Audio Cables

Audio Cables: Science at Work, Perception at Play

Let's start with a fact most Disc Jockeys can agree on: Given a superior, high resolution system, well recorded music and an experienced listener, the difference between the best and worst audio cables is substantial. We will try to explain this fact with known, legitimate electronic principles that are often dismissed as "voodoo" even by those who readily acknowledge that different brand cables can indeed "sound" different!

Consider the following analogy to demonstrate how the sum of many very small related factors that shouldn't really matter can become significant: Suppose the timing in our car engine is just slightly off spec. We can be told that it won't really be noticeable. Now suppose the valve lifters are not quite adjusted to their optimum height. Again we will be told the same thing. Perhaps the jets on a carburetor (on an old car!) are not quite set perfectly. While each of these problems can be virtually inconsequential on their own, the sum of all these minor imperfections will result in a car that runs very rough and is low on power!

The Skin Effect

The "skin effect" is one of several frequency dependent phenomenon. Our precious music is electronically encoded in the form of a rapidly varying electromagnetic wave that passes through a conductive metal (wires) and causes the displacement of a shared surface cloud of electrons. People often speak of the movement of electrons as the signal, which isn't quite right. In fact, the velocity of the signal is much faster (close to light speed) than the speed at which the electrons move. The reason the signal does not travel at light speed is ultimately due to reactive damping effects of the cable itself. The wave really travels through the conductor, displacing electrons much the way a wave, which is a non-physical entity (energy), travels through water. However, this is still an over simplification as the exact details of signal propagation remain an enigma with no universally agreed upon complete explanation for the phenomenon. The true behavior is probably best explained by an interaction of both particle (matter) and wave (energy) properties similar to that of light conduction.

As an electromagnetic wave (the signal) penetrates into a conductor, it is quickly damped in amplitude such that the higher the frequency, the shorter a distance it will travel before it is damped. This is analogous to the way quicker temperature changes penetrate a shorter distance into thermoconductors than slower ones per unit of time. Moreover, the deeper the frequency travels, the more it is damped, until it reaches an energetic equilibrium that becomes its "ride depth" or depth of penetration. Higher frequencies are continually pushed out from the center of the conductor to their ride depth (the "skin" of the wire) by a force, the changing magnetic field, which is produced by the rapidly fluctuating AC current. This force is a result of self-inductance which is a phenomenon resulting in the opposition to a change in direction of a signal (AC) due to locally circulating "eddy currents."

The "skin depth" is often decided on from a common formula; (depth of penetration=1/sq root (frequency*pi*magnetic permeability*conductivity) to calculate the depth to which, for example, a 20K frequency will penetrate and hence how thick a conductor could be used for the intended frequency. From this formula it could be mistakenly concluded that we only need to use a conductor whose radius is smaller than the depth of penetration of the highest frequency in audio (20 khz). Also, from this formula it is evident that Silver wires actually have an even shorter depth of penetration necessitating even smaller conductors than copper! This is because of the different conductive characteristics of Silver.

What is overlooked is where this formula originally derives from. To calculate to what depth a given frequency penetrates is a function of to what degree the frequency is attenuated since it is a continuously increasing effect. The above formula actually yields the 1/e (inv log of a rather ugly formula) depth to which a frequency penetrates before it is damped to 36% power (64% power loss). We may calculate, if we want, the distance a 20kHz wave would penetrate before it is 99% damped which as you might expect, is greater. If however, we calculate the distance it can travel before it is only 1% damped, for instance, we find it is much shorter and well within the smallest conductor size used in virtually any audio cable! This formula is very conservative when applied to audio because it and others were originally derived for application in radio communication electronics where the skin effect is a much more serious problem due to the much higher frequencies (mega hertz and higher) involved.

At very high radio frequencies, the signal only rides on the very outside or the conductor and does not penetrate into the conductor at all. The skin effect has somewhat different implications for complex audio frequencies than for single very high RF carrier signals, since audio band frequencies are continually cycling through a gradient of differential resistance as they travel through the cable. An audio signal consists of extraordinarily complex multi-frequency bundles whose precise timing relative to each other (phase) must remain constant in order to accurately convey the original event. The subtle skin effect non-linearity's produce very small phase shifts between these grouped frequencies which is probably manifested in the form of diminished transient accuracy and reduced or altered harmonic structure.

The sensible choice therefore, is to use conductors that are small as possible to keep this gradient of differential resistance as short as possible which is why we insist on using multiple, very small, individually insulated conductors (the popular "Litz" concept) in place of one larger one. This is one of the two reasons we use two or more runs of the smallest feasible gauge pure Silver conductors in all our designs. Use of smaller conductors must however, be compensated by using more of them to avoid increasing simple DC resistance and producing current limiting effects. It also requires a very precise, symmetrical design.

Capacitance

Capacitance is an energy storage phenomenon that is put to use in an audio circuit by separating a positive and negative charge between an insulator. Audio cables are prone to this phenomenon which also has the curious property of producing energy loss in the higher (audio) frequencies depending on the value. Electrical energy in the form of a charge is stored in the dielectric (insulating material) and released quickly back into the signal path as the signal changes polarity. The phenomenon is used (along with inductors) intentionally in speaker crossovers for instance to divide different frequencies to different drivers, i.e. highs to the tweeter. The problem is this stored charge is released somewhat out of phase (slightly time delayed) to the main signal which is another small source of distortion. This is why no high-end audio pre-amplifier uses tone controls and also why higher order (i.e. forth order) crossovers are generally avoided.

To our alternating current, capacitance is actually a type of resistance since it opposes voltage changes. This relates to the "propagation velocity" inherent to different types of dielectrics. Propagation velocity varies greatly from one design to the next, and is not 100% dependent on simply the capacitance of the cable or the degree of energy storage of the dielectric however. Recall that the line level musical signal is mostly just rapidly fluctuating voltage. Transient information refers to the initial portion of this very rapidly changing information (particularly the slope of the change over time) and is a crucial aspect of realistic playback hence the slew rate of an amplifier; the speed with which it can deliver voltage changes in response to changes in signal voltage. For these reasons, it should be no surprise that even capacitance that only attenuates frequencies beyond the audio range (20khz) could be relevant to audio.

The closer the proximity of and the more parallel the two "plates" in capacitor, wires in our case, the higher the capacitance. There are several simple solutions to minimize this problem; first separate the conductors as much as possible and again use very small gauge wire since "plate" surface area is also part of the equation for capacitance. