75-material for Low-Frequency EMI Suppression Demystified

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Abstract

Ferrites are ceramic components that can be used to suppress electromagnetic interference (EMI) in certain applications. This paper will discuss the basic properties of solid round ferrite cores, the impact an air-gap can have on the performance of these cores, and special considerations. In particular, this paper focuses on the use of 75-material in low-frequency suppression applications since its permeability is relatively high compared to other soft ferrites used for this purpose, making the effect of an air-gap much greater.

Solid Core Magnetic Properties

To find the appropriate ferrite core, several factors need to be considered under nominal conditions:

- Material type
- Number of turns
- Core size

The frequency of the noise is the main driver for material selection. Some materials, such as 75, are best suited for low-frequency EMI issues, while others, such as 61, are best serving the VHF range. This is primarily due to the material's permeability, μ, which is a complex property that represents the inductive (μ') and resistive (μ'') influences of the ferrite at different frequencies. It should be noted that for the purpose of this paper $\mu = \mu_s$, the series permeability at low magnetic flux levels.

Taking 75-material as an example [4]:

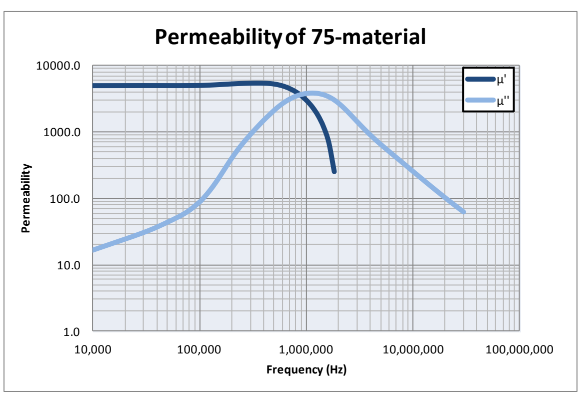

Figure 1: Permeability versus Frequency for Fair-Rite P/N 2675540002.

As you can see, at low frequencies μ' is dominant – meaning that the core is mostly inductive and thus blocks EMI noise. At higher frequencies, μ'' is the main driver of the core's impedance and it becomes more resistive – meaning it absorbs the noise. To show this, let's consider the core's impedance over frequency [1]:

$$Z = j\omega L_s + R_s = j\omega\, L_o(\mu' - j\mu'') \quad [\Omega]$$

where:

L_s = series inductance
R_s = series loss resistance
L_o = air core inductance

Notice we've introduced a new parameter – L_o. This is the inductance if the core had unity permeability relative to air and is dependant on the number of turns and core size [1]:

$$L_o = \frac{\mu_o N^2 A_e}{l_e} \quad [\text{H}]$$

where:

μ_o is the permeability of free space, a known constant ($4\pi \times 10^{-9}$ H/cm).
N is the number of turns.
A_e is the effective cross-sectional area of the core (cm^2)
l_e is the effective magnetic length (cm)

The number of turns, N, is decided by the designer and refers to the number of times the cable passes through the aperture of the core. A single turn (N = 1) means that the cable travels straight through the core. To increase the impedance, the designer can add turns.

The effective cross-sectional area and the effective magnetic length are directly related to the geometry of the core. For a solid round ferrite core, it is easier to consider them together as part of the "core factor," C_1 [1]:

$$C_1 = \frac{l_e}{A_e} = \frac{2\pi}{h \ln\left(\frac{r_O}{r_i}\right)} \; [\text{cm}^{-1}]$$

where:

h = core length (axial thickness) (cm)
r_o = outer radius (cm)
r_i = inner radius (cm)

The two radii, r_o and r_i, and the core length, h, are all parameters that can be found from the Fair-Rite catalog. With this information, we can now calculate the impedance of a solid core [1]:

$$Z = j\omega\left(\frac{\mu_o N^2\, h \ln\left(\frac{r_o}{r_i}\right)}{2\pi}\right)(\mu' - j\mu'')\ [\Omega]$$

Let's take Fair-Rite part number 2675540002 with a single turn as an example [4]:

$$Z = j\omega\left(\frac{\mu_o (1)^2\, 2.860 \ln\left(\frac{0.5\times 1.430}{0.5\times 0.635}\right)}{2\pi}\right)(\mu' - j\mu'')\ [\Omega]$$

$$Z = j\omega(4.643\ \times 10^{-9})(\mu' - j\mu'')\ [\Omega]$$

Figure 2 shows this complex impedance over frequency:

