New Understandings of the Use of Ferrites in the Prevention and Suppression of RF Interference to Audio Systems

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ABSTRACT

Building on the work of Muncy, [1] the author has shown that radio-frequency current on cable shields is often coupled to audio systems by two mechanisms – "the pin 1 problem" and shield-current-induced noise (SCIN). [2, 3, 4, 5] An improved equivalent circuit for a ferrite choke is developed that addresses both dimensional resonance within ferrites and the self resonance of inductors formed using those materials, then compared with measured data. Field tests show that chokes formed by passing signal cables through ferrite cores can significantly reduce current-coupled interference over the range of 500 kHz to 1,000 MHz. Guidelines are presented for diagnosing the causes of EMI from sources as diverse as AM broadcast transmitters and cell phones. Solutions are presented for use in new products and for RFI suppression in field installations.

AUTHOR'S POSTSCRIPT [NOT PART OF ORIGINAL PUBLICATION]

It should be obvious from the analysis presented here that once the form an equivalent circuit that correctly characterizes a ferrite choke is known, determination of the values of L_D, R_D, C_D, L_C, C_C, and R_C from empirical data is a trivial exercise. The author had intended to address this matter and include an example, but time pressures during the period when this paper was written got in the way. Because in most chokes the two resonances are widely separated in frequency, each parallel R component is simply the value at resonance, and the associated values of L and C are then determined from the value of X based on the value of Q associated with the measured bandwidth. The exercise is, as the saying goes, left to the interested student, using any classic text on radio frequency circuits as a reference (for example, any edition of Terman, "Electronic and Radio Engineering"). JB 6/15/06

INTRODUCTION

Four basic mechanisms often combine to cause RF interference to audio systems. They are:

1. An audio cable will be excited as an antenna by radio signals that surround it, causing ***current*** to flow along its length. Most of the ***current*** will flow on the ***shield***, but the current can also induce a common mode voltage on the signal conductor(s).
2. Improper termination of cable shields within equipment (the Pin 1 problem) injects RF ***shield current*** directly into the equipment, [6] where it is detected by several well known mechanisms. [2]
3. Imperfect inductive coupling between conductors of a shielded twisted-pair cable converts ***shield current*** to a differential voltage on the signal pair (SCIN).
4. Inadequate low-pass filtering of signal input and outputs lets RF present on the signal conductors into equipment. Equipment can be sensitive to both differential mode voltage (between the signal conductors) and common mode voltage (an equal voltage on both signal conductors).

Analysis of these mechanisms shows that RF ***common-mode current*** is a major contributor to all of them, so eliminating or reducing ***common-mode current*** should be the key to eliminating the interference. Experimental work near various high power MF and HF transmitters, and in the author's laboratory with VHF and UHF transmitters, confirmed this hypothesis. In the field tests, virtually all cases of AM broadcast interference in both microphones and input equipment, many of them quite severe, were either eliminated or greatly reduced when a cable connecting the microphone to the input equipment was wound around a toroidal ferrite to form a multi-turn RF choke (Fig 2). Comparable reductions in interference were obtained at VHF and UHF by passing the signal wiring through a ferrite cylinder to form a single-turn choke (Fig 1).

The latter technique is well known, but the method of using multi-turn chokes is not. Indeed, it is widely believed that ferrites are not useful for suppression below about 30 MHz. This paper reports on research documenting the performance of a variety of ferrite parts over the range of 300 kHz to 1 GHz, focusing on those that are potentially the most useful at suppressing interference to audio systems.

Figure 1 – Typical Ferrite Cores

Figure 2 – A Multi-turn Choke on a 2.4" o.d. core

FERRITES

Ferrites are partially conductive ceramics consisting of various oxides of iron, cobalt, nickel, zinc, magnesium, and other metals. Manganese-Zinc (MnZn) mixes are used mostly below a few megahertz, while Nickel-Zinc (NiZn) parts are most widely used at VHF and UHF. This distinction is far from rigid, and at least one MnZn mix is quite useful well into the VHF spectrum (Figs 8, 22). Depending on the material used, the bulk resistivity of ferrites varies from very high to rather low.

When a ferrite surrounds a conductor, the high permeability of the material provides a much easier path for magnetic flux set up by current flow in the conductor than if the wire were surrounded only by air. The short length of wire passing through the ferrite will thus see its self inductance multiplied by the high relative permeability of the ferrite. The ferrites used for suppression are ***soft*** ferrites – that is, they are not permanent magnets.

Permeability is the characteristic of a material that quantifies the ease with which it supports a magnetic field. ***Relative*** permeability is the ratio of the permeability of the material to the permeability of free space. The relative permeability of non-magnetic materials like air, copper, and aluminum is 1, while magnetic materials have a permeability much greater than 1. Typical values (measured at power frequencies) for stainless steel, steel and mumetal are on the order of 500, 1,000 and 20,000, respectively. Various ferrites have values from the low tens to several thousand.

[Note: throughout this paper, the symbols $\boldsymbol{\mu}$ and $\boldsymbol{\varepsilon}$ are used to represent the permeability and permittivity of materials relative to the permeability and permittivity of free space, $\boldsymbol{\mu_0}$ and $\boldsymbol{\varepsilon_0}$. Permittivity can be thought of as a property of a material used as a dielectric (insulation) between the plates of a capacitor that supports the storage of an electric field within the dielectric. That is, a high value of permittivity results in greater capacitance.]

Traditional analysis of ferrite chokes as circuit components, as well as their characterization on product data sheets, has used the simple series equivalent circuit of Fig 3. In that circuit, the choke is analyzed as an inductance L_S, having a series loss component, R_S. This gross oversimplification has led to serious misunderstandings about the behavior of these very useful components. One of the objectives of this paper is to rectify that condition.

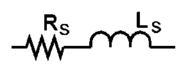

Figure 3 – Traditional, but oversimplified, series equivalent circuit of a ferrite choke

Ferrite components are most often analyzed using the concept of complex permeability, $\boldsymbol{\mu = \mu'_S + j\,\mu''_S}$, where $\boldsymbol{\mu'_S}$ quantifies the conventional series equivalent inductive component and $\boldsymbol{\mu''_S}$ quantifies the series equivalent resistance. Using this notation,

$$\mathbf{Z = R_S + j\omega L_S = j\omega L_0\,(\mu'_S + j\,\mu''_S)}$$

where $\mathbf{L_0}$ is the inductance of the same choke without the presence of the ferrite material (that is, if the core had a relative permeability of 1). Fig 4 shows complex permeability for a ferrite material that can be effective for suppression at UHF.

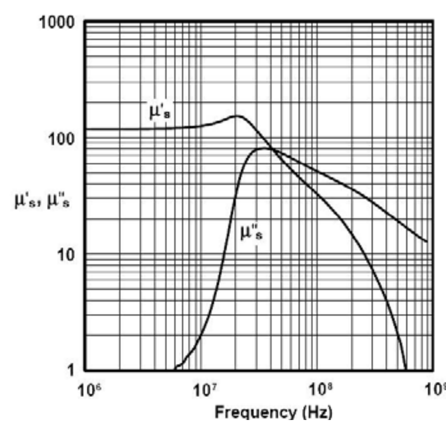

Figure 4 – Complex permeability of a NiZn ferrite useful for suppression at UHF (Fair-Rite #61)

The approximate equivalent circuit of a wire surrounded by a ferrite is <u>two</u> parallel resonant circuits of relatively low Q that are in parallel with each other. (Fig 5)

Snelling [7, 8] showed that there can be a dimensional resonance within any ferrite part related to the velocity of propagation, $\boldsymbol{V_P}$, of the field within the ferrite, and standing waves that are set up when the dimension of the cross-section of the core is one half wavelength. In any medium, $\boldsymbol{V_P} = \boldsymbol{\mu\varepsilon}\mathbf{c}$ where **c** is the speed of light. $\boldsymbol{V_P}$ varies over at least two orders of magnitude from one material to another. For any given material, the smaller the core, the higher will be the frequency of this resonance, and to a first approximation, the resonant frequency will double if the core dimension is halved.

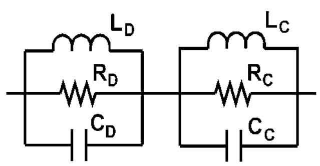

Figure 5 – The equivalent circuit of a ferrite choke

Snelling [7] observed that if the medium is relatively lossy, as most ferrites are in the portion of the spectrum where they will be used for suppression, both $\boldsymbol{\mu}$ and $\boldsymbol{\varepsilon}$ will be complex, and that in such a medium, there will be a quadrature standing wave that gives rise to a peak in the observed magnetic loss and dielectric loss at resonance. He also observed that there will be no standing waves, and thus no dimensional resonance, if the product of the magnetic loss tangent ($\boldsymbol{\mu'_S/\mu''_S}$) and the capacitive loss tangent ($\boldsymbol{\varepsilon''_P/\varepsilon'_P}$) is much much greater than 1 (that is, if the total loss is high enough to damp the standing wave).

This dimensional resonance is accounted for by the first parallel resonant circuit consisting of $\mathbf{L_D}$, $\mathbf{C_D}$, and a loss component, $\mathbf{R_D}$, that is mostly due to eddy currents (and some hysteresis) in the core. The second parallel resonance is formed by $\mathbf{L_C}$ and $\mathbf{C_C}$, the inductance and stray capacitance associated with the wire (or coil of wire) passing through (or wound around) the core, and $\mathbf{R_C}$ accounts for the resistance of the wire. $\mathbf{C_C}$ has two common components. First, there will be stray (parasitic) capacitance between the turns of a coil wound around a ferrite core. Second, the ferrite core will act as a dielectric between the two ends of the conductor passed through it. The latter effect will also be present for a multi-turn choke wound around the core.

If the two resonances are widely separated in frequency, they will appear as independent resonances, but if they are closely spaced, they will typically merge into a single resonance of lower Q.

As with all inductors, the inductance of a coil will be proportional to the square of the number of turns passing through the core. But as the number of turns increases, so does the stray capacitance of the winding. The parallel combination of C_C and C_D can cause either or both resonances to move down in frequency. The graphs of the resistance (and the impedance) of a practical ferrite choke vs. frequency exhibits a broad peak at resonance.

Even without the ferrite, the formation of a multi-turn choke will multiply the inductance of a single turn by the square of the turns ratio, and the presence of the ferrite multiplies both the R and L components by the complex permeability of the ferrite.

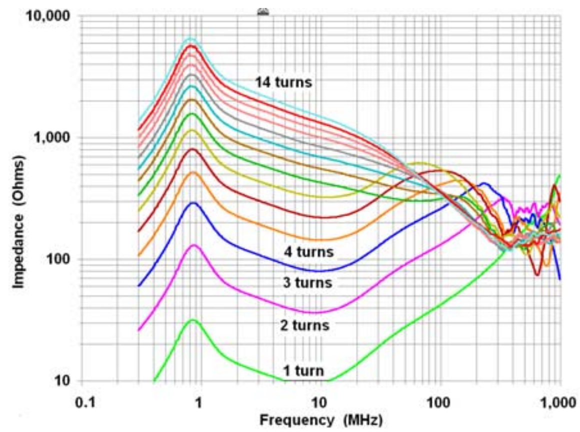

Figure 6a – Impedance of chokes wound around the 2.4" o.d. MnZn toroid of Fig 2 (Fair-Rite #78)

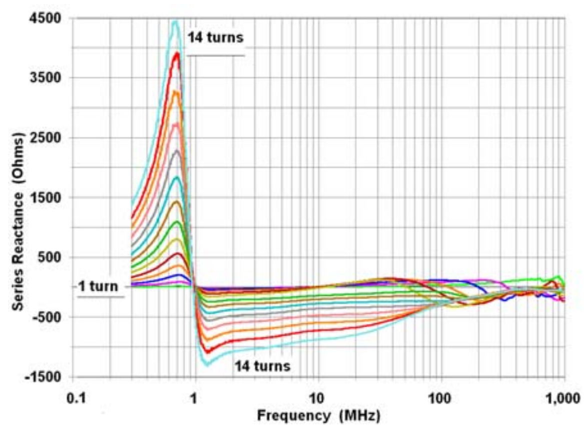

Figure 6b – Equivalent series reactance for the chokes of Fig 6a

Fig 6 is measured data for multi-turn chokes wound around a Fair-Rite #78 core like that of Fig 2. Cores made from this family of MnZn ferrite materials typically have dimensional resonance in the 1 MHz range. For such materials, the frequency of the dimensional resonance does not change with increasing turns because the stray capacitance of the winding, C_C, is more than two orders of magnitude smaller than C_D, the capacitance associated with the dimensional resonance. The resonance of C_C and L_C occurs above 1 GHz for a single turn, moving down to about 320 MHz for two turns, 220 MHz for three turns, 170 MHz for four turns, 100 MHz for five turns, and 60 MHz for six turns, but for 7 or more turns, the resonant peak becomes far less pronounced and eventually disappears.

Fig 7 is measured data for multi-turn chokes wound on a Fair-Rite #43 NiZn toroid of the same size as that in

Fig 2. The velocity of propagation in this core material is about two orders of magnitude greater than for the MnZn material, which would place its dimensional resonance in the hundreds of MHz range, but because the material is quite lossy at these frequencies, no standing waves are established, and only the parallel resonant circuit of the coil applies. Thus, dimensional resonance in this core, which is widely used for suppression at VHF and UHF, is not a sufficiently large factor to be significant. For this family of ferrites, the combined resonance of the coil and the dimensional resonance moves down in frequency more than in proportion to the number of turns!

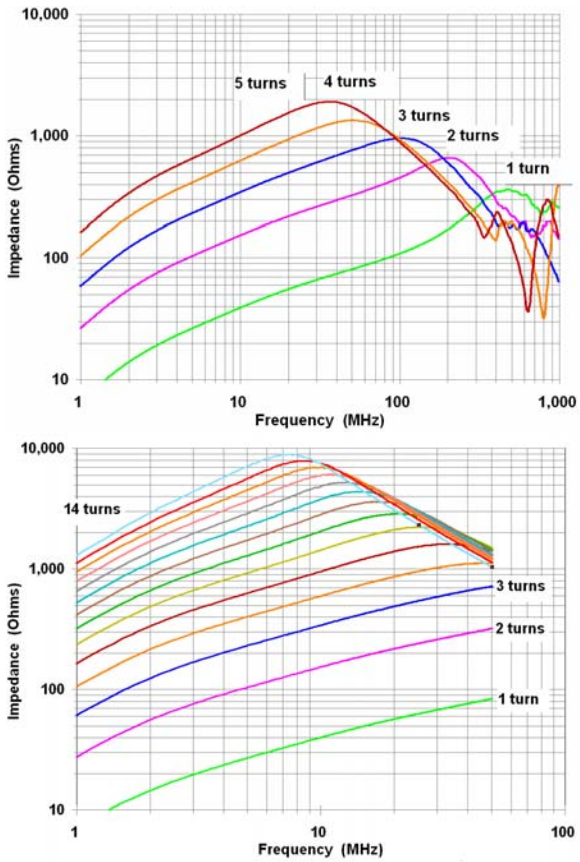

Figure 7 – Impedance of multi-turn chokes on the same size core, but made from Fair-Rite #43

Fig 8 is measured data for chokes wound on a new MnZn material that is optimized for suppression at HF and VHF. Dimensional resonance is present in this material (although quite well controlled). It can be seen as a broad plateau of the impedance curve for 1-7 turn chokes, and a broadening of the response that results from merging of the dimensional resonance with the resonance of the coils having a greater number of turns.

An important benefit of the above relationships is that a ferrite material that is effective for suppression with a <u>single</u> turn over the range of 20-200 MHz can be effective over the range of 0.5 - 20 MHz if <u>14 turns</u> are wound around it. It is this set of principles that allows toroidal chokes to effectively suppress strong interference from AM broadcast transmitters.

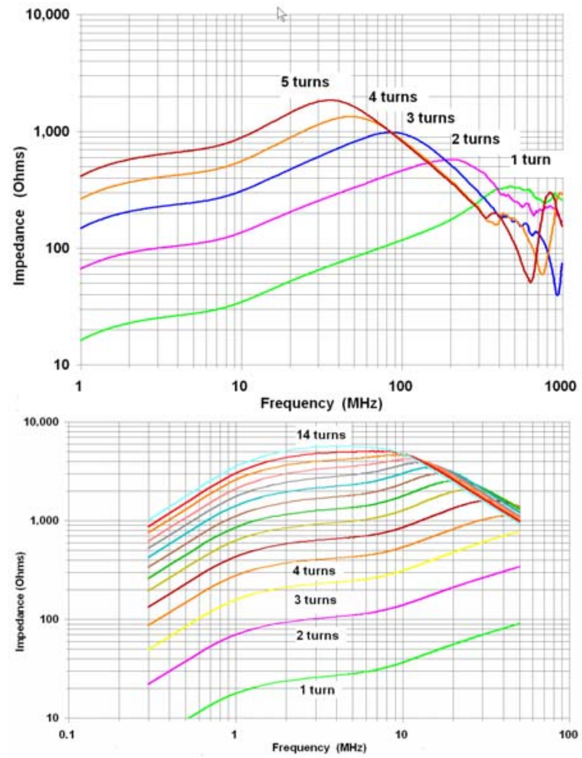

Figure 8 – Impedance of multi-turn chokes on the same size core, but made from Fair-Rite #31 (MnZn)

SERIES OR PARALLEL EQUIVALENT?

A brief discussion of series and parallel equivalent circuits is in order. Many impedance analyzers express the impedance between their terminals as Z with a phase angle, and the series equivalent R_S, X_S. They could just have easily expressed that same impedance using the parallel equivalent R_P and X_P, (Fig 14) BUT – R_P and X_P will have values that are numerically different from R_S and X_S. There is also an important analytical "mindset" we need to adopt when thinking about how series and parallel circuits behave. In a series circuit, the <u>larger</u> value of R_S and X_S has the greatest influence, while in a parallel circuit, the <u>smaller</u> value R_P and X_P is dominant. In other words, for R_P to dominate, R_P must be smaller!

Both expressions of the impedance are correct at any given frequency, but whether the series or parallel representation is most useful will depend on the physics of the device being measured and how that device fits in a circuit. We've just seen, for example, that a parallel equivalent circuit is a more realistic representation of a ferrite choke –the values of R_P, L_P, and C_P will vary far less as frequency changes than if we use the series equivalent. [R_P, L_P, and C_P won't be <u>constant</u> because the basic physical properties of all ferrite – permeability, resistivity, and permittivity – all vary with frequency.]

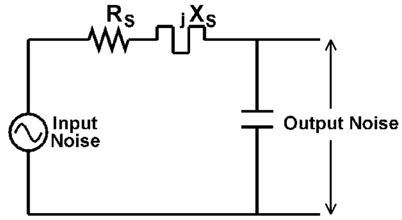

Figure 9 – The choke is part of a voltage divider

In spite of all this, virtually all product data for ferrite chokes is presented as series equivalent R_S and X_S. Why? First, because it's easy to measure and understand, and second, because ferrite chokes are most often used as series elements of a voltage divider! Fig 9 and 14 are both useful representations of the voltage divider formed by a ferrite choke and a small bypass capacitor across the device input. Which representation we use will depend on what we know about our ferrite. If we know R_P, L_P, and C_P and they are constant over the frequency range of interest, Fig 5 or 14 may be more useful, because we can insert values in a circuit model and perhaps tweak the circuit. But if we have a graph of R_S and X_S vs. frequency (like Fig 10), Fig 9 will give us a good answer faster. Because we will most often be dealing with R_S and X_S data, we will use the series circuit for most of our remaining examples. Another reason for using R_S and X_S is that the impedance of two or more ferrite chokes in series can be computed simply by adding their R and X components, just as with any other series impedances!

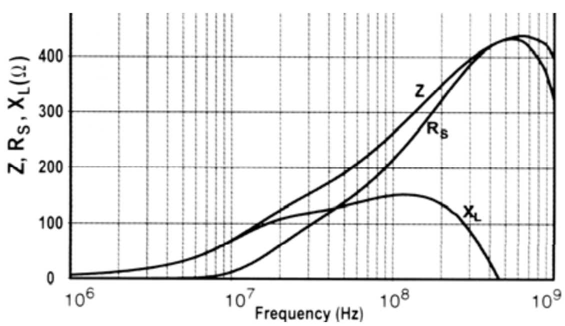

Figure 10 – A single-turn choke using a small clamp-on sleeve made of the material of Fig 4

Data sheet plots of R_S, X_L, and Z for a standard ferrite part (Fig 10) are the series equivalent parameters of the resonance(s) that occur when a wire is passed through the core to form a simple choke. Depending on the ferrite material and its dimensions, that resonance may be due to stray capacitance, dimensional resonance, or a combination of both. Without exception, these data sheets fail to show the capacitive component of the reactance, but it is there!

Fig 10 also illustrates the general behavior of most ferrites used for suppression, although the frequencies at which the transition from one behavior to another occurs will be different for each ferrite part. At low frequencies, X_L is increasing linearly with frequency (this is a semi-log plot), but above about 25 MHz, μ'_S becomes smaller and μ''_S becomes larger (Fig 4), so X_L gradually stops increasing with frequency while R_S gets larger. Above 100 MHz, the choke has a lot of loss but very little inductance, and begins to tend toward the resonance that occurs around 450 MHz. At resonance, R and Z peak, and X goes through zero and becomes capacitive.

Another point regarding equivalent circuits – we know that the equivalent circuit of loudspeakers and enclosures can be quite complex if we want to get the most information out of them, but that added complexity comes at the price of greatly increased complexity when we write the equations. The same is true of ferrite chokes – there is resistance in the wire, there is capacitance between the winding and the core, and so on. For purposes of understanding ferrites for suppression, the equivalent circuits used in this paper are good enough. In a different application (RF transformers, power inductors, etc.), a more detailed analysis might be in order. If the more complex parallel equivalent circuits of Fig 5 and 15 help us understand why a multi-turn coil wound around a ferrite core causes the resonance to move down in frequency as the number of turns is increased, the additional complexity is worth the trouble.

IMPEDANCE AND CORE GEOMETRY

When we speak of a single turn ferrite choke, we mean that a conductor passes through the core once. Some generalizations can be made with respect to how the size and shape of a ferrite core affects the impedance of the choke that is formed.

1. Below resonance, resistive and inductive components of its impedance are proportional to the length of the core that the conductor passes through.
2. Below resonance, both resistive and reactive components of its impedance are proportional to ***ln (D/d)***, where ***D*** is the outer diameter of the core and ***d*** is the inner diameter.
3. Increasing the length of the core, and increasing its cross section, will tend to lower the frequency of resonances associated with the choke.
4. Based on #1 and #2, impedance will be increased by using a long core that fits snugly around the conductor – up to the point where the core is large enough, or the frequency is high enough, for resonance to occur.

An important implication of these realities is that greater suppression at UHF can be achieved by using multiple small single-turn chokes in series along a cable than by using one larger part. The reason is simple – although the larger part may have a higher impedance below resonance, the resonant frequency may be well below the frequency to be suppressed, and the capacitances, $\mathbf{C_D}$ and $\mathbf{C_C}$, associated with the larger core make it ineffective at the higher frequency. The smaller core moves the resonances to a higher frequency, and although each core contributes less impedance at resonance, they can be effective if multiple cores are used in series along a conductor.

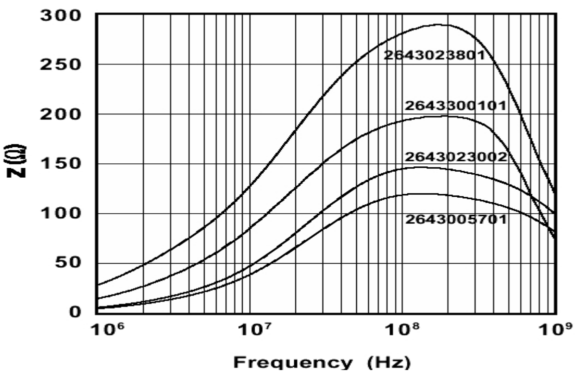

Figure 11 – These small cylindrical beads, all made with Fair-Rite #43 material, differ only in length

PARASITIC EFFECTS

In general, ferrite cores tend to have very little leakage flux – that is, because of their high permeability, they tend to contain all of the flux produced by current on the wire passing through them. On the other hand, small values of capacitance can be obtained by placing a ferrite core parallel to and very close to a ground plane. The wire passing through the core will have parasitic capacitance to the ground plane, with the ferrite acting as the dielectric.

