New Methods in Modeling EMC Ferrites

Functional equivalent circuit representations can be modeled for ferrite beads.

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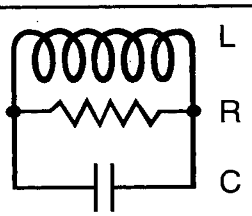
INTRODUCTION

Ferrites are well-known components and are offered by many suppliers all over the world. But many engineers have difficulty selecting the right ferrite for their applications and estimating the effects of introducing ferrites into a circuit. The reason is simple, and a challenge to ferrite suppliers: it is the lack of proper equivalent circuits for commercially available ferrites with which engineers can calculate circuit analysis software programs such as SPICE. This article provides the information necessary to develop these equivalents with respect to selected applications concerning EMI.

THE IMPEDANCE IDEOLOGY

Nearly all EMI ferrite suppliers give figures for impedance in their data books. But what can the engineer do with these data? Of course, they are not useless, but they are also not enough. Fortunately, modern measuring instrumentation provides sufficient information such that the entire product line of a supplier can be screened for equivalent circuits in just a few days.

If radiation or reception of electromagnetic waves or currents are investigated, transmission line equivalents or their unwanted sons, parasitic antennas, are found to be integral parts of the system. One must answer the question: what happens to terminated lines with only a frequency-dependent impedance which cannot be put into a circuit analysis program? A lumped constant filter with a condenser at its end shorts unwanted frequencies, but a transmission line terminated with a condenser or an inductive load reflects energy, generating a chain of resonances which pose problems for the EMI engineer. What is needed is dissipation of energy, and ferrites answer this need due to their lossy nature.



$$Y = \frac{1}{j\omega L} + \frac{1}{R} + j\omega C$$

$$Z = \frac{1}{Y}$$

***Figure 1**. Simple Equivalent Circuit.*

Many manufacturers give impedances in the form $Z = R + jX$ because their measuring equipment can do it. The figures are correct but have no physical significance. To use them as equivalent circuit models is not feasible for a wider frequency range. A simple, but for the purpose of EMI control, sufficient equivalent circuit is given in Figure 1.

Network analyzers approximate these measured impedance values $|Z|$ and θ and plot the values $|Z'|$ and θ' for comparison to the measured curves. Figure 2a shows an equivalent circuit which is a close approximation of the real measurement. It is a tube.

This example illustrates that it is possible to get a nearly perfect equivalent with frequency independent components. These components can be run through a circuit analysis program to calculate circuit behavior. Ferrite suppliers should measure such parameters under extreme conditions to determine worst-case equivalents dependent on temperature, dc current penetration and so on.

It is clear that a wire through this tube has a very small impedance at low frequencies and that the impedance transformed by the ferrite is a nearly perfect resistance at higher frequencies due to the losses in the ferrite. Negative capacitances really do not exist, but for calculation purposes they can be used. They are measures of some stray inductance.

Some remarks on the measurement procedure seem to be useful. A suitable network analyzer needs an impedance measurement kit and a clip fixture. For very exact measurements, the calibration of short and load should incorporate the inductance of the naked wire which is then compensated for by the software during the calibration process. Thus, the result of a measurement is really the additional influence of the ferrite tube or ring or bead around the wire (one turn). The square law says that two turns yield a nearly fourfold impedance and so on.

Figure 2b shows the results of using a network analyzer like HP 4195A to calculate the equivalent circuit based on the impedance measurement of $|Z|$ and θ. It is possible to alter the parameters from the analyzer to get other equivalents $|Z'|$ and θ' and their performance. The algorithm for equivalents seems to be a good phase approximation.

The proper selection of the right frequency range to be suppressed is essential. An equivalent R/L/C has a root locus as shown in Figure 3.

A frequency $f_g = 1/2\,\pi\tau = R/2\,\pi L$ is equal to the frequency at which μ' and μ'' become equal. Figure 4 shows an estimate of the relationship of the initial permeability μ_i and the frequency f_g where μ' and μ'' become equal, where μ' is the real part of the permeabil-

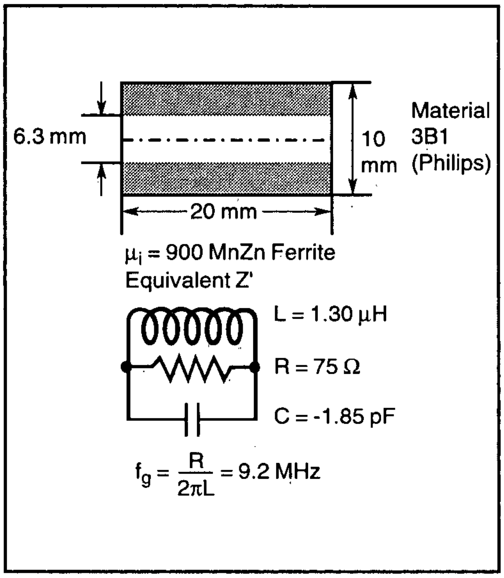


Figure 2a. Equivalent Circuit.

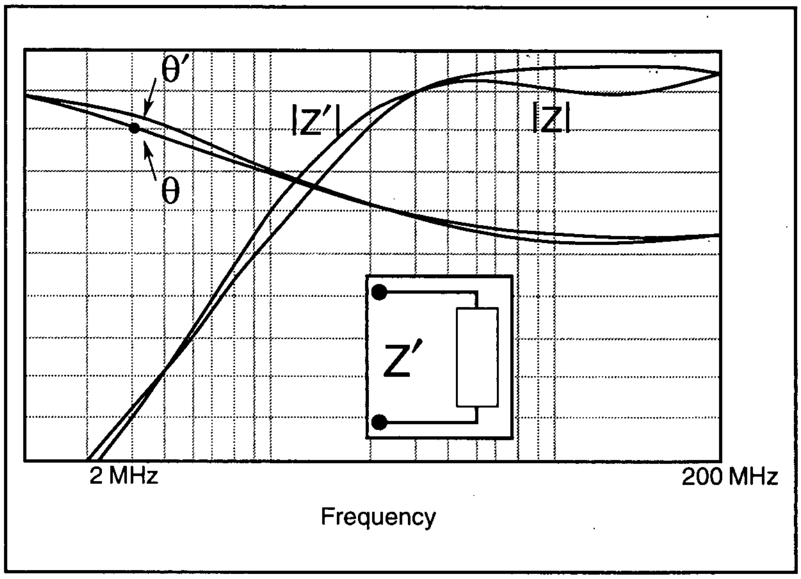


Figure 2b. Comparison of Theoretical and Empirical Data.

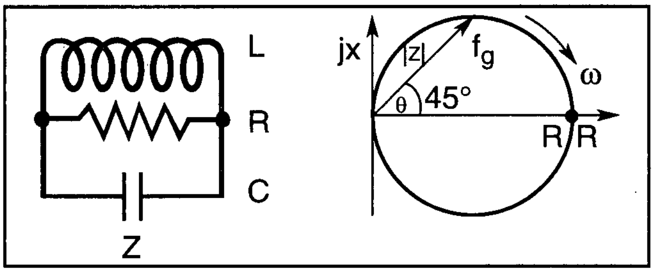
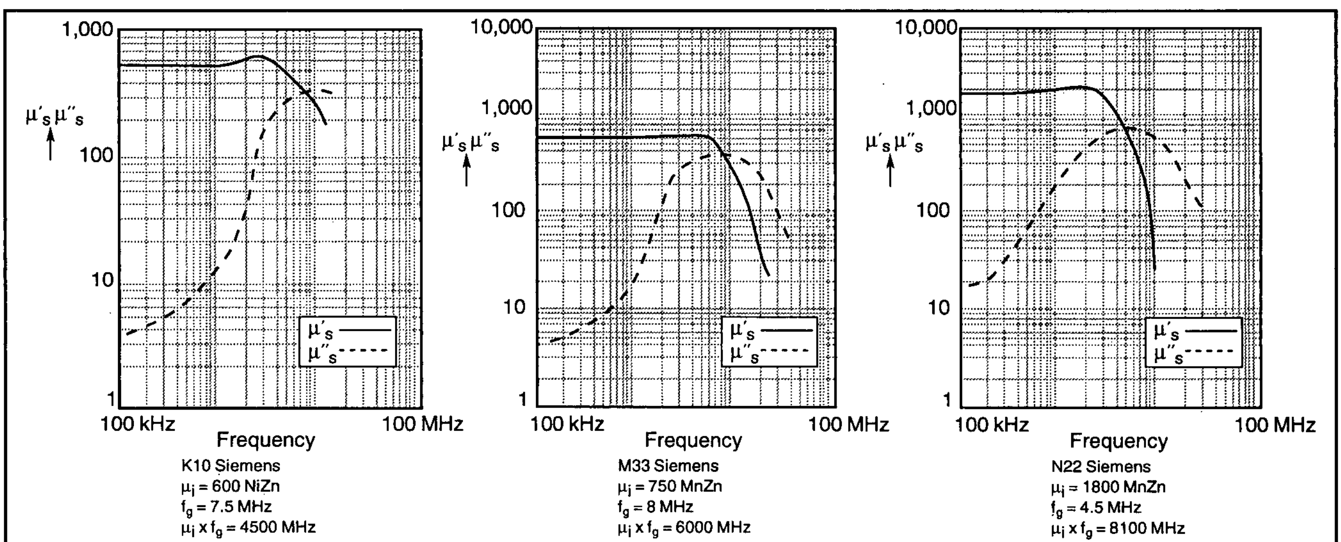


Figure 3. Generic Equivalent Circuit of Ferrite Bead.

ity and µ″ is the imaginary part. The higher the μ_i, the lower the f_g. Because of the influences of geometry, temperature, tolerances and magnetizing force during the measurement, the rule of thumb μ_i x f_g = 5000 - 10,000 MHz is a good guide for selecting the proper material. The relation L/R of a ferrite core or bead is a material property. The magnitude of these values depends on the geometry $L \sim n^2\mu_i A/\ell$, where L = magnitude, n = number of windings, A = cross section, and ℓ = magnetic length.

Consider a component with an R in the equivalent circuit of 100 Ω. At which frequency does it work fully as an energy-sink, and what frequencies may pass unattenuated? At f_g ω_g x L = 100 Ω, half of the current passes through the inductance. At about 4 f_g, frequencies are mostly absorbed and at 0.25 f_g, frequencies pass nearly unattenuated. This is correct for an L/R equivalent, usually realized by nickel-zinc ferrites. Although NiZn ferrites give good results, their practical use is limited to higher μ_i by a too-low Curie temperature, so a μ_i of about 800 may be the highest value having a Curie temperature over 135 C. Manganese-zinc ferrites can be mixed with a μ_i greater than 10,000, but they have not only a high permeability, but also a high relative dielectric constant



The higher the μ_i, the lower the frequency at which µ' = µ" = fg. Other suppliers use other ferrite mixtures with different properties, but the general rule μ_i ↔ fg is valid.

Figure 4. Estimation of the rule $\mu_i \times f_g \approx$ constant.

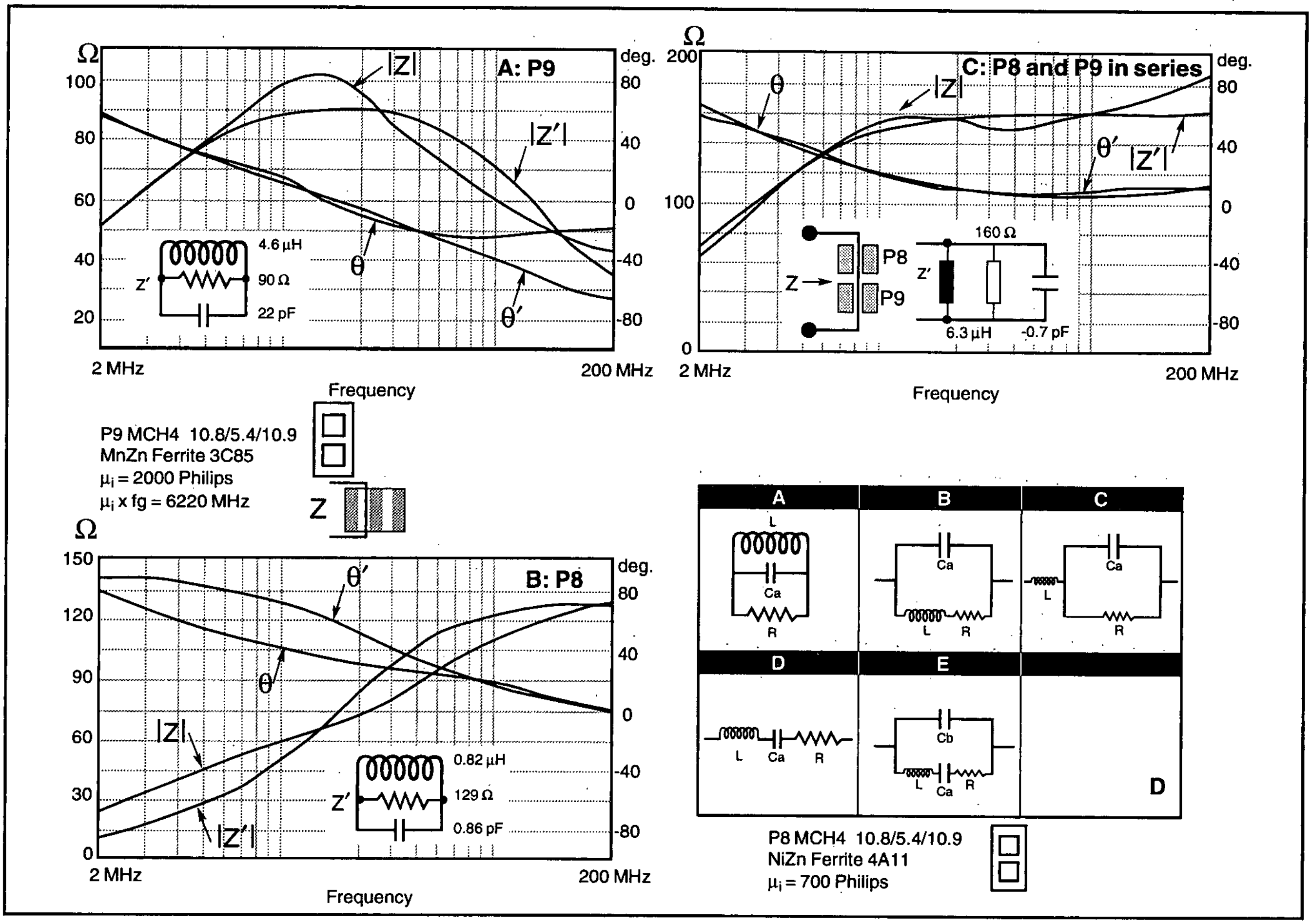


Figure 5. Examples of ferrite two-hole cores of the same size and different materials and their usefulness in a broadband resistive suppression.

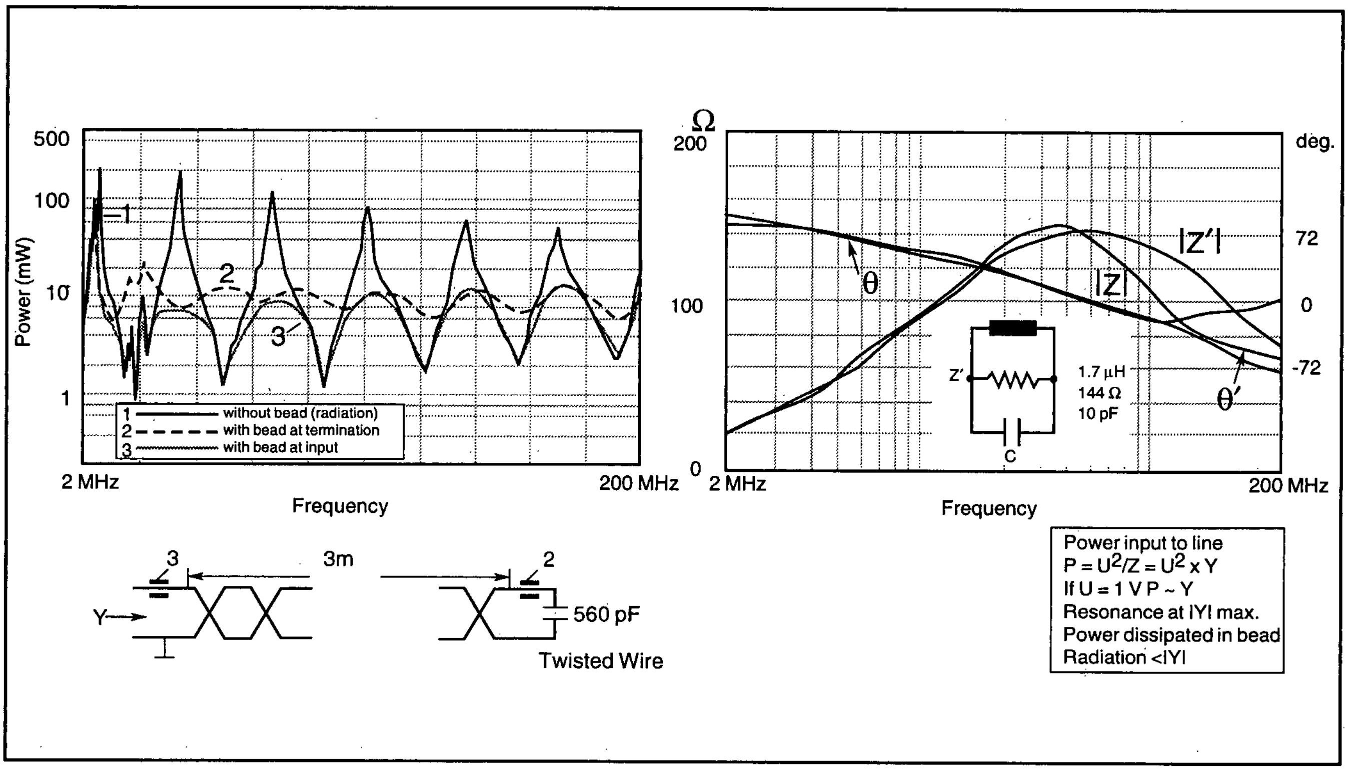


Figure 6. Reduction of line resonance using a ferrite bead S3 which dissipates input power.

ε (about 50,000) leading to high capacitances in the equivalent and therefore a limited range to higher frequencies.

In Figure 5a the impedance Z and its phase θ is plotted from a two-holed rectangular core, measured with a wire through one hole. Its material is MnZn ferrite 3C85 with an μ_i of 2000. Looking for the frequency f_g ($\theta = 45^o$) one may get f_g about 3 MHz, calculated 3.11 MHz and $\mu_i \times f_g = 6220$ MHz.

Figure 5b shows the impedance of a core with the same size but having a NiZn ferrite material 4A11 with $\mu_i = 700$. Its measured f_g is about 8 MHz but its calculated f_g is 25 MHz, because it is rather difficult to get a close equivalent to its Z-shape. For estimation purposes, showing that this core will act well above 20-40 MHz is sufficient.

Figure 5c shows how both cores in series compensate for their shortcomings, giving a nearly perfect L/R circuit working well above 5 MHz up to several hundred MHz. These examples show how to utilize this measuring method and to calculate simple equivalents.

Figure 5d shows what equivalent circuits may be selected for approximating measurements for different components. For ferrite beads and coils, Type A gives proper results.

Figure 6 illustrates how to use ferrite beads to reduce unwanted radiations. A 3-m long twisted pair line is terminated by 560 pF. To demonstrate line resonances, the representation of the admittance Y = 1/Z was selected by the analyzer. If one assumes a power source of 1 V and input resistance of zero, the power input to the line is $P = U^2 \times Y$, and for $U = 1\ V_{eff}$ the power is equal to Y in the maximum and minimum points.

Curve 1 gives |Y| without beads, showing rather high peaks for radiation or dissipation in the cable insulation. Curves 2 and 3 show a great reduction of input power, curve 2 by some kind of resistive line termination and curve 3 by giving the 1 V source the input impedance of the bead S3. In both cases, most of the input power is then dissipated in the ferrite bead.

Looking at the low frequency side, a resonance of curve 1 at 5.48 MHz is present. This resonance is due to line inductance and termination capacitance and can not properly be reduced by the bead. The mistake is using a termination capacitance as low as 1 nF.

CONCLUSION

Ferrite suppliers should supply mean and worst-case equivalent circuits as shown. Suppliers should also make research on broadband high loss materials or compounds available. If this were done, designers would be able to proceed with comprehensive and practical information on ferrites and selection.

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