Understanding How Ferrites Can Prevent and Eliminate RF Interference to Audio Systems

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Over the past few years, we've been learning about some important mechanisms that can combine to cause radio frequency (RF) interference to sound systems. They are:

1. An audio cable will be excited as an antenna by radio signals that are nearby, and *current* will flow along its length. Most of this *current* will flow on the *shield*. Antenna action will also cause a voltage to be impressed along the length of the cable, which can appear as a common-mode component 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, where it is detected.
3. Inadequate balancing of shielded cable converts RF *shield current* to a differential voltage on the signal pair – "shield-current-induced noise" (SCIN).
4. Inadequate low-pass filtering of signal input and outputs lets RF present on the signal conductors into equipment. Equipment can be susceptible 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 *shield current* is a major contributor to all of them, so eliminating or reducing *shield current* should be the key to eliminating the interference. Experimental work near WGN's 50 kW AM transmitter confirmed this hypothesis. At WGN, virtually all cases of interference in both microphones and input equipment, many of them quite severe, were either eliminated or greatly reduced when a cable connecting the mic to the input gear was wound around a toroidal ferrite (Fig 1) to form an RF choke that reduces that current.

Fig 1 – A toroidal ferrite choke

Fig 2 – Ferrites are made in many forms

To test the effectiveness of ferrite chokes in audio RFI applications, selected product samples were ordered, and a series of tests were run. Extensive laboratory work has shown that ferrite chokes make very effective RFI filters if properly applied. This Tech Topic studies the use of ferrites to eliminate RF interference to audio systems.

Ferrites are ceramics consisting of various metal oxides formulated to have very high permeability. Iron, manganese, manganese zinc (MnZn), and nickel zinc (NiZn) are the most commonly used oxides. 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 "magnified" by the 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. Fig 3 shows complex permeability μ'_S and μ''_S for a ferrite material optimized for suppression at UHF. [For the engineers among us, $\mu = \mu'_S + j\,\mu''_S$. Thus μ'_S is the component of permeability defining ordinary inductance, and μ''_S defines the loss component.]

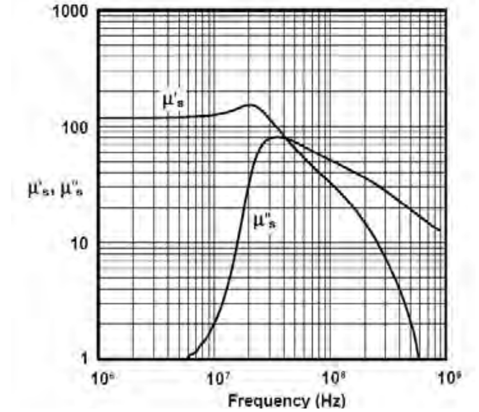


Fig 3 – Permeability of a typical ferrite material (Fair-Rite #61)

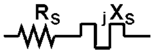


Fig 4a – Data sheet impedance

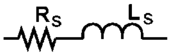


Fig 4b – Over-simplified equivalent circuit of a ferrite choke

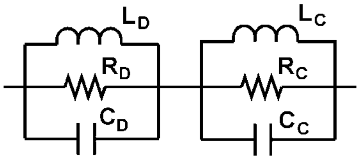


Fig 4c – A better equivalent circuit of a ferrite choke

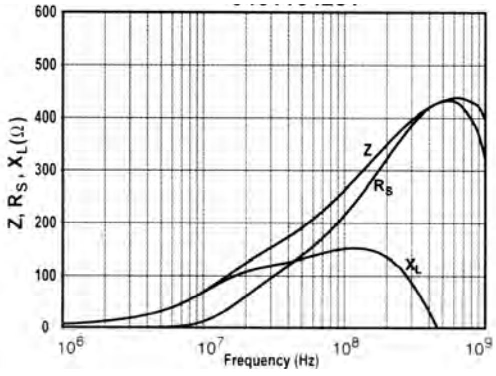


Fig 5 – A UHF material (Fair-Rite #61)

Data sheets characterize ferrite chokes by graphing their series equivalent impedance, and chokes are usually analyzed as if their equivalent circuit had only a series resistance and inductance, as shown in Fig 4a and 4b. The actual equivalent circuit is closer to Fig 4c. We'll learn more about it as we go along.

Fig 5 is the manufacturer's data for a cylindrical bead of 5 mm O.D. and 23 mm long, defined in terms of the series R and X_L. Interestingly, X_L goes off the graph above resonance, but it isn't zero. In fact, there is negative reactance contributed by the capacitors in Fig 4c.

Below resonance, the impedance of a ferrite choke is proportional to the length of the wire that is enclosed by the ferrite material. Fig 6 shows the impedance of a family of beads that differ primarily in their length. There are also small differences in their cross section, which is why the resonant frequency shifts slightly.

Manufacturers vary the chemical composition (the *mix*) and the dimensions of ferrites to achieve the desired electrical performance characteristics. Fig 5 is data for a sleeve made of a material useful in suppressing RFI above 200 MHz. The material used for the beads of Fig 6 is optimized for suppression at VHF (30-300 MHz).

Like all inductors, the impedance of a ferrite choke below resonance is approximately proportional to the square of the number of turns passing through the core. Figure 7 is measured data for multi-turn chokes wound around the toroid of Fig 1 (2.4″ O.D x 1.4″ I.D. x 0.5″). This ferrite is optimized for the VHF range (30-300 MHz). Fig 8 shows data for chokes wound around the same size toroid, but using a material optimized for suppression above 200MHz. The data of Fig 9 are for toroids of the same size, but wound on a material optimized for use below 5 MHz.

We'll study the L_D C_D resonance first. A classic text (***Soft Ferrites, Properties and Applications*** by E. C. Snelling, published in 1969), shows that there is a dimensional resonance within the ferrite related to the velocity of propagation within the ferrite and standing waves that are set up in the cross-sectional dimensions of the core! In general, 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. In Fig 4c, L_D and C_D account for this dimensional resonance, and R_D for losses within the ferrite. R_D is mostly due to eddy currents (and some hysteresis) in the core. Now it's time to account for R_C , L_C, and C_C.

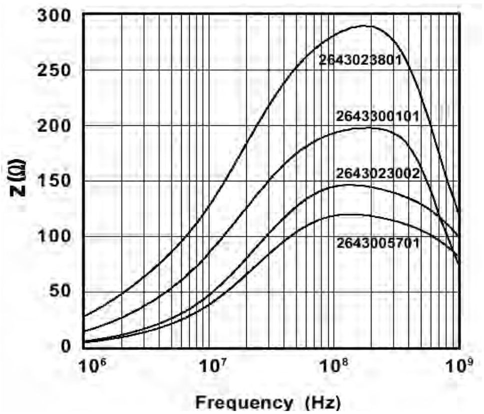


Fig 6 – Small cores of different lengths

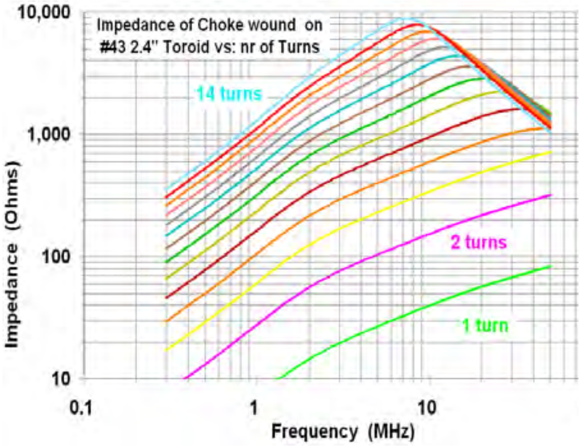


Fig 7 – Impedance of multi-turn chokes wound on the core of Fig 1 (Fair-Rite #43).

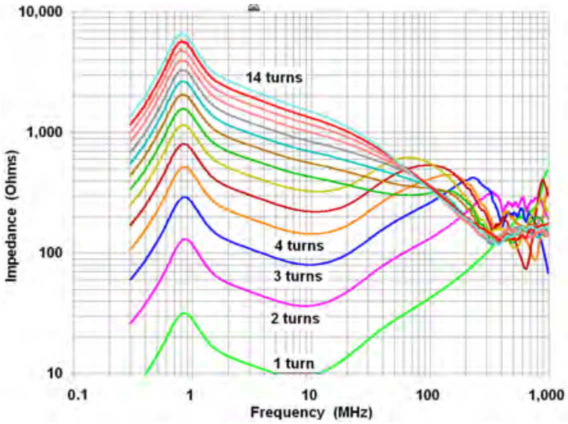


Fig 8 – Impedance of multi-turn chokes on a core of the size/shape of Fig 1, but of a material optimized for performance below 2 MHz (Fair-Rite #78)

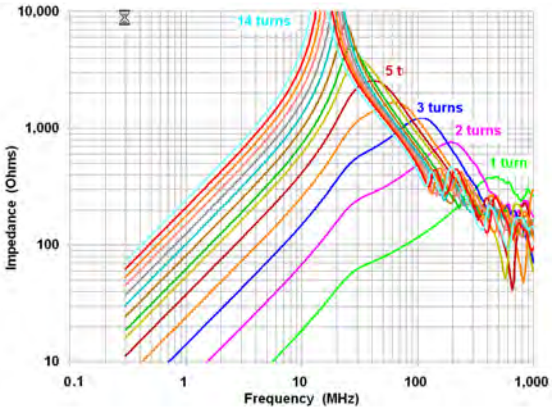


Fig 9 – Impedance of multi-turn choke on a core of the size/shape of Fig 1, on a material optimized for performance above 200 MHz (Fair-Rite #61).

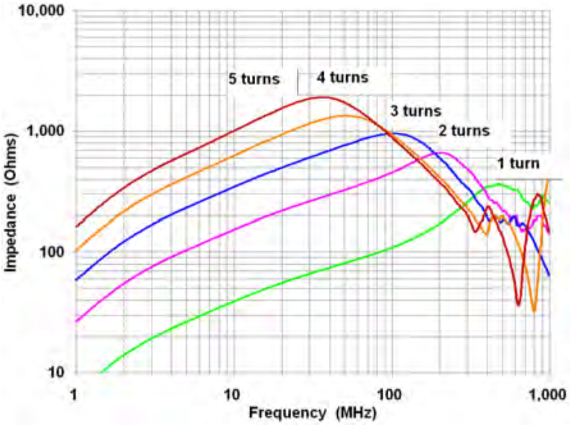


Fig 10 – Chokes of Fig 7 with fewer turns, measured to 1 GHz (Fair-Rite #43)

Note that there are <u>two</u> sets of resonances for the chokes wound around the #78 material (Fig 8), but only one set for the chokes of Fig 7 and 9. And for all three materials, the upper resonance starts just below 1 GHz for a single turn and moves down in frequency as the number of turns is increased. Fig 11, the reactance for the chokes of Fig 8, also shows both sets of resonances. That's why the equivalent circuit must include two parallel resonances!

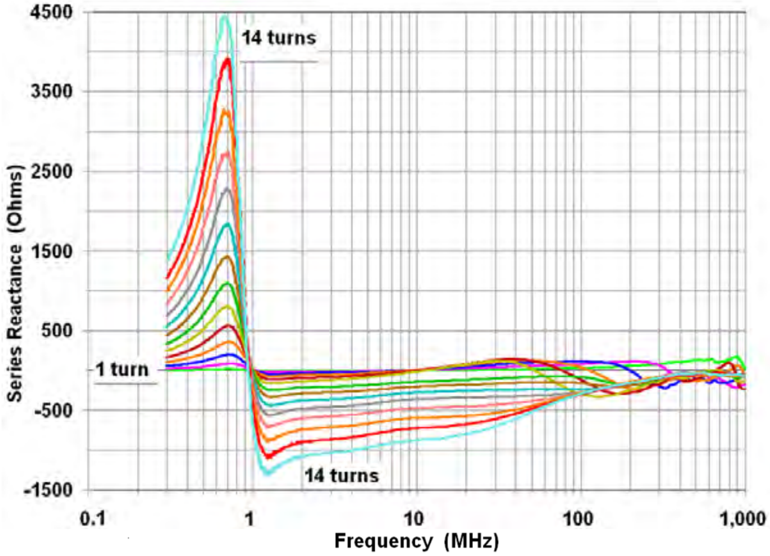


Fig 11 – Series reactive component of the chokes of Fig 8

The difference between these materials that accounts for this behavior is their chemical composition (i.e., their mix)! #78 is a MnZn ferrite, while #43 and #61 are NiZn ferrites. The velocity of propagation in NiZn ferrites is roughly two orders of magnitude higher than for MnZn, and, at those higher frequencies, there is too much loss to allow the standing waves that establish dimensional resonance to exist.

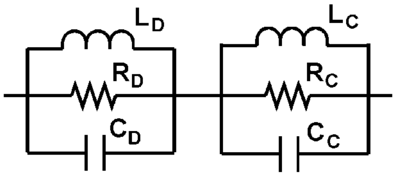


Fig 12
A multi-turn choke

To understand what's happening, we'll study Fig 12, our first order equivalent circuit of a multi-turn choke. L_C and R_C and C_C are the inductance, resistance, (including the effect of the μ of the ferrite), and stray capacitance associated with the wire that passes through the ferrite. This resonance moves down in frequency with more turns because both L and C increase with more turns. The dimensional resonance does not move, since it depends only on the dimensions of the ferrite and its V_P!

Let's talk briefly about series and parallel equivalent circuits. Many impedance analyzers express the impedance between their terminals as Z with a phase angle, and the series equivalent R_S, and X_S. They could just have easily expressed that same impedance using the parallel equivalent R_P and X_P 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 larger value of R_S and X_S has the greatest influence, while in a parallel circuit, the smaller value R_P and X_P is dominant. In other words, for R_P to dominate, X_P must be large!

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 remain more or less constant as frequency changes than if we use the series equivalent. [R_P, L_P, and C_P won't be constant, because the physical properties of all ferrite – permeability, resistivity, and permittivity – all vary with frequency.]

But 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, second, because we tend to forget there is stray capacitance, and third because ferrite chokes are most often used as series elements of a voltage divider! Fig 13a and 13b are both useful representations of the voltage divider formed by a ferrite choke and a small bypass capacitor across the device input. Which 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 13a 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, Fig 13b 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 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! ***When you look at the data sheet plots of*** R_S, X_L, ***and Z for a standard ferrite part, you are looking at the series equivalent parameters of their dominant resonance. For most MnZn materials, it is dimensional resonance, while, for most NiZn materials, it is the circuit resonance.***

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 circuits of Fig 12 and 13 are good enough. In a different application (RF transformers, power inductors, etc.) a more detailed analysis might be in order.

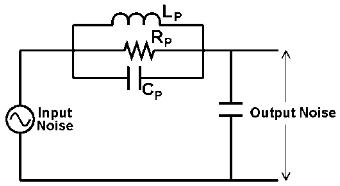


Fig 13a – Series element of divider is a parallel resonance circuit

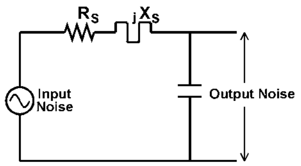


Fig 13b – Series element of divider is series equivalent with a graph of data

Fig 14 shows how a choke might be used to reduce common mode current flow on a shield of an audio cable. Because that cable is also an antenna, it will have some impedance of its own, depending on its length and the frequency of the interfering signal. If the antenna is shorter than a quarter-wave it will look like a capacitance, and can resonate with the inductance of the ferrite choke. When this happens, the current is limited only by the resistance of the circuit – in this case, the loss component of the choke. The choke can also be capacitive, and the antenna can be inductive, as it would be if it were longer than a quarter-wavelength. Antenna theory tells us that these impedance relationships will repeat in increments of ½ wavelength. The last thing we want is to increase the RF current, and we would prefer to not have to worry about how long the antenna (mic cable) is.

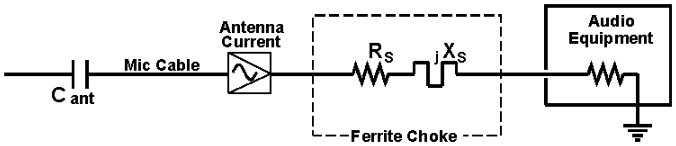


Fig 14 – The choke interacts with the cable

Thus the general rule that all ferrite chokes should be designed to operate in the frequency range where their series equivalent resistance is large and their series equivalent reactance is small! This rule applies to both single turn and multi-turn chokes. This is accomplished by selecting a suitable material, the size of the material, and the number of turns.

Now let's do some engineering work using what we've learned. The question is, can we achieve sufficient suppression by simply passing a mic cable through a ferrite to form a single turn choke, and if so, what ferrite materials are needed? An examination of Fig 7 suggests that the choke used for the WGN tests probably had Z on the order of 750 ohms at 720 kHz (WGN's operating frequency), and this choke was pretty effective. Tests in my lab suggest that an impedance of at least 800 – 1,000 ohms is needed at VHF and UHF. Thus a target design resistance of at least 700 – 1,000 ohms would seem to be appropriate.

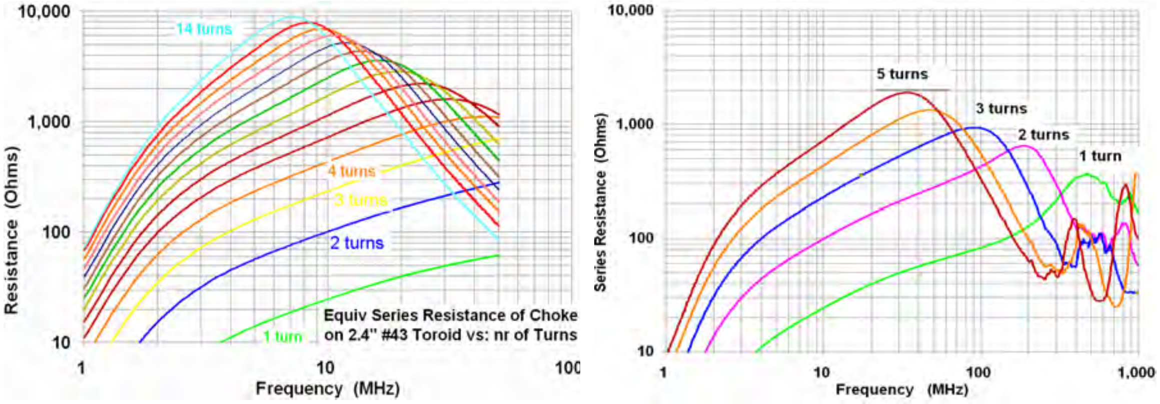


Fig 15 – Series R of chokes on the #43 2.4″ toroid

But there's more to it than the impedance of the choke – the rest of the RF circuit has a lot to do with how much suppression will occur. Fig 16 shows the most common circuit – equipment is well grounded (at the frequency of the interference), most typically in an equipment rack, and there is some impedance between the input and the enclosure. This becomes the classic voltage divider of Fig 13 – the voltage on the antenna will divide between the choke and the input impedance of the audio equipment. So to achieve good suppression, we simply need the impedance of the choke to be much higher than the series combination of the antenna and the path to "ground" (Fig 14) or the antenna, the internal common mode input impedance of the equipment, and the path to "ground" (Fig 16).

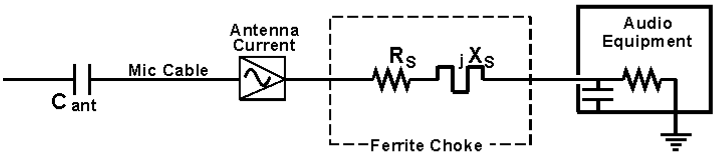


Fig 16 – A ferrite choke on wiring connected to grounded equipment.

Fig 17 shows the condition of equipment that is <u>not</u> well grounded. Perhaps it is a microphone on a stand, suspended above a choir, or held by a performer. The return path for antenna current is through whatever capacitance may happen to exist between the equipment and "ground" (or some object that is large enough to act as the other half of the antenna – at higher frequencies, this could be the performer holding the mic).

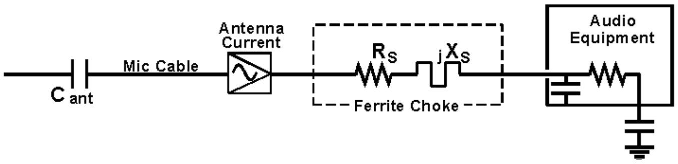


Fig 17 – A ferrite choke on wiring connected to un-grounded equipment

Fig 17 explains some interesting things we observed at WGN, where Ron Steinberg and I were set up outdoors in a forest preserve across the road, and running our equipment from one of his gasoline-powered generators. Our setup consisted of a condenser mic on a stand, connected by two lengths of 125 ft of cable to a small mixer that had both a pin 1 problem and poor filtering of its input circuit. One of the cables had a foil/drain shield, so it produced a lot of SCIN, while the other, with a braid shield, produced a lot less. While Ron plugged various mics in to test their susceptibility, I listened at the mixer. Some of the mics were clean until Ron cupped his hands around them to make the change, when they began detecting RF. Why? The capacitance between his body and earth completed the circuit so that enough current could flow to excite either a pin 1 problem or SCIN in the mic! This same mechanism (or the lack of it) is why we rarely have RFI problems with lavalier capsules, but often do have RFI problems with their impedance converters (often called the power adapter, it sits between the thin cable going to the capsule and the balanced pair going to the mix console!

A similar thing occurred at the mixer. We grounded the power system neutral to a length of ½″ conduit driven into the earth. Before we connected that ground, almost no RF was detected by the mixer. Again, without the earth connection, the impedance of the path to earth (for antenna current) provided by the capacitance between the generator and the earth was too high to allow much current to flow on the mic cable shield.

There doesn't always need to be a return path other than the equipment itself – the body of many microphones is a sufficiently large fraction of a wavelength to act as the other half of the antenna at UHF frequencies! A quarter-wavelength (a very effective antenna) at cell phone frequencies (850 MHz) is only 3.5".

Fig 18 shows the resistance of chokes formed using the largest ferrite clamp-on part I could find using a material optimized for HF performance (the large clamp-on in Fig2). One such clamp-on part would provide about 300 ohms between 60 and 180 MHz, so four or more could be effective in suppressing interference from 27 MHz citizens band transmitters, and three or more would suppress FM broadcast and low-band VHF television transmitters. The data suggests that a choke of 6-8 turns would work to suppress AM broadcast RFI picked up by one or two mic cables, but simply using it as a clamp-on on a 16-pair snake (1 turn) wouldn't make a dent. Not only that, but using ten such clamp-ons would provide only about 120 ohms series resistance at 1 MHz. Large clamp-ons can also be a problem solver when a multi-turn choke is needed on smaller diameter cables and it is inconvenient to remove large connectors. More about this later.

The solid #31 cylinders of Fig 19 (the largest in Fig 2) are a bit more useful for suppression of AM broadcast – ten of them would provide 350 Ω at 1 MHz, 20 of them about 700 Ω. Even protected by really good heat-shrink, that would a pretty awkward package on a portable mic snake, and since the ferrites are quite brittle, probably wouldn't be roadworthy. It might be a viable (although not inexpensive) alternative for fixed installations though.

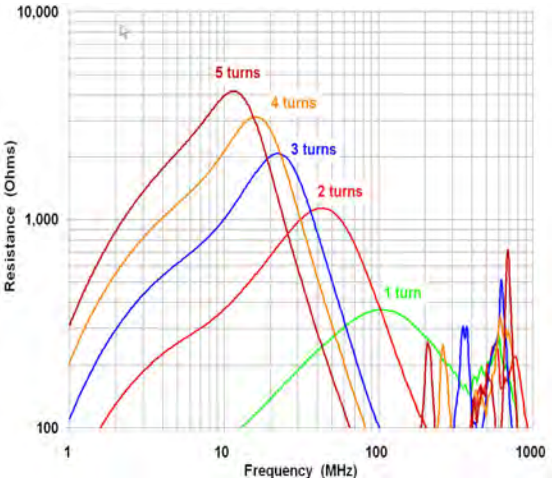


Fig 18 – Series resistance of chokes on the 1" i.d. hf clamp-on ferrite in Fig 2 (Fair-Rite 0431177081)

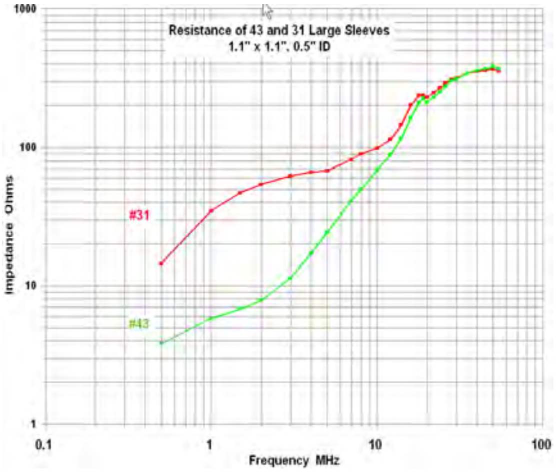


Fig 19 – Series resistance of two very large solid cylinders

It is clear, then, that if suppression is needed below about 20 MHz, the most practical solution using standard parts is to form multi-turn chokes by winding the audio cables around ferrite toroids or a large clamp-on part. The additional good news is that very effective RFI filters for the AM broadcast band and ham HF frequencies can be fashioned from these parts, especially the new #31 material. Ferrites using the #31 mix have a very low-Q dimensional resonance above 2 MHz that pushes up the impedance curve below 10 MHz and making it far more useful than #43.

Chokes like that shown in Fig 1 should be able to eliminate almost any pin 1 or SCIN RFI problem between 500 kHz and 50 MHz. Fig 15 and Fig 21-23, which show the resistive component of the impedance of 2.4" O.D. toroids suitable for use below 200 MHz, provide the information needed to make the right choice. Once you know the frequency(or frequencies) of the interference, and use the material and number of turns that provides the highest practical resistance over that frequency range!

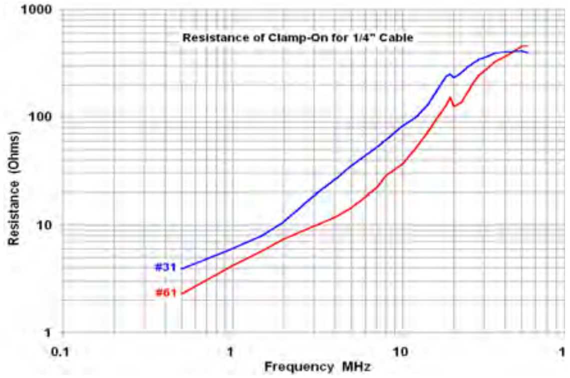


Fig 20 – Series resistance of two medium-sized clamp-ons for 1/4" cables

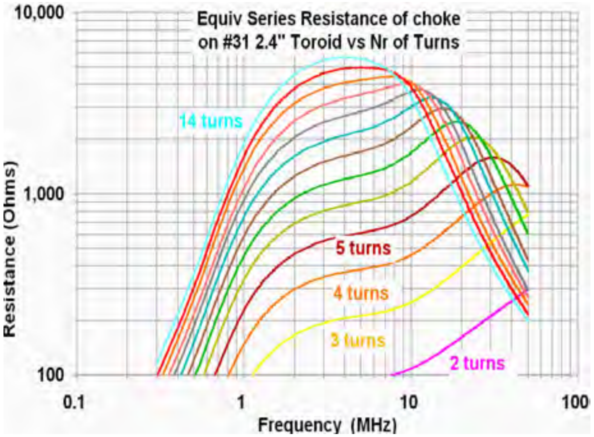


Fig 21 —Series Resistance of Multi-turn chokes wound on the #31 toroid

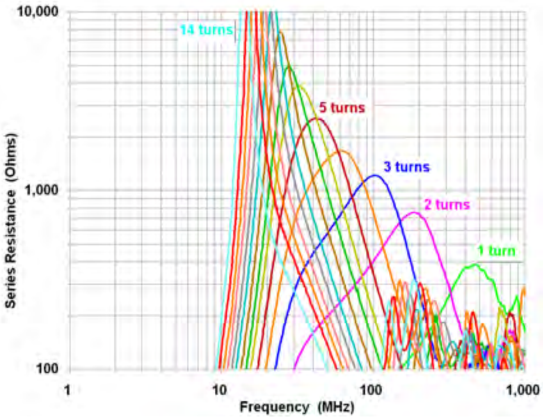


Fig 22—Series Resistance of Multi-turn chokes wound on the #61 toroid

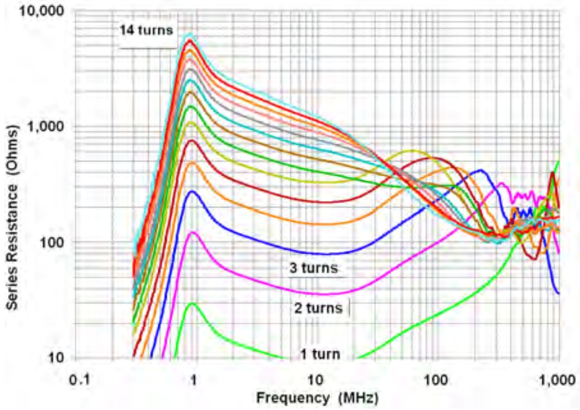


Fig 23—Series Resistance of Multi-turn chokes wound on the #78 toroid

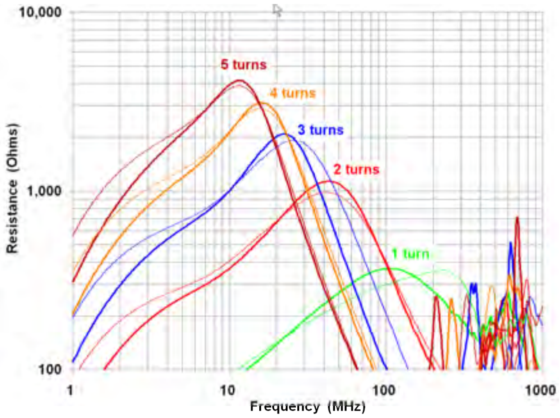


Fig 24 – Series resistance of chokes on two large #31 clamp-on parts. Heavy lines are Fair-Rite 0431177081, (1" I.D.); lighter lines are Fair-Rite 0431176451 (0.7" I.D.)

The data of Fig 24 are for chokes wound around two very large clamp-on parts. The largest of these parts (1" I.D.) is ideal when the suppression that multi-turn chokes can provide is needed, but the connector is too large to fit through the toroid and it isn't easy to remove it. The smaller part behaves similarly and provides better suppression (that is, higher series R over greater bandwidth), but its 0.7" I.D. is too small to fit cables that are likely to be used with larger connectors. Thus, the larger part, 0431177081, is by far the better choice for this application, even though it costs twice as much.

As it turns out, there's another important principle at play here that I'll call *threshold effect.* To understand it, let's look again at the simple series circuit of Fig 16, and let's say that for a particular antenna (mic cable) working into a particular piece of gear, the series impedance at the frequency of the interference is 300 Ω. If we are able reduce the RF current by 6 dB, the detected interference will drop by 12 dB (because all detection is square law). That would make the interference roughly half as loud. To do that, a choke must add enough resistance to double the total impedance. In other words, we need to end up with 600 Ω. But what if the antenna circuit is capacitive and our choke is inductive at that frequency? Some of the impedance we are adding will increase the current because it resonates with the antenna, so we may need to add more than 300 Ω to hit 600 Ω! *How many times have you heard someone say, "ferrite beads don't work on this problem – I added one and nothing happened." In fact, they were simply below the threshold impedance needed in that particular circuit!*

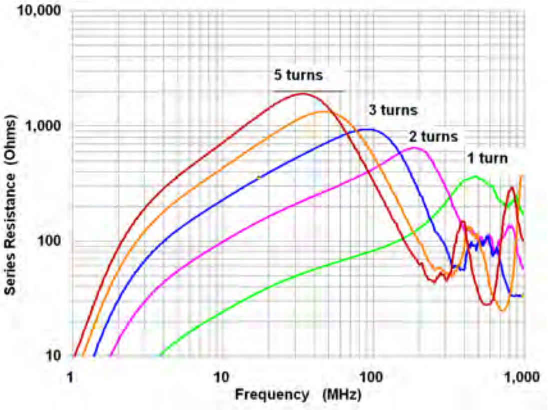


Fig 25 – Series resistance of 1-5 turn chokes wound on #43 toroid

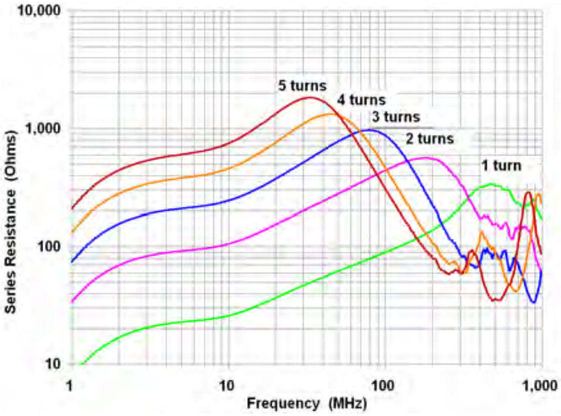


Fig 26 – Series resistance of 1-5 turn chokes wound on #31 toroid

Some other interesting conclusions can be drawn from the data (Fig 22, 23, 25, 26). There is little difference between chokes wound on the various VHF and UHF toroids for 1-5 turns – they all look about the same (but not the #78 material). It is below 50 MHz where they act very differently. Thus, if you need suppression between 30 MHz and 200 MHz, they work almost equally well, although the #61 material has a slight advantage over certain narrow frequency ranges. Each additional turn moves the resonant frequency down by a factor of roughly 2:1 between 1 and 4 turns. And the impedance at the shifted resonant frequency increases approximately as $N^{1.5}$ between 1 and 4 turns (that is, not as much as N^2 but more than N). Although I haven't seen measurements, I suspect that other core shapes made from the same family of materials will act similarly. So if you know the resonant frequency and the Z at resonance for a different ferrite part, you can use these "rules of thumb" to estimate how many turns will move the choke down to the frequency range you need.

The length of wire between the choke and the equipment can act as an antenna if it is long enough. Where should ferrite chokes be placed to provide maximum rejection?

- A choke should be within $\lambda/20$ of the equipment at the frequency of the interference it is choking.
- Chokes can be placed in series on a cable to cover different frequency ranges, and the choke covering the higher frequency range should be closer to the equipment.
- Chokes may be needed at both ends of cables longer than about $\lambda/8$.

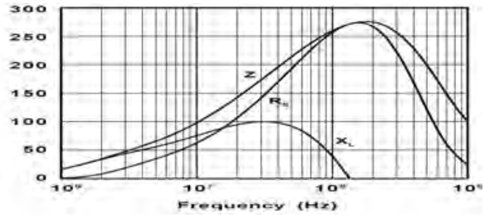
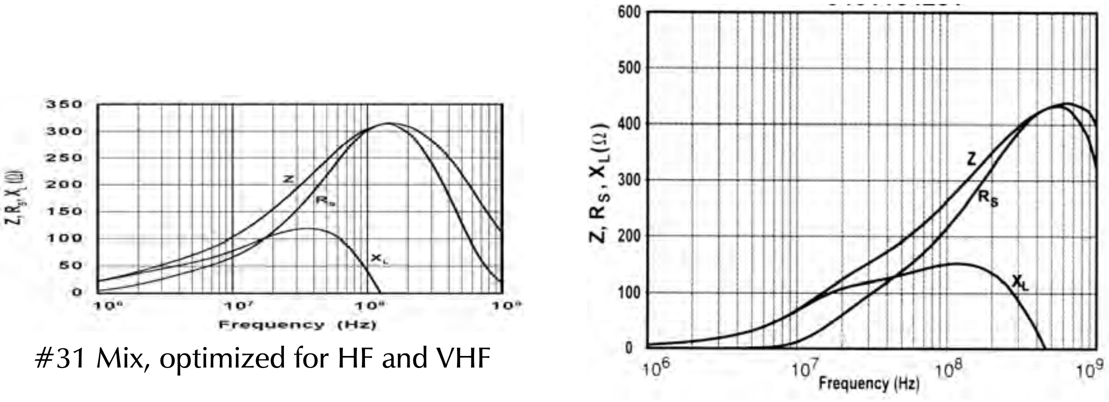


Fig 27 – #44 Mix, optimized for HF and VHF
(to the same scale as Fig 28)

The new #44 mix is interesting for reasons that don't show up on a plot of impedance vs. frequency. Ferrites can vary widely in resistivity, depending on their composition. The #44 mix is one of several that has relatively high resistivity, so that bare wires can be wound in contact with it. The Fair-Rite catalog includes a broad selection of multi-turn beads wound with this material, and many are useful at HF.



#31 Mix, optimized for HF and VHF

#61 Mix, optimized for UHF

Fig 28 – Two clamp-ons for ¼″ cable (single-turn characteristics)

There are easier solutions for VHF and UHF interference. Figs 27-28 show the performance of clamp-on ferrites that can easily be attached to a mic cable, either adjacent to the mic to eliminate a susceptibility in the mic, or at the mix console to solve a susceptibility there. The #31, #43, and #44 materials (and similar materials from other manufacturers) would be the weapon of choice for interference from FM and VHF-TV, while the #61 (UHF) material would be the best choice to eliminate interference from UHF TV and cell phones. In nearly all cases, two or more beads will be needed. Studying the catalogs will yield more good choices. Tests in my lab show that multiple #61 and #43 ferrites can significantly reduce susceptibility of some condenser microphones to VHF broadcast and cell phone interference that is related to shield current. A single clamp-on rarely makes a dent in the interference, but three or more usually does. This would seem to confirm our initial "rule of thumb" guideline that a series resistance of at least 750 – 1,000 ohms is needed to provide RFI suppression. Or, as my dear grandmother used to say, *"If a little's good, more's better!"*

That doesn't mean that selecting the right ferrite part for UHF suppression is easy – it can be tricky, especially if the culprit is cell phones! The major fly in the ointment is ***circuit resonance***. To understand why, consider where the capacitance is coming from for a single turn choke. Because the ferrite is an insulator, it acts as a dielectric for a capacitance formed between the two ends of the wire passing through it. When a longer core is used to increase the impedance, the inductance increases, more of the core is in proximity to the wire, so the capacitance also increases, and the resonant frequency moves down. The net result is that for any given material and core size, a point of diminishing returns is reached where making the material larger moves the resonance too far below the 850 MHz frequency of the cell phone. Above resonance, the effectiveness of these VHF and UHF parts drops pretty quickly, as that capacitance swamps the resistance. That's why multiple small parts can work better than one larger one! And the problem is even more difficult if the interference source is a cell phone operating around 1.9 GHz! Ferrite manufacturer Steward has a new material claimed to produce resonances in the 1 GHz range. We'll see.