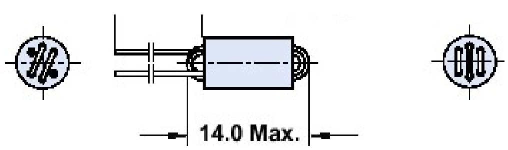

Figure 12 – A wound bead (dimensions are mm)

As previously noted, the resistivity of ferrites varies over several orders of magnitude, depending on their composition (the "mix"). Some ferrites have such high values of bulk resistivity that bare wires can be used in the "wound beads" of Fig 12. Some other mixes have much lower values of resistivity, and must be treated as conductors. When using beads to form circuit isolators for use in testing microphones for susceptibility to EMI, it was necessary to insulate beads from each other to prevent leakage from one circuit to another via the beads. [3, 5]

Ferrites can exhibit amplitude non-linearity at high signal levels due to saturation (that is, μ decreases as the material saturates). In audio applications, saturation would likely occur only if an individual ferrite were applied to one conductor of a high power loudspeaker circuit. If the ferrite were applied ***common mode*** (that is, if both conductors pass through it), their fields will cancel and no saturation will occur unless the common mode current is sufficient to saturate it.

Ferrites also exhibit a reduction in their permeability with increasing temperature. Again, the threshold of this effect is unlikely to be reached in typical audio applications.

SUPPRESSION AND CIRCUIT GEOMETRY

The circuit of Fig 13 operates by "brute force" – the ferrite choke simply reduces EMI by reducing common mode current. Without the choke, the antenna (mic cable shield) has an effective path to earth, and thus is an efficient antenna. The choke reduces that efficiency by adding loss in series with it. The choke also forms a divider with the common mode input impedance of the device it is protecting. However, good common mode rejection generally requires that the common mode impedance of the input stage be high, so good input stages generally have an input impedance that is too high to be of much help. [10]

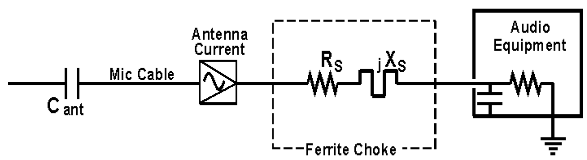

Fig 13 – A choke interacts with the input circuit

When suppression must be achieved in the field, and without modifications to equipment, a large choke is often the only practical means. Luckily, it is a quite powerful means, but a relatively large choke can be required, especially for suppression below 30 MHz.

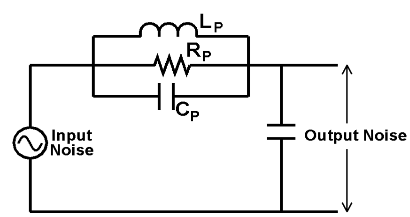

Figure 14 – Parallel equivalent circuit of choke in a voltage divider

When designing ferrite chokes into equipment however, several other degrees of freedom are available. Fig 14 shows a ferrite choke, represented as its parallel equivalent components, forming a low pass filter with a capacitance that is placed across the signal line. In such a configuration, the combination of a much smaller choke and relatively small capacitance can form a very effective filter. Fig 14 also makes it clear that above resonance, the choke will look like a capacitor, and will lose its ability to reject the interference.

The circuit shown is unbalanced; when used with a balanced input, beads should be placed on both circuit conductors. Figure 15 shows how beads can be used with balanced interfaces. In this capacitor microphone, the beads are "loaded" by small value capacitors (on the order of 100 pF) to form a low pass filter.

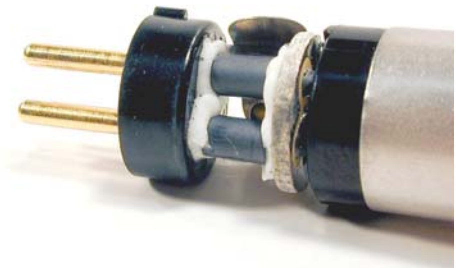

Figure 15 – Ferrite beads protect a microphone

THE VICTIM AS PART OF THE ANTENNA

For all of the mechanisms discussed here, victim audio equipment is part of an antenna system that receives radio frequency (RF) interference. To understand that, consider Figures 16 and 17, which are two of the most fundamental antenna types. The antenna of Figure 16 can be any length, but will be most efficient if the length on each side of the feedpoint is some odd number of quarter-wave lengths. Likewise, the antenna of Figure 17 will be most efficient if it is some odd number of quarter-wavelengths.

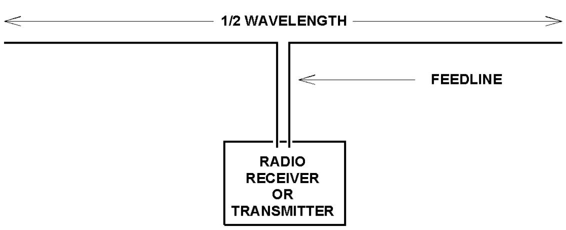

Figure 16 – An efficient antenna

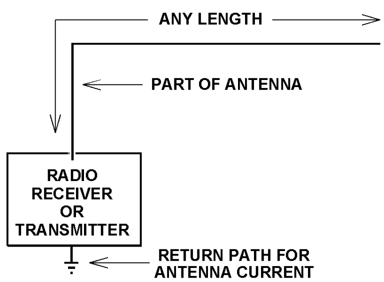

Figure 17 – An efficient antenna

In Figure 16, the two halves of the antenna provide a current maxima at the feedpoint. Another way of looking at it might be to say that one half of the antenna serves as a "counterpoise" for the other. The body of a typical microphone, which is one-quarter wave long in the range of 350 – 500 MHz, can be the counterpoise for the mic cable connected to it (Fig 18), and a person holding the microphone would form an effective counterpoise down to at least 40 MHz. If the mic had a pin 1 problem (that is, it violated AES48) all of the antenna voltage and current would be applied directly to the circuit board. And even if AES48 were observed, inadequate input filtering could combine with SCIN to allow RF to enter the microphone and cause interference.

Microphone and loudspeaker wiring will nearly always act as efficient receiving antennas unless it is enclosed in grounded conduit. Virtually all audio equipment will be grounded via the power system to which it is connected, and that ground connection provides the return path illustrated in Fig 17. And even if the equipment were not grounded (for example, on an outdoor film shoot with the mixer operating on battery power), other wiring (and even the mix operator's body) would likely form an effective counterpoise.

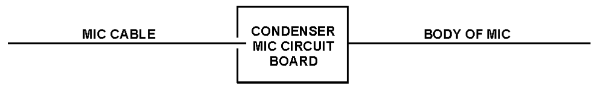

Figure 18 – The body of a microphone can be the other half of a dipole

APPLICATIONS GUIDELINES AND DATA

RESISTANCE IS THE KEY TO SUPPRESSION

When used to suppress radio frequency interference, the loss component is generally of far greater use than the inductive or capacitive component. To understand why this is true, one must consider the complete circuit of which the choke is a part. The primary function of the ferrite is to suppress current on the conductor that it surrounds. In systems where the ferrite is used for suppression, the current is usually established by the conductor acting as an antenna, either receiving or radiating RF noise. (Fig 20)

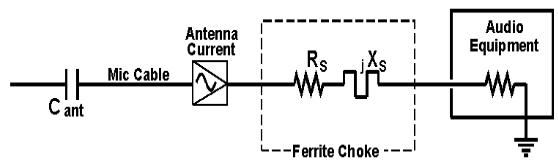

Figure 20 – The inductive component of the choke can resonate with an antenna (mic cable) that is electrically shorter than a quarter-wave

An antenna that is electrically shorter than one-quarter wavelength will look like a capacitive reactance, and one that is longer than one-quarter wavelength but less than one-half wavelength will look inductive. For longer antennas, this pattern will repeat at intervals of one-half wavelength. In cases where the wire looks reactive, the reactance added by the ferrite choke can resonate with the reactance of the wire and increase the current rather than reduce it. On the other hand, the resistive component will always reduce the current. The selection of a ferrite part for suppression of RF current thus includes the choice of a material, size, and shape that results in an equivalent circuit that is predominantly resistive over the widest range of frequencies that require suppression.

For all practical purposes, the usefulness of a ferrite choke for suppression is greatest for several octaves below, and up to about an octave above, its resonant frequency. At higher frequencies, the resistive component is shunted out by the capacitive component. At lower frequencies, there is insufficient resistance or inductance to limit the current.

Virtually all detection of RF interference is proportional to the square of the voltage or current. [2] Thus, a 6 dB reduction of antenna current or the voltage coupled into equipment, will result in a 12 dB reduction in the detected interference.

Antenna current will be reduced in proportion to the total circuit impedance, which is the complex combination of the series R and X. An electrically short antenna has a relatively high capacitive reactive impedance; when a choke is added, the inductance will cancel some or all of that reactance, but it should add resistance. When the resistance is equal to the initial reactance of the antenna, current will be roughly the same, and no suppression will be achieved. In other words, the antenna impedance is a threshold below which the choke has little effect. But if the resistance is increased to twice that initial reactance, current will be roughly 6 dB less, and detected RF will be about 12 dB weaker. And from that point, each doubling of choke resistance will reduce the detected interference by about 12 dB.

USING MULTI-TURN CHOKES

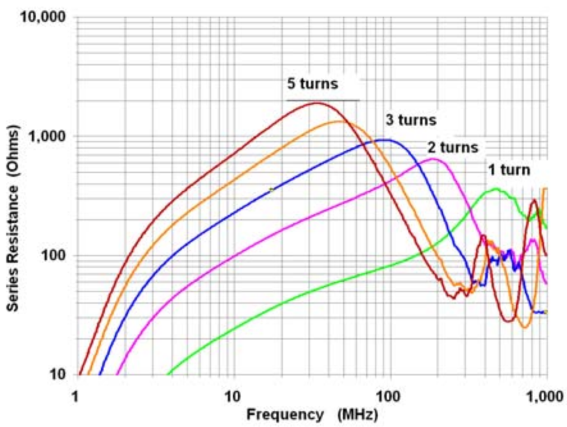

Figure 21 – Series equivalent resistance, #43 toroid

Figures 21 to 24 are measured data for multi-turn chokes wound around toroids made with four different ferrite mixes like that in Fig 2. A toroid of this size is particularly useful because at least 14 turns of typical microphone cable (0.21" o.d.) can be wound around it without removing the attached XL connector.

As part of the research reported here, a variety of microphones and input equipment were subjected to a wide range of interference sources, including AM broadcast transmitters, ham radio transmitters operating in the HF, VHF, and UHF spectrum, broadcast sources in the VHF and UHF spectrum, and cell phones operating around 900 MHz. For all "brute force" suppression applications, as illustrated in Fig 9, a general "rule of thumb" became apparent – ***to achieve significant suppression by the "brute force" method, the ferrite choke should present a resistive impedance of at least 700 – 1,000 ohms, and more is better. For audio wiring that is long enough to be an effective antenna at broadcast frequencies, the total impedance, including the inductive component, will also be beneficial as long as the resistive component is large.***

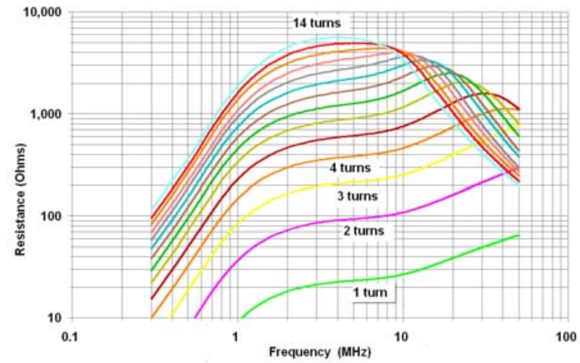

Figure 22 – Series equivalent resistance, #31 toroid

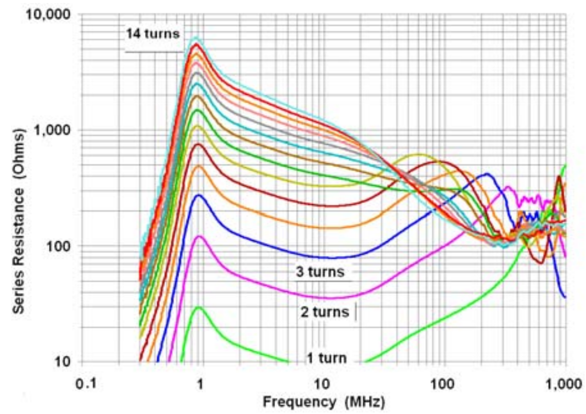

Figure 23 – Series equivalent resistance, #78 toroid

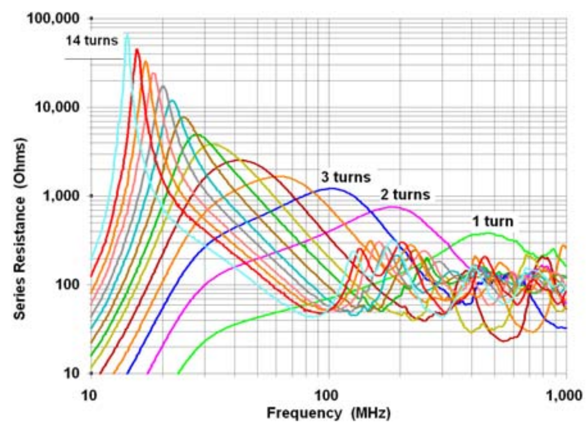

Figure 24 – Series equivalent resistance, #61 toroid

Using this guideline, the data of Figs 21 to 24 can easily be used to predict the effectiveness of multi-turn chokes for use with sources between about 500 kHz and 50 MHz. Of all the materials studied, the #31 material, is by far the most useful below 100 MHz, thanks to the broad frequency range over which it provides a high resistive impedance. It also provides the greatest resistive impedance over the AM broadcast band. A 14-turn choke will provide very effective suppression from below 1 MHz to above 15 MHz, a range of more than 1 decade! Fourteen turns on #43 provides equal suppression from about 2 MHz to about 15 MHz, or roughly one octave less. The #61 material is a poor choice for suppression for the same reason that it is extremely useful as a core for transformers and baluns in medium power transmitting applications – its loss is quite low below about 20 MHz.

SINGLE TURN CORES AT MF AND HF

Figure 25 – Equivalent series resistance of single turn chokes using two large solid cylindrical cores

As part of the research reported here, a variety of other cores were measured and evaluated for their use with audio systems, including some cores large enough to fit around audio multicables (mic snakes). Based upon the "rule of thumb" cited above, none of these parts is suitable for use as single turn chokes below about 30 MHz, and even in that application, at least two chokes in series would be required to achieve a reasonable level of suppression. On the other hand, the large "clamp-on" core shown in the upper right of Figure 1 could be quite effective if used to form a multi-turn choke around cables when it is impractical (or labor intensive) to remove a connector too large to fit through a solid core. Fig 25 is measured data (using a less precise measurement method) of the largest solid cylinders (top center in Fig 1) in the Fair-Rite catalog made with a material suitable for use at HF.

MULTIPLE FERRITE CHOKES ON A LINE

Multiple ferrite chokes can be placed on a single cable to increase the choking impedance, or to cover multiple frequency ranges. While it is possible that the inductive reactance of one choke may be cancelled by the capacitive reactance of the other choke, the resistive components will add, and the result will be more effective suppression.

It has been shown that audio cables are quite lossy at high radio frequencies. [9] It is also true that for a random long wire antenna that is many wavelengths long (Fig 17), the portion of the antenna within one or two wavelengths of the receiver (the victim equipment) makes the greatest contribution to the received signal. In the work reported in [2], interference injected using handheld VHF and UHF transmitters was observed primarily when the transmitter was at standing wave maxima along the cable, and only in the most problematic microphones was interference observed more than about one wavelength along the cable.

The above leads to these general guidelines:

1. The length of cable between a choke and the equipment it is protecting should be a small fraction of a wavelength at the frequency of the interference. Thus, VHF/UHF chokes should be within a few cm of equipment, while chokes to suppress AM broadcast frequencies can be a meter away.

2. When multiple chokes are placed on a cable to suppress multiple frequency ranges, the choke covering the highest frequency range should be nearest to the equipment.

3. When equipment at both ends of a cable is susceptible, chokes should be placed at both ends of the cable to suppress interference at frequencies for which the cable is longer than about 10% of a wavelength. Thus, a single choke would likely protect a 30 m cable against AM broadcast interference, but both ends of a 1m cable will require chokes for protection from cell phones.

SUSCEPTIBILITY TO CELL PHONES

Many capacitor microphones have considerable susceptibility to cell phones, mostly due to pin 1 problems (that is, they do not conform to AES48). A new XL "EMC" connector was developed in response to work in the AES Standards Committee Working Group on EMC, and early "pre-production" samples were found to be quite effective in suppressing that interference when used on the cable that mates with the problematic microphone. [2] That connector is now in production.

The connector combines three key features. First, a capacitor having essentially concentric geometry connects the shield to the connector shell in a manner that minimizes the parasitic inductance of the connection between the shield and shell. This provides what is essentially a "feed through" bond for the shield to at least 1 GHz. Second, a ferrite bead is placed around the wire to pin 1, which presents a high (and predominantly resistive) series impedance in the VHF and UHF spectrum.

The ferrite bead has two benefits. First, it lowers the Q (and the frequency) of the resonance that is formed between the capacitor and the inductance of the connection through pin 1 when the connector mates with equipment that conforms to AES48 (that is, pin 1 is connected directly to the shield enclosure in that equipment). More important, at VHF and UHF, the bead disconnects the shield from pin 1 of equipment with a pin 1 problem, and the capacitor properly connects it to the shielding enclosure of the equipment. In addition to "working around" pin 1 problems in a piece of equipment, the concentric capacitor also reduces the common mode voltage at VHF/UHF by improving the connection of the shield to the shielding enclosure.

The third key feature of the new connector is construction intended to improve the contact between its own shell and the shell of a mating connector.

When one of the EMC connectors is not available, or if more suppression is needed, ferrite chokes can be placed around the interconnecting cable to reduce shield current. Cell phones transmit in two ranges – around 900 MHz, and around 1.8 GHz. Ferrite beads must be very carefully chosen if self resonances above 800 MHz are to be achieved. In general, the beads must be rather short, and a single bead will rarely add enough impedance to provide adequate suppression. However, multiple beads added in series along the cable may achieve that result.

THE MEASURED DATA

Two levels of instrumentation were used to obtain the data presented here. Initially, all data were obtained using a low cost antenna bridge, the AEA model CIA-HF. This resulted in data good enough to support the author's general study of the topic, but for the most part, not nearly as good as the author would like to publish. That instrument has three fundamental shortcomings. First, the stray capacitance of the input is on the order of 12 pF. Second, the maximum impedance that can be measured is 1,000 ohms. Third, the instrument is ambiguous with respect to the sign of the reactive component of the impedance. The result is poor accuracy when measuring unknowns of relatively high value, or at the upper end of its range (54 MHz). Fig 25 is from that data set.

