials that has a cubic crystalline structure. It is a magnetic ceramic with susceptibilities and permeabilities that are dependent on the field strength and magnetization curves that exhibit hysteresis. It is hard and brittle and grayish to black in color. Ferrites have the general chemical formula $MO.Fe_2O_3$, where MO is generally two or more divalent metal oxides compounded with 48 to 60 mole percent iron oxide.

The end user should remember the following important points:

- Ferrite is a ceramic. It will chip and break if handled roughly. It

* *Soft Ferrite: The difference between hard and soft ferrites is not tactile, but rather a magnetic characteristic. Soft ferrite does not retain significant magnetization, whereas hard ferrite magnetization is considered permanent.*

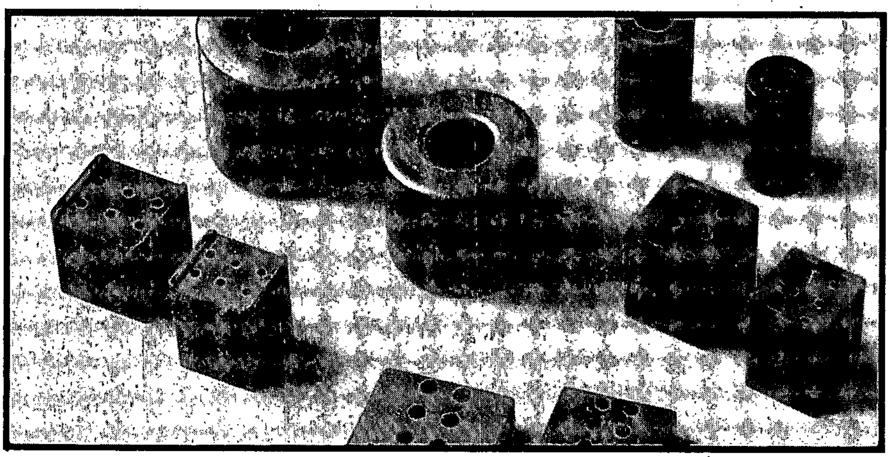

FIGURE 2. *Ferrite Parts Before and After Sintering Showing 15 Percent Dimensional Shrinkage.*

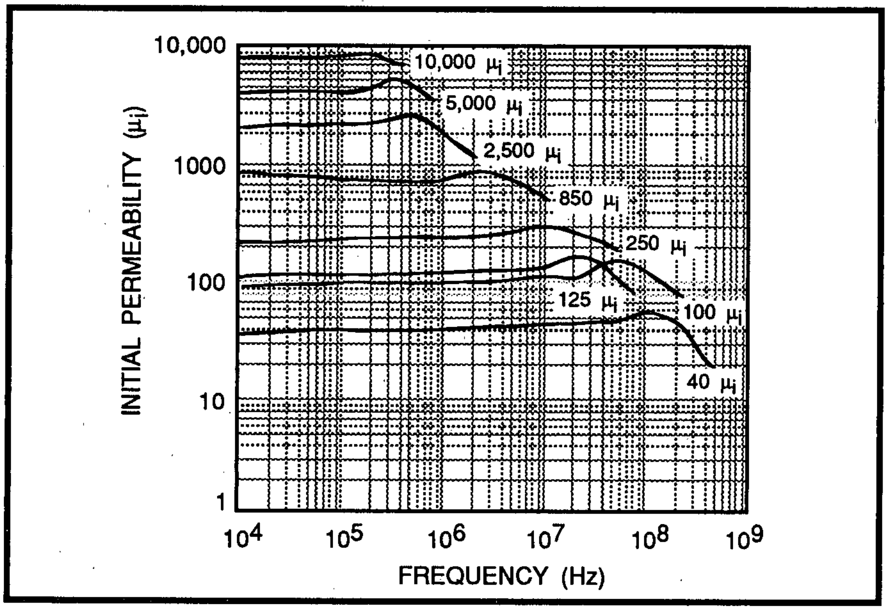

FIGURE 3. *Initial Permeability vs. Frequency for Various Ferrite Materials.*

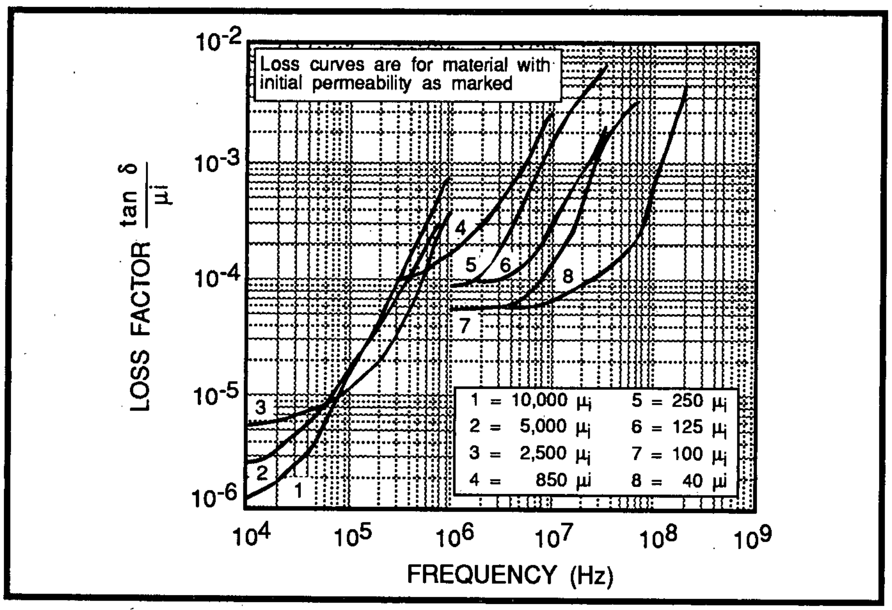

FIGURE 4. *Loss Factor vs. Frequency for Ferrite Materials Represented in Figure 3.*

is not quite as fragile as porcelain, but probably should be treated as carefully as fine china. Often these chips or cracks affect the appearance of the core but not the performance.

- Ferrite is sintered (fired in kilns). Ferrite's mechanical and electromagnetic characteristics depend heavily on the sintering process which is time, temperature, and atmosphere dependent.
- Ferrite shrinks when sintered. The shrinkage may vary from 10 percent to 17 percent on a dimension (the pressed core volume is as much as 60 percent larger than the sintered value) depending on the specific ferrite. Figure 2 is a photograph of cores before and after firing. Maintaining dimensional tolerances and preventing warpage and/or cracking related to the shrinkage during the sintering process are fundamental concerns.
- Ferrite has a cubic crystalline structure with the chemical formula $MO.Fe_2O_3$. The addition of various amounts of divalent metals (MO), such as zinc, nickel, manganese and copper, allows the creation of many different materials for a variety of end uses.
- Ferrite's magnetic characteristics can be affected by pressure, temperature, field strength, frequency and time.

UNDERSTANDING THE MAGNETICS

Although permeability and quality factor play a role in the performance of a ferrite EMI suppressor, the frequency of usage usually puts these parameters beyond the point of meaningful definition. As will be discussed later, the core's impedance is specified instead.

The permeability of a material is a complex parameter consisting of a real and an imaginary part. The

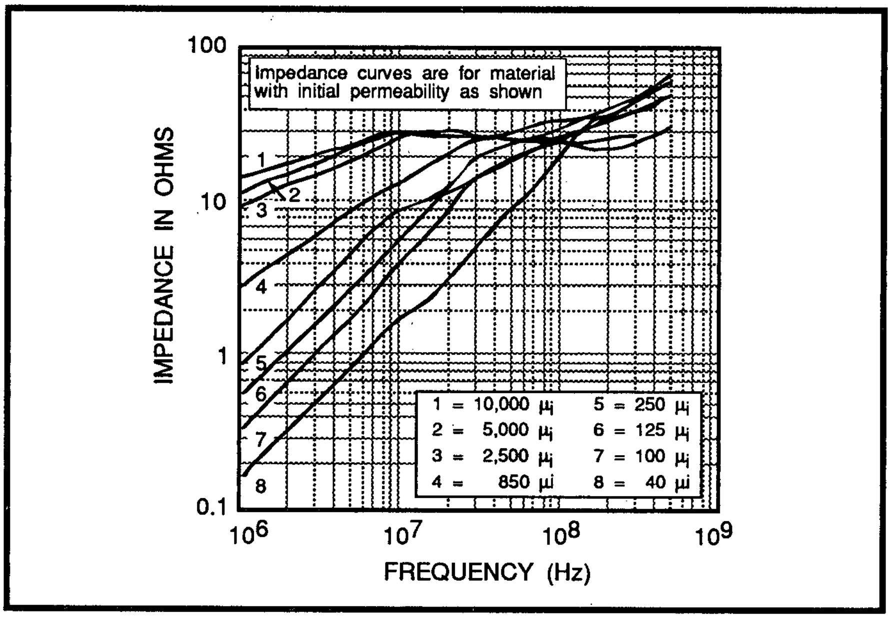

FIGURE 5. *Impedance vs. Frequency for Ferrite Materials Represented in Figures 3 and 4.*

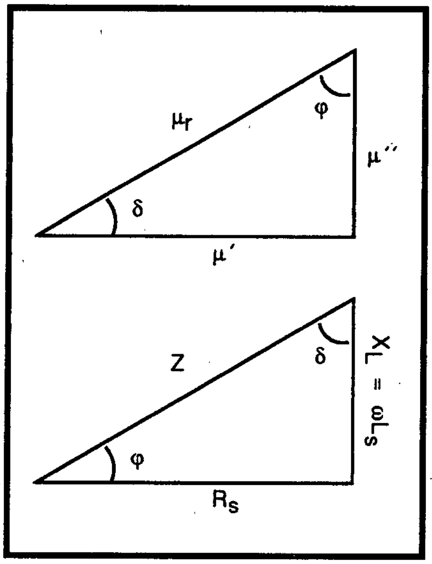

FIGURE 6. *Vector Relationship Between Real and Imaginary Components of Impedance, Complex Permeability, Series Resistance and Inductive Reactance.*

real component represents the reactive portion and the imaginary component represents the losses. These may be expressed as series components (μ_s', μ_s'') or parallel components (μ_p', μ_p'').

The curves in Figure 3 are typical graphs of the permeability (μ_s') versus frequency for various ferrite materials. The curves of Figure 4 are plots of loss factors ($\tan \delta/\mu_i$) in parts per million (ppm) versus frequency for the same materials. The total loss tangent ($\tan \delta$) is the reciprocal of the Q factor and is a measure of the energy lost or incurred as the magnetization alternates. The real part of the permeability (μ_s') of these materials ranges from 40 to 10,000. In almost all cases, μ_s' of the material first remains constant with frequency, then rises to a maximum value after which it falls off sharply. The material loss component μ_s'' rises to a peak as μ_s' falls. This is principally due to ferromagnetic resonance or spin precession resonance. It should be noted that the higher the permeability the lower the frequency at which this occurs. This was first observed by J.L. Snoek and given the relationship:

$$f_{res} = \gamma M_{sat}/3\pi(\mu_i - 1)\,\text{Hz} \qquad (1)$$

where:

f_{res} = frequency at which μ_s'' is maximum
γ = gyromatic ratio $\approx 0.22 \cdot 10^6\, A^{-1}m$
μ_i = initial permeability
$M_{sat} \approx 250\text{-}350 \cdot 10^3\, Am^{-1}$

This same relationship can be approximated by:

$$f_{max} \approx B_{sat}/\mu_i\ \text{MHz} \qquad (2)$$

where f_{max} is the frequency limit of useful core inductance, not to be confused with the maximum usable frequency for attenuation.

The impedance of a ferrite core is considered to be a series combination of the inductive reactance ($j\omega L_s$) and the loss resistance (R_s), both of which are frequency dependent. At low frequencies the impedance of the suppressor core is primarily the inductive reactance, which is a function of the material's permeability, and unwanted signals are mostly reflected. As the frequency increases, the inductive reactance decreases. Even so, the total impedance increases due to increasing losses, and unwanted signals are absorbed.

Figure 5 represents curves of impedance versus frequency for the same ferrite materials in Figures 3 and 4. Comparison of the three graphs shows that as the permeability decreases, the losses increase and the impedance rises to a maximum, then either levels off or declines.

The following equations relate the series impedance and the complex permeability (Figure 6):

$$\begin{aligned} Z &= j\omega L_s + R \\ &= j\omega L_o(\mu_s' - j\mu_s'')\,\text{ohm} \end{aligned} \qquad (3)$$

so that

$$\omega L_s = \omega L_o \mu_s'\ \text{ohm} \qquad (4)$$

$$Rs = \omega L_o \mu_s''\ \text{ohm} \qquad (5)$$

where: L_o = Air Core Inductance

$$\text{and } \tan \delta = \frac{R_s}{\omega L_s} = \frac{\mu_s''}{\mu_s'} = \frac{1}{Q} \qquad (6)$$

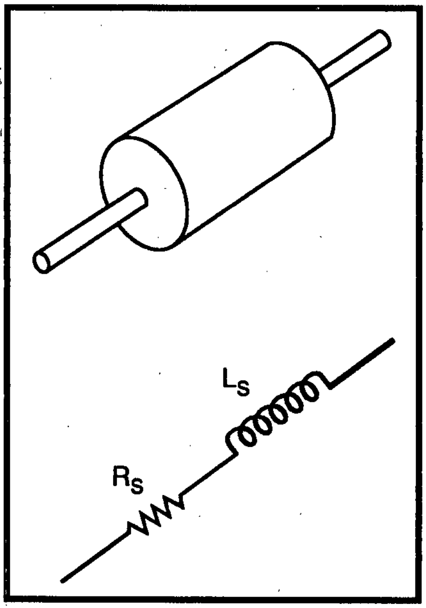

FIGURE 7. Equivalent Circuit of a Ferrite Core, an Inductor in Series with a Resistor.

$$\tan \Phi = \frac{\omega L_s}{R_s} = Q \qquad (7)$$

$$Z = [(\omega L_s)^2 + R_s^2]^{1/2} \qquad (8)$$

Figure 7 is the simplest representation of the equivalent circuit of a ferrite core, an inductor in series with a resistor.

HOW TO CHOOSE THE OPTIMUM FERRITE

The designer or the retrofitter choosing the ferrite for optimum performance in combatting EMI should know the following:

- Frequency of the unwanted signals
- Source of the EMI
- Environmental conditions, temperature, and field strengths, ac and dc
- Whether high resistivity is required because of multiple turns, conductor pins in a connector filter plate, or position in the circuit
- The circuit impedance, source and load
- How much attenuation is required
- The allowable space on the board

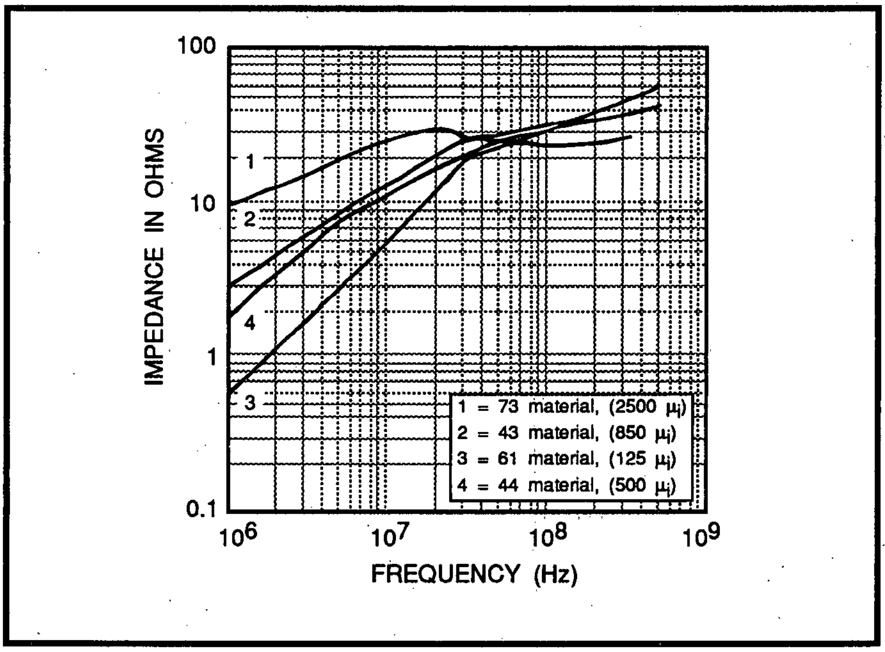

FIGURE 8. Impedance vs. Frequency for Four Suppressor Materials.

The choice of the best ferrite material is based on the frequency or frequency range of the interference that must be suppressed.

Although most manufacturers of ferrite cores produce more than 10 materials, only a select few have been offered for use in the suppression of EMI. The impedance versus frequency curves for four major suppressor materials are shown in Figure 8. The 73 material is a high permeability, 2500 μ_i, low resistivity (10^2 ohm-cm) manganese zinc material, which is the material of choice for suppressing signals of 30 MHz or less. A wideband suppressor material, 43, is a medium permeability, 850 μ_i, higher resistivity (10^5 ohm-cm) nickel zinc material, designed for suppression of signals between 25 and 200 MHz. The third material, 61, is a low permeability, 125 μ_i high resistivity (10^8 ohm-cm) nickel zinc material that is recommended for use at frequencies above 200 MHz. The fourth material, 44, is similar in many respects to the 43 material. It provides much higher volume resistivity (10^9 ohm-cm), but somewhat lower impedance over the same frequency range.

A comparison of Figure 8 with Figure 5 shows why manufacturers have limited production to several choice materials. Simply stated, why offer 10 materials, when three or four will cover the same frequency range effectively?

Covering the broadest frequency range with several materials is economical for both the manufacturer and the consumer, but if the application frequency is specific, rather than over this range, the most effective material may not be one of those offered. As an example, if optimum attenuation must be achieved at between 1 and 10 MHz, a 5000 or 10,000 permeability material could be much more effective than the standard 2500 permeability. Figure 9 shows the impedance versus frequency curves for the same size bead in three different materials. Comparisons show that the impedance of the 10,000 permeability material is superior up to 6 MHz, at which point the 5000 permeability material becomes more effective. At approximately 14 MHz, the standard 2500 permeability material takes over. Therefore, if the requirement is

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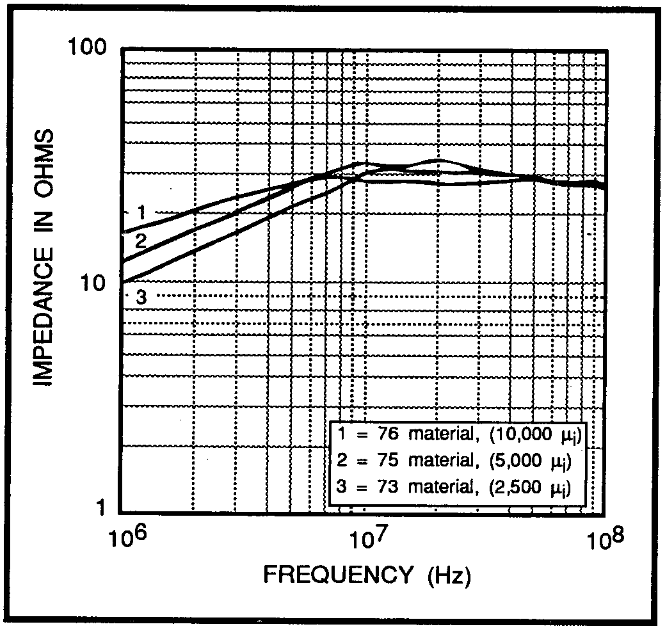

FIGURE 9. *Impedance vs. Frequency for Three Different High Permeability Materials Demonstrating the Low Frequency Impedance.*

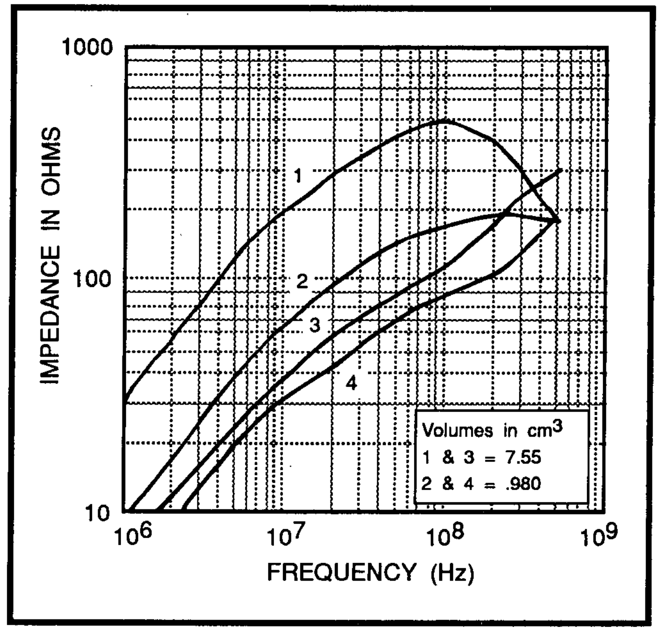

FIGURE 10. *Impedance vs. Frequency for Beads in the Same Material, Two Each with the Same Volume, Using HP 4191A.*

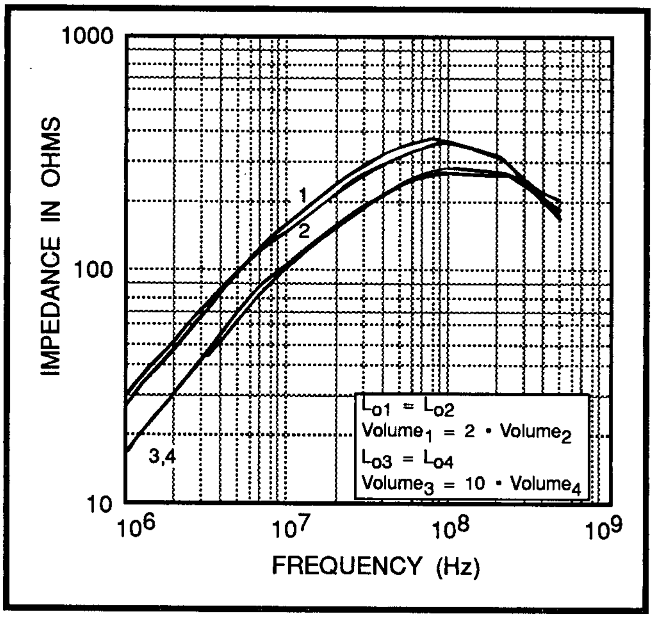

FIGURE 11. *Impedance vs. Frequency for Shield Beads, in the Same Material, all with Different Volumes, Two Each with the Same L_o, Using HP 4191A.*

for maximum attenuation below 15 MHz and the ferrite manufacturer doesn't offer the higher permeability material in its standard suppressor, the buyer should procure samples.

In general, the higher the permeability, the lower the optimum attenuation frequency, and conversely, the lower the permeability, the higher the attenuation frequency. This is frequency limited at both ends, since low frequency attenuation is reflective and high frequency attenuation is limited by the core and circuit resonance.

THE CORE

Once the material has been chosen, the size and shape of the core should be selected.

Figure 10 is a set of impedance versus frequency curves for four different beads in the same material, two each with the same volume. Figure 11 is a set of curves of impedance versus frequency for the same material, with different volumes. These curves show that increasing the core volume does not guarantee an increase in impedance.

The same relationship that exists between the low frequency inductance of a core and the core's initial permeability can be used to approximate a core's impedance. This relationship is the core's air inductance, or L_o. It can be used as a proportion between two cores of the same material at the same frequency to approximate the impedance of one, knowing the impedance of the other. It is valid only below the resonant frequency, which is a function of the material and geometry of the core and/or winding/circuit conditions. The relationship is:

$Z = K \cdot L_o$
Toroidal $L_o =$
$.0461\ N^2 \log_{10} (OD/ID)\ Ht\ 10^{-8}\ (H)$
$Z =$
$$.0461\ K\ N^2 \log_{10} (OD/ID) Ht\ 10^{-8}\ \text{ohm} \qquad (9)$$

where all dimensions are in mm.
$K = Z/L_o$ ohm/H 10^8
N = Number of turns = 1

This is a very useful tool for maximizing the imped-

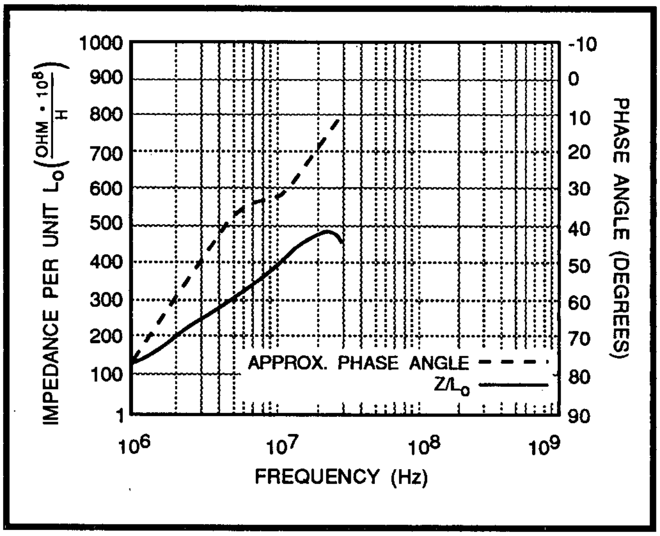

FIGURE 12. *Nominal Impedance Per Unit L_o and Average Phase Angle vs. Frequency for the 73 Material Using HP 4191A.*

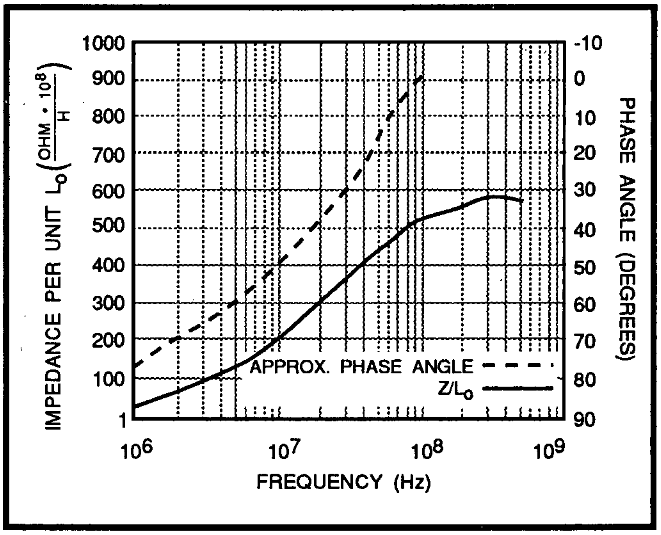

FIGURE 13. *Nominal Impedance Per Unit L_o and Average Phase Angle vs. Frequency for the 43 Material Using HP 4191A.*

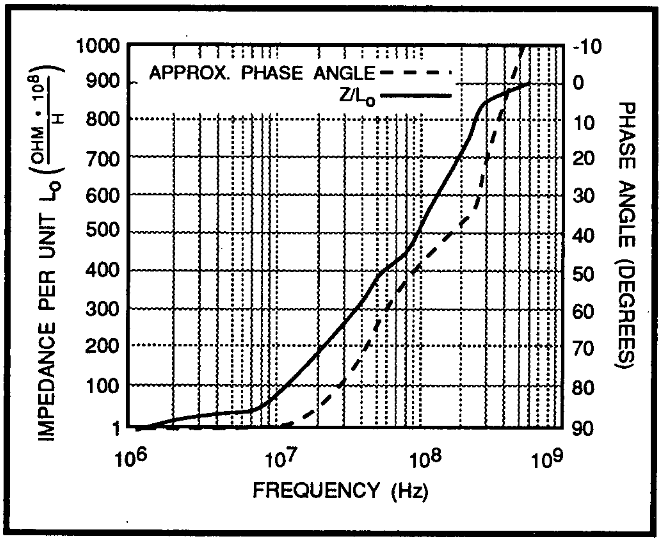

FIGURE 14. *Nominal Impedance Per Unit L_o and Average Phase Angle vs. Frequency for the 61 Material Using HP 4191A.*

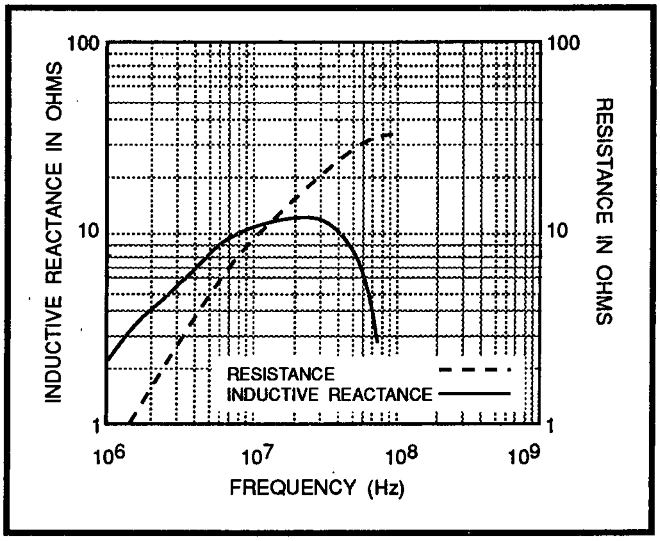

FIGURE 15. *Inductive Reactance (ωL_s) and Series Resistance (R_s) for Sample Bead.*

ance of a core within the allowable space, after the best material has been chosen. It reconfirms the fact that in most cases greater impedance will be obtained by increasing the length of the core rather than the diameter for the same increase in volume.

Figures 12, 13, and 14 are graphs of the average impedance per unit L_o, and phase angle (Φ) for the 73, 43, and 61 materials respectively. To determine the impedance of a core using these graphs, the designer needs to know the physical dimensions of the core, the frequency of concern, and the material.

As an example:

A designer utilizing a ferrite core aims to guarantee maximum impedance for the frequency range of 25 MHz to 150 MHz. The 43 material is chosen. The core must accept a #22 awg wire, and fit in a space of 10 mm x 5 mm. The inside diameter will be specified as .8 mm.

Using the graph in Figure 13, Z/L_o at 25 MHz for the 43 material is $350 \cdot 10^8$ ohm/H. Solving the estimated impedance by first using 10 mm for the outside diameter of the bead and 5 mm for the length, by using Equation 9:

$$Z = 350\,10^8 \cdot 0461 \cdot \log_{10}(10/.8)\,5 \cdot 10^{-8} = 88.5\,\text{ohm}$$

Then using 5 mm for the outside diameter and 10 mm for the length:

$$Z = 350\,10^8 \cdot .0461 \cdot \log_{10}(5/.8)10 \cdot 10^{-8} = 128.4\,\text{ohm}$$

In this instance, as in most, maximum impedance is achieved by using the smaller OD with the longer

Continued on page 303

length. If the ID were larger, for instance 4 mm, the reverse would have been true.

The same approach may be used for different materials, dimensions and frequencies.

The previous discussion assumes that the core of choice is cylindrical. If the ferrite core being used is for flat ribbon, bundled cable, or a multi-hole plate, the calculation for the L_0 becomes more difficult, and fairly accurate figures for the core path length and effective area must be obtained in order to calculate the air core inductance. In all cases though, the increase in impedance will be directly proportional to the height/length as long as the increase in height/length does not cause the core to be in resonance.

The phase angle Φ plotted for each of the three materials is an average. The inductive reactance and the series resistance can be calculated according to $\omega L_s = Z \sin\varphi$ and $R_s = Z\cos\varphi$. Figure 15 illustrates these calculations for a bead in the 43 material.

THE ENVIRONMENT

As stated, ferrite's magnetic parameters can be affected by temperature and field strengths.

Figures 16 and 17 show the impedance versus temperature for a core in the 73, 43, and 61 materials at 25 and 100 MHz. The most temperature stable of these materials is 61, with a decrease in impedance of 8 percent at 100°C and 100 MHz as compared with over 25 percent for the 43 material at the same frequency and temperature. These curves may be used to adjust the specified room temperature impedance if desired attenuation is to be at elevated temperatures.

BIASES

As in the case of temperature, dc

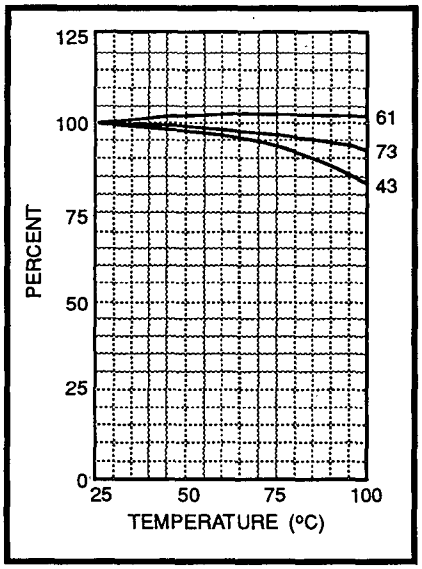

FIGURE 16. *Percent of Original Impedance vs. Temperature at a Frequency of 25 MHz for Three Suppressor Materials.*

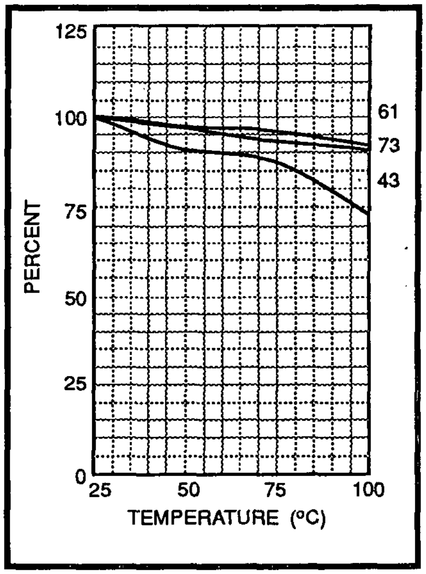

FIGURE 17. *Percent of Original Impedance vs. Temperature at a Frequency of 100 MHz for Three Suppressor Materials.*

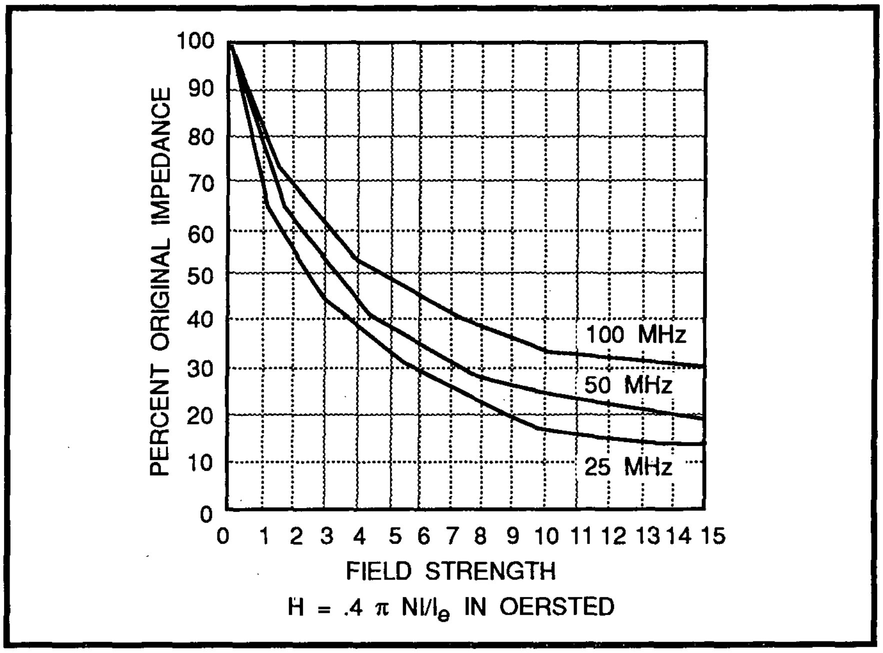

FIGURE 18. *Impedance vs. Field Strength, H, in Oersted, for the 43 Material for Three Frequencies.*

and 50 or 60 Hz power current will also affect the same intrinsic ferrite characteristics which in turn will result in lowering the impedance of the suppressor core.

Figure 18 illustrates the effect of dc bias on the initial impedance of the 43 material. The curves depict the degradation in impedance as a function of field strength, H in oersted, for frequencies of 25, 50 and 100 MHz.*

** When using the curves for percentage original impedance vs. field strength, it is important to note that the smaller the original impedance and the higher the frequency, the less the apparent degradation due to an increase in applied field. For ferrite cores with small values of impedance, the decrease in impedance caused by an applied field is limited by the impedance of the wire used in making the measurement, which can be 20 ohms at 100 MHz. Therefore, when using these curves, particularly at frequencies of 100 MHz or greater, if the calculated value with dc bias is less than 30 ohms, the user should know that the limit has been reached.*

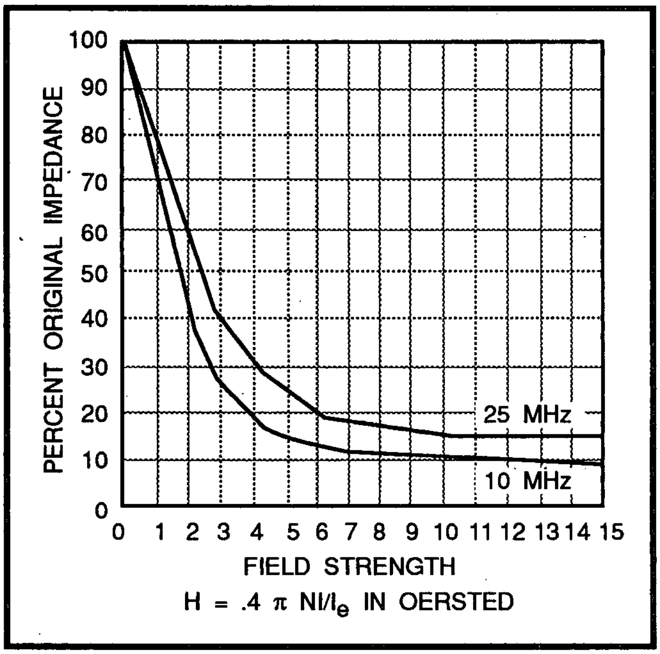

FIGURE 19. *Impedance vs. Field Strength, H, in Oersted, for the 73 Material for Two Frequencies.*

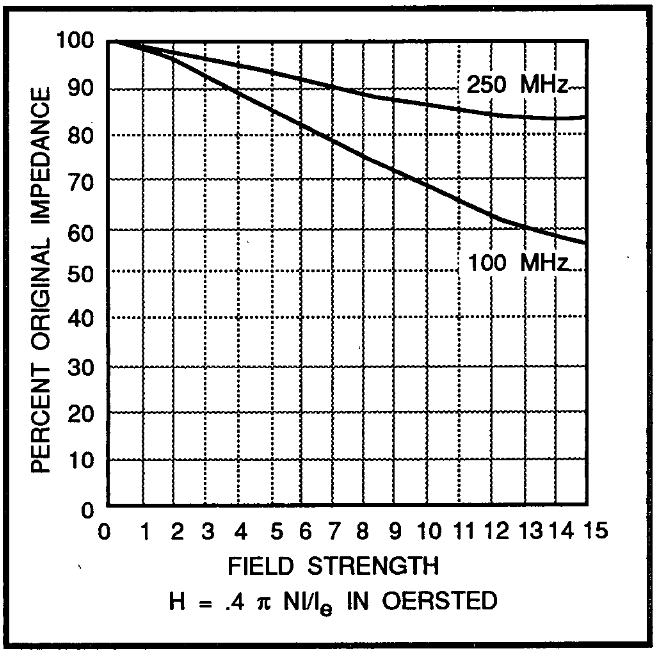

FIGURE 20. *Impedance vs. Field Strength, H, in Oersted, for the 61 Material for Two Frequenices.*

In the design example cited earlier, the user chose a 43 material ferrite core with a 5 mm outside diameter, .8 mm inside diameter and a 10 mm length. Suppose this core will be exposed to 1 amp dc, and the resulting impedance must be determined. In order to calculate the field strength, H, the path length of the core must be established. This is a lengthy procedure that involves first calculating the core constants, C1 and C2, then using these to find the path length.

For a cylindrical core these calculations reduce to:

pair length $l_e =$

$$2\pi \log_e((r_2/r_1)/(1/r_1 - 1/r_2)) = .55 \text{ cm} \quad (10)$$

and

$$H = .4\pi NI/l_e = 2.28 \text{ oersted} \quad (11)$$

where: $r_1 = \dfrac{ID}{2} \quad r_2 = \dfrac{OD}{2}$

The curves confirm that the greatest degradation in impedance occurs at the lower frequency, 25 MHz, and for 2.28 oersted the resulting impedance will be approximately 52 percent of the original, or in this case, 66.8 ohms (0.52 · 128.4 ohms).

Similar plots are made for the 73 material in Figure 19, and the 61 material in Figure 20. Two frequencies are plotted for the 73 material, 10 and 25 MHz, and two for the 61 material, 100 and 250 MHz.

RESISTIVITY

The dc resistivities of ferrites can range from 10 ohm-cm to more than 10^9 ohm-cm. Generally, high permeability manganese zinc ferrites have low resistivities, below 10^2 ohm-cm, while nickel zinc ferrites have resistivities that range from 10^5 to 10^{12} ohm-cm. In most instances this parameter is measured using low voltage, and since a ferrite's resistivity is voltage sensitive, these values may not be valid if the body of the core itself is exposed to high dc or ac values. Ferrite materials are available that have a resistivity of 10^9 ohm-cm measured with 1000 volts. If the frequency that must be attenuated is lower than 25 MHz, requiring a manganese zinc ferrite, coating the core with Parylene, epoxy, or polyurethane varnish or insulating the wire may be the only solution.

INCREASING IMPEDANCE

Impedance can be increased significantly by adding turns to a bead or a coil on a slug. Figure 21 is a graph of impedance versus frequency for a large toroidal core with one, two and four turns. The impedance will increase in direct proportion to the turns squared, but the frequency at which the maximum impedance is reached is lowered due to the additional capacitive effects.

Figure 22 is a graph of different plots of impedance for the same size slug and same number of turns in different materials. The impedance gained by this type of configuration can be significant. Again there is a trade-off; increasing the number of turns lowers the resonant frequency at which the impedance becomes maximum, therefore narrowing the effective frequency band. The lower the initial permeability of a material, the higher the frequency where this occurs.

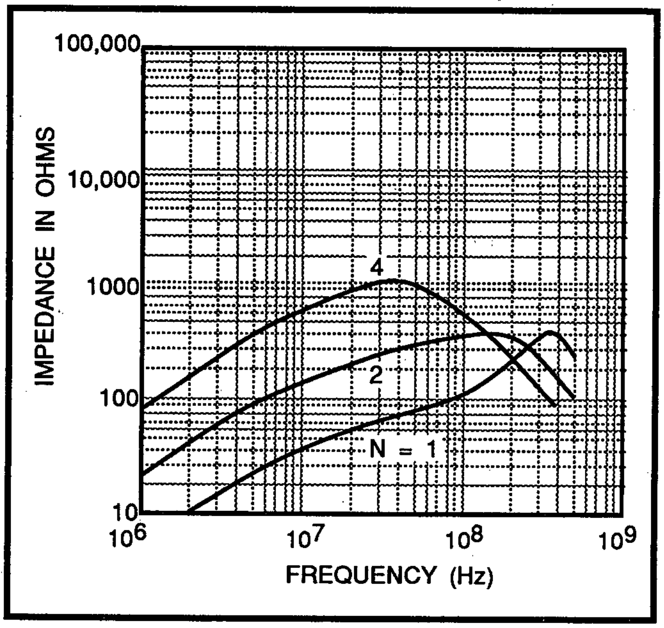

FIGURE 21. *Impedance vs. Frequency for a Large Ring Core with One, Two, and Four Turns.*

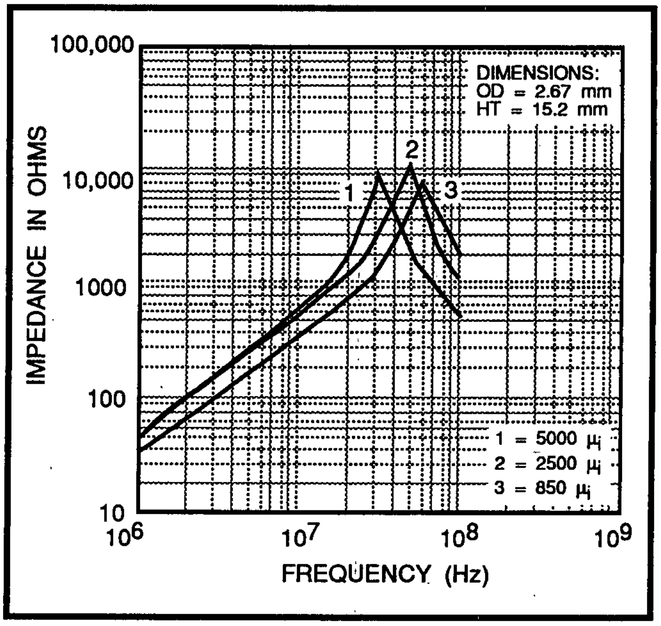

FIGURE 22. *Impedance vs. Frequency for Slug-Type Core in a Coil Varying Material.*

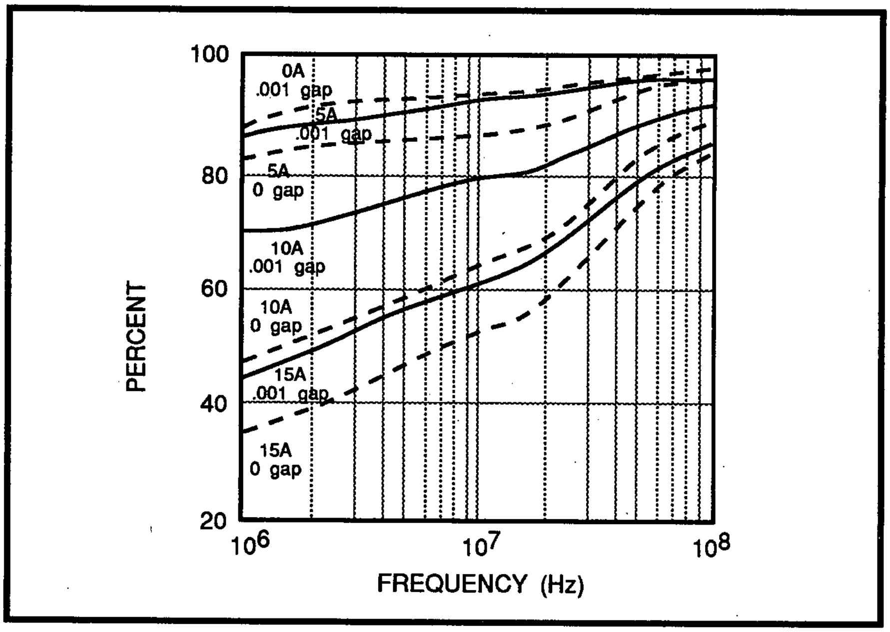

FIGURE 23. *Effect of dc Bias on a Flat Ribbon Cable Core with Different Currents and Airgaps.*

INCREASING DC HANDLING

Introducing an airgap in the core's path length can decrease the degrading effects of dc bias. The larger the gap, the less effect the bias will have on the impedance. Gaps vary from finishing gaps in mated parts to the gap found in open magnetic circuits, such as a slug. Figure 23 shows the effects of dc bias on a flat ribbon cable core with different currents and airgaps. Note that the higher the frequency the less the effect of the gap and the current.

SPECIFYING THE CORE

Impedances can be specified at different frequencies for each material. The impedances of the cores are controlled to meet a minimum at the lower frequency, and at the higher frequency the tolerance is ±20 percent. The measuring equipment is an HP 4193A (HP 4191A for frequencies above 100 MHz). Impedance values measured on other equipment, even if it is Hewlett-Packard, may not be the same.

Most manufacturers are specifying cores for EMI applications in terms of impedance, but often the end user needs to know the attenuation. The relationship that exists between these two parameters is:

$$\text{Attenuation} = 20 \log_{10} Z_s + Z_{sc} + Z_L / Z_s + Z_L \text{ dB} \quad (12)$$

where:

Z_s = Source impedance
Z_{sc} = Suppressor core impedance
Z_L = Load impedance

This relationship is dependent on the impedance of the source generating the noise and the impedance of the load receiving it. These values are usually complex numbers that can be infinite in scope and easily obtained by the designer.

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***CHOOSING A FERRITE FOR THE SUPPRESSION OF EMI** . . .* *Continued from page 306*

Selecting a value of one ohm for both the load and the source impedance, as may be the case when the source is a switch mode power supply and the load is many low impedance circuits, simplifies the equation and allows comparison of ferrite cores in terms of attenuation.

Under these conditions, the equation reduces to:

$$A = 20 \log_{10} Z_{sc}/2 \text{ db} \qquad (13)$$
$$Z_{sc} >> 1 \text{ ohm}$$

SUMMARY

Ferrites are high frequency resistors.

Ferrites used in the application of noise suppression are chosen for their lossy characteristics. The higher the value of loss angle, over the broadest range, the better the material as an attenuator. Ferrites are manufactured in a large variety of sizes and shapes and in several materials, covering a broad frequency range. They are easy to use and an inexpensive solution to what can often be a very costly problem.

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