Here are some guidelines for maximizing the suppression provided by a ferrite choke at the UHF frequencies used by ***cell phones*** and ***digital wireless mics*** (600-900 MHz and 1.9 GHz). All are aimed at keeping the resonant frequency high.

- Suppression is usually greatest at resonance, and falls off rapidly above resonance.
- Always use a single turn choke for UHF interference.
- Use a core with an I.D. that fits the conductor as snugly as possible.
- Use the thickest core (O.D. – I.D.) that doesn't put the resonance below the frequency of interest – but no thicker. This can be a delicate balancing act!
- Avoid cores longer than about 0.375″.
- Use the core(s) that provide the greatest ***resistance*** at the frequency of interest, and use more in series along the cable if you need more suppression.
- If a product has RFI problems at both low and high frequencies, use chokes for each frequency range in series, placing the chokes for the highest frequency range closest to the equipment that receives the interference.

So far, we've talked only about ferrites, but there are other very reliable system installation techniques that are well known to minimize RFI. They are:

1) Never use parallel wire (zip cord) for loudspeaker wiring. Always use twisted pair cable for loudspeaker wiring. Why? It's quite common for audio output stages to lack the low-pass filters needed to reject RF, so any RF picked up by the loudspeaker wiring will be coupled back to a driver stage via the feedback loop, where it will then be detected and amplified. And, of course, it is well known that a twisted pair provides good rejection of magnetic and electric fields, but we tend to forget that this still applies at radio frequencies.

2) Avoid the use of shielded cables with a drain wire if the system will be exposed to strong RF below 10 MHz (AM broadcast, ham transmitters, light dimmers). Any cable with a drain wire will have significantly greater SCIN below about 10 MHz than a cable that uses a good braid shield. On the other hand, foil-shielded cables provide better shielding above 20 MHz. The best cable, if you can find it, is one that has both a foil and braid shield. Second best are those with very dense braid shields.

   Both of these cable mechanisms are quite powerful -- simply switching from zip cord to twisted pair for loudspeaker wiring, or from foil/drain cable to a good braid cable, can easily reduce RFI by 20-30 dB if that is how the RF is getting in.

3) We know that pin 1 problems are a common cause of RFI, so fixing them is always worth the trouble. The best fix is one that disconnects the cable shield from the connector pin that goes to the circuit board, and connects the cable shield instead to the equipment's shielding enclosure. This is particularly important with VHF and UHF interference sources. Don't forget that pin 1 problems can occur with unbalanced inputs and outputs too – if the equipment has RCA and/or ¼″ connectors mounted to a circuit board, you can bet your lunch that it's got a pin 1 problem! Vol 31 #2 and #3 of the SynAudCon Newsletter has a detailed discussion of Pin 1.

   Unfortunately, lots of equipment with pin 1 problems is designed in a manner that makes it difficult to fix them. That's where ferrite chokes save our bacon!

4) There's a tendency on the part of many audio equipment manufacturers to design excessive bandwidth into their products. This happens for two reasons. First, it costs a few extra dimes to include the components needed to limit the bandwidth.

Second, some (many?) misguided souls think they can improve audio sound quality by extending the bandwidth into the MHz range, which in turn can improve the phase response at very high audio frequencies. While flat phase response is a wonderful thing, extending the bandwidth of an audio system's inputs and outputs to 100 kHz should achieve that objective with even the simplest of filters, and extending it beyond about 200 kHz almost guarantees interference from nearby AM broadcast stations. The use of more sophisticated filter topologies allow sharper cutoffs with minimal phase shift in the passband.

Using braid-shielded audio cable greatly reduces the likelihood that equipment like this will see enough RF for audible detection to occur, but if additional help is needed, a good input transformer with a Faraday shield (Jensen and Lundahl are the good brands) acts as an effective low pass filter to block the RF.

5) RF interference often enters equipment and systems by more than one path. You may eliminate or reduce the interference coupled into one path, but not achieve the full elimination. *Always suspect more than one path, especially with interference that is especially strong or persistent*. Continue implementing all of the "right" techniques throughout the system, even when the first things you do don't seem to be accomplishing much. One dominant path may be "swamping" the weaker ones you are fixing. Eventually you'll find the dominant one.

ACKNOWLEDGEMENTS

Thanks are due Bill Whitlock, without whose counsel and criticism I would probably still be stumbling around in the dark; to Ron Steinberg (K9IKZ), whose AEA analyzer has been on loan to me for two years, giving me the capability to begin poking around this puzzle, to Dr. Leo Irakliotis (KC9GLI) for finding the rare Snelling text (in the third basement of the University of Chicago library) that was the key to understanding all of this; to someone on a ham radio email list who pointed me to the Snelling text; to Fair-Rite Products Corp, for providing every sample I requested and publishing excellent technical data on their products, and to an anonymous researcher for providing all the good data!

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