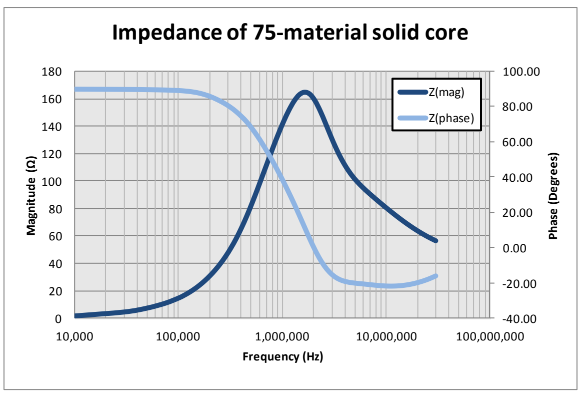

Figure 2: Magnitude and phase of the calculated impedance.

Mapping this back to L_s and R_s, Figure 3 shows that the inductance is the main driver of the impedance at lower frequencies whereas the resistance becomes the dominant contributor at higher frequencies, above 1 MHz.

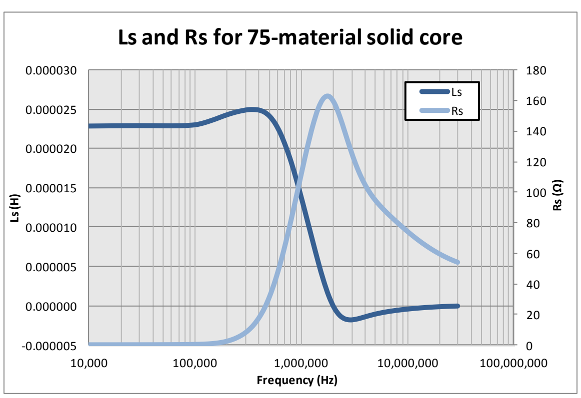

Figure 3: Series inductance and resistance versus frequency.

At this point it is useful to cover a topic known as "magnetic loss tangent" since this will become useful in the next section when calculating the complex permeability. This parameter is a measure of the magnetic inefficiency of the system based on the angle between the real (μ') and imaginary (μ'') parts of the material permeability [3]:

$$\tan(\delta) = \frac{\mu''}{\mu'}$$

These magnetic losses can come from three sources: hysteresis losses (related to magnetic flux density), eddy current losses (related to frequency), and residual losses (inherent to the ferrite). Note that this calculation assumes that the hysteresis losses and eddy current losses are negligible.

Split-Core Magnetic Properties (Air-Gap)

So far we have considered the impedance of a solid ferrite core. However, when the engineer is troubleshooting an EMI noise issue the particular device under test (DUT) may be an assembly – making it difficult to apply a solid core since the cables cannot be easily de-terminated. Therefore, split-cores are typically used during this development phase and possibly in production depending on the application and cable routing.

When calculating the impedance of a split core, there is added complexity because an air-gap is introduced into the magnetic circuit. Although the air-gap is very often minimized through various finishing processes, it still has some impact on component performance as it tends to lower the inductance (and subsequently the impedance at lower frequencies) because it becomes less dependent on the ferrite's permeability [2]. Since 75-material has a relatively high initial permeability as compared to other materials that are offered for EMI suppression, this air-gap becomes highly influential to the overall performance.

Specifically, we now need to consider A_e, the effective cross-sectional area, and l_e, the effective magnetic path length, separately since it is no longer a homogenous structure. These two parameters are now comprised of two portions – one associated with the core and one associated with the air-gap. Assuming the air-gap is small compared to the core, A_e can remain the same for both (although if the gap becomes too large then fringing can occur, thus affecting this parameter). However, the effective magnetic path length, l_e must now be adjusted to account for the length of the gap (l_g) in order to remain accurate. To visualize this, consider the following image:

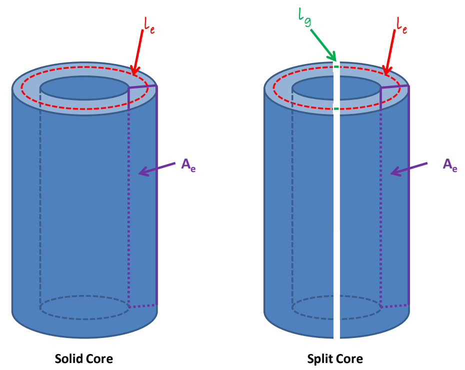

Figure 4: Solid core versus split core configurations.