To obtain accurate impedance data up to 1 GHz, a Hewlett Packard HP8753C Network Analyzer was used with the companion HP85046A S-Parameter Test Set and an HP 85052D 3.5mm calibration standards kit. The 85046A uses APC7mm connectors, so an APC7mm-to SMA(male) between series adapter was used to provide a test port receptacle that was compatible with the SOLT (short, open, and load) standards in the 85052D 3.5mm calibration kit. Before beginning measurements, these calibration standards were used to perform a full 1-port vector correction on the analyzer, thus establishing the measurement plane at the SMA interface. The SMA interface then served as the connection point for the inductors being measured.

All measurements were made for conductor sizes much smaller than a microphone cable shield. Conductor size has little influence on inductance, so the data are a good representation of the behavior of chokes wound using microphone cables below the resonance between $\mathbf{L_C}$ and $\mathbf{C_C}$. If a larger conductor size causes the windings to be closer together, stray capacitance will increase and the resonant frequency will be lower for a given number of turns. This matter was investigated early on by comparing measurements of #22 wire with those using 0.21" o.d. microphone cable. Differences were found to be negligible for wound chokes below 30 MHz, which is the range in which they find greatest application.

SUMMARY AND CONCLUSIONS

1. Ferrite chokes can be an effective tool for reduction of RF interference to audio systems. The term choke, however, is misleading, because when used for suppression, their loss is of greater value than their inductance.

2. Audio cables can be wound on toroidal, cylindrical, and even "clamp-on" style cores to form multi-turn chokes that provide effective suppression between 500 kHz and 50 MHz.

3. A single turn choke (that is, a cable passed through a ferrite core) is generally most effective at frequencies greater than 50 MHz, and relatively ineffective much below that frequency.

4. Passing multiple turns through a ferrite core will lower the frequency range at which over which the core provides suppression by a factor approximately equal to the number of turns. The effectiveness of the choke at the lower frequency will increase a bit less than in proportion to the square of the number of turns.

5. Ferrite materials exhibit a velocity of propagation equal to the product of their complex permittivity and permeability. This causes a ***dimensional*** resonance when a cross-sectional dimension is $\lambda/2$ if the material is not very lossy. Dimensional resonance is most often a factor in MnZn materials.

6. The frequency at which dimensional resonance occurs is determined by the permeability and permittivity of the ferrite and its dimensions. For any given material, the resonant frequency will be increased by making the ferrite smaller.

7. All chokes formed using ferrites exhibit a ***circuit*** resonance due to the combination of their inductance and stray (parasitic) capacitances. Chokes are generally most effective near that resonant frequency. A relatively low Q choke (that is, one that is relatively lossy at resonance) can remain effective for up to an octave above and three octaves below resonance.

8. The frequency at which ***circuit*** resonance occurs is determined by the permittivity and geometry of the ferrite core, and the geometry of the wire passing through or wound around the

core.

9. The more complex equivalent circuit for ferrite chokes proposed herein accounts for these resonances, thus providing greater insight into their behavior than the commonly used simple series resistance and inductance model, especially at high frequencies.

10. At frequencies well below resonance, the impedance of a ferrite choke is a series resistance and inductance, and the magnitude of both components will be approximately proportional to the distance the wire traverses within the ferrite material, the square of the number of turns, the permeability of the material, and ln(D/d), where D and d are the outside and inside diameters of the core. ***Thus, below resonance, a long core that fits a cable snugly, but has a larger outer diameter, will maximize the choking impedance. A point of diminishing returns is reached when core becomes large enough to make the circuit resonant frequency more than about 1.5X the frequency of the interference.***

11. Ferrite materials, and chokes formed using them, generally have low loss (high Q) at lower frequencies and high loss at higher frequencies. In general, ferrite materials used for suppression should have high losses at the frequency of the interference, while materials used for power transfer should present low loss to the signals they are carrying. Thus, a particular ferrite core may be quite useful for power circuits only at low frequencies, but useful for suppression only at high frequencies.

12. Audio cables act as antennas to receive RF interference. A non-resonant antenna will have a complex impedance that is capacitive if it is shorter than λ/4 and inductive if it is longer than λ/4 but shorter than λ/2. Reactance present in a choke added for suppression that is of the opposite sign from the antenna reactance will increase antenna current, but resistance will always reduce the current (and reduce the interference). ***Thus, a choke that has a higher value of equivalent series resistance at the frequency of the interference will provide more effective suppression.***

13. For "brute force," "outside the box" suppression, where there is no low impedance load to form a voltage divider with the choke, the complex series impedance of an antenna (audio cable) at the frequency of the interference establishes a threshold impedance that a series suppression must match before significant suppression can occur. Above that threshold, suppression of the RF signal improves by up to 6 dB for each doubling of the choke resistance. Since virtually all detection mechanisms follow square law, this results in a 12 dB reduction in audible interference. As a practical "rule of thumb," 1,000 ohms should be considered the minimum value at which useful suppression will occur.

14. Multiple chokes along a single line act as any other series components – that is, their total impedance will be the complex sum of their series equivalent resistances and their equivalent series reactances. Thus, except to the extent that reactances cancel, multiple chokes in series along a single line will increase suppression.

15. When the frequency of the interfering signal is in the UHF range, maximum suppression will generally be achieved by using multiple small cores in series.

16. If multiple chokes are required for suppression in more than one frequency range, the choke covering the highest frequency range should be nearest to the input terminals.

17. The length of audio cable between victim equipment and the choke will act as an antenna. Thus, the length of exposed cable between the choke and the victim equipment should be the smallest practical fraction of a wavelength at the frequency of the interference, and λ/20 should be considered a maximum length.

18. When the length of a cable connecting equipment having poor immunity exceeds λ/10 at the frequency of strong interference, suppression is likely to be required at both ends of the cable.

19. A choke can be made more effective by adding a shunt capacitance, $\mathbf{C_L}$, as a load to form a low pass filter. This configuration is a good choice for filters built into equipment, and allows smaller components to provide greater suppression at lower frequencies. Such a filter exhibits a relatively low Q resonance between the inductance and the capacitive load (thanks to the loss component of the choke). The attenuation curve of the filter resembles that of a single pole filter at higher frequencies. Maximum attenuation occurs at the resonant frequency of the choke itself, and degenerates to the ratio of the capacitive divider formed by $\mathbf{C_C}$ and $\mathbf{C_L}$.

20. The permeability of a ferrite core is reduced by high currents due to saturation, and also by increasing temperature. Saturation and temperature rise due to dissipation in high power circuits can be avoided if both send and return conductors are wound through the core such that the resulting fields are opposing.

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