Without getting into complex equations and derivations, the *effective* permeability (μ_e) of the core is now dependant on both permeabilities and path lengths. Since the permeability of air is much lower, a larger gap will lower the effective permeability more. To see how this affects performance, consider a generic expression of the inductance of a core as follows [1]:

$$L = \left(\frac{\mu_o \mu\, N^2 A_e}{l_e}\right) \text{ [H]}$$

When an air-gap is introduced, and assuming this gap is considerably smaller than the core itself ($l_g \ll l_e$), the effective permeability becomes [1]:

$$\mu'_e = \frac{l_e}{\frac{l_e}{\mu'} + l_g}$$

$$\mu''_e = \mu'_e \tan(\delta)_{\text{gapped}}$$

where

$$tan(\delta)_{gapped} = \frac{\tan(\delta)}{\mu'}\, \mu'_e$$

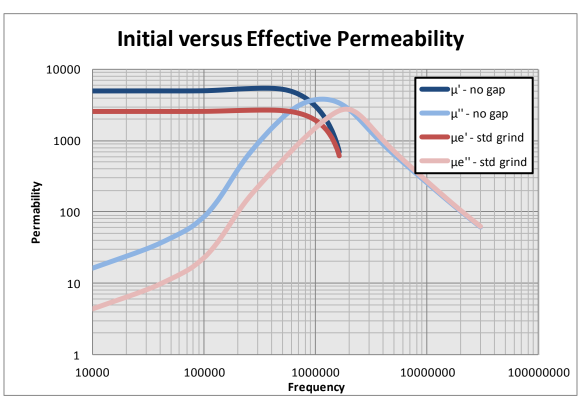

Figure 5: Calculated effective permeability for 2675540002.

Given this particular configuration, the only difference between the two inductance equations is in the effective permeability. This can be mapped back to the impedance equation to show the effect an air-gap has on the core's performance:

$$Z = j\omega\left(\frac{\mu_o N^2\, h \ln\left(\frac{r_o}{r_i}\right)}{2\pi}\right)(\mu_e' - \; j\mu_e'') \text{ [}\Omega\text{]}$$

Considering again Fair-Rite P/N 26755400002 with various gap surface finishes:

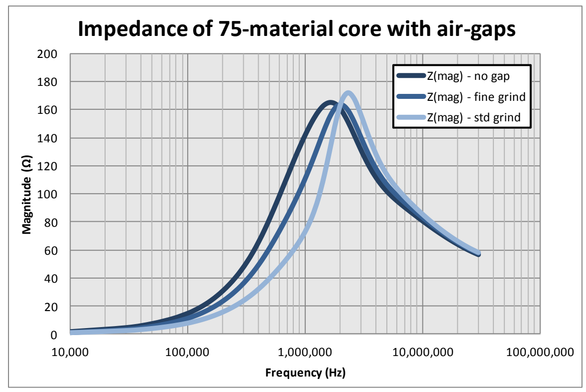

Figure 6: Calculated impedance for three different air gaps.

As Figure 6 illustrates, at lower frequencies the impedance can drop dramatically. Another way of evaluating the effect of an air-gap is to consider the impedance at a certain frequency over varying gap lengths:

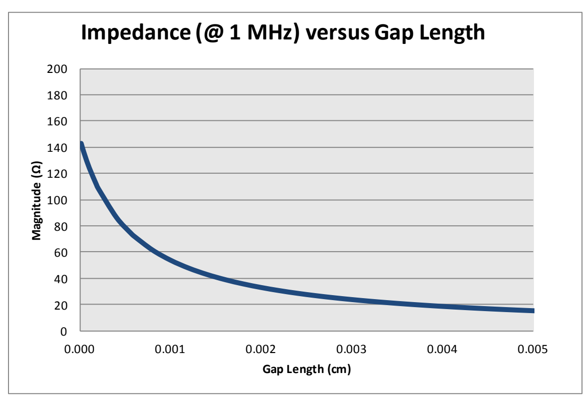

Figure 7: Calculated gap length versus impedance at a set frequency.

As you can see, keeping this gap as small as possible is essential to effectively suppress EMI noise at low frequencies. Hence, Fair-Rite has developed a process to ensure a minimal gap and maximize the split core performance to closely resemble that of a solid core. In addition, it is essential that the mating surfaces of the split core are cleaned well to remove debris before use.

Special Considerations

When comparing the calculated and measured values of the aforementioned cores, it is important to note that there are other effects that lower the impedance of the gapped ferrites at higher frequencies.

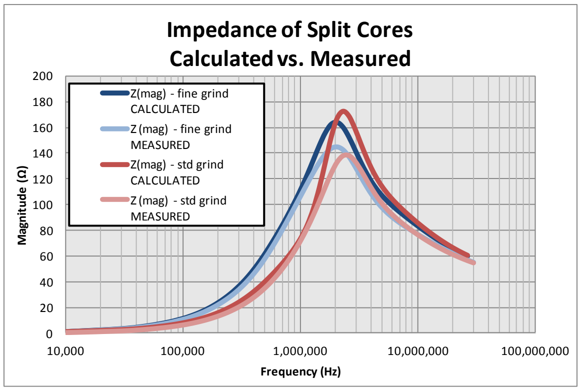

Figure 8: Calculated versus measured impedance for split cores.

While the curves track well at lower frequencies, higher frequencies introduce other effects such as eddy currents, dimensional resonance, and geometric dependencies that could degrade the performance. Therefore, while the purpose of this paper is to demystify there are still some effects of an air-gap in a 75-material split core yet to be discussed but are beyond the scope of this paper.

One important consideration when choosing to use a ferrite such as 75-material cores is DC bias, which is why this product is ideal for common-mode noise applications. Due to the nature of these types of components, derating occurs in applications where the current is high and compromises the effectiveness of the part. To circumvent this issue, it is suggested that both current-carrying conductors pass through the core so that the fields generated by the signal will cancel each other, while any common-mode noise is suppressed.

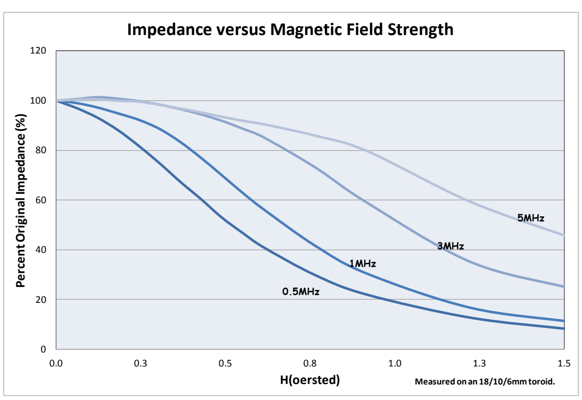

Figure 9: Impedance (Z) versus Magnetic Field Strength (H) at various frequencies.

Another consideration is temperature stability. Depending on the material, the permeability can vary slightly or drastically over the operating temperature range of the DUT. For 75-material, the initial permeability can change 0.6% per degree Celsius in an operating range from 20° - 70°C. While this is more stable than 31, another low-frequency suppression material which changes 1.6% per degree Celsius, it is still something that needs to be considered when designing a ferrite component into an application that may see a wide range of temperatures.

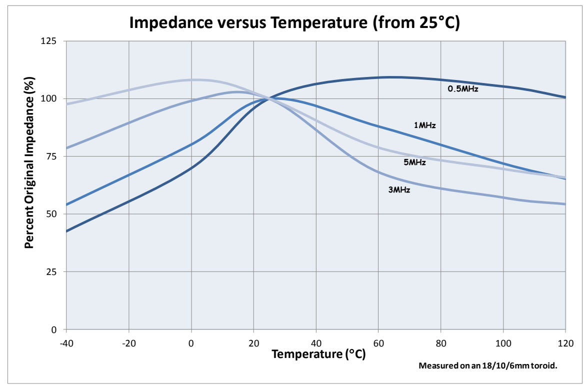

Figure 10: Impedance versus Temperature

References:

[1] Snelling, E.C. (1988) *Soft Ferrites: Properties and Applications.* Essex, UK. Butterworth & Co.

[2] Erickson, Robert and Maksimovic, Dragan. (2001) *Fundamentals of Power Electronics*. New York, NY. Springer.

[3] Goldman, Alex. (2006) *Modern Ferrite Technology*. New York, NY. Springer.

[4] Fair-Rite Catalog, Seventeenth Edition.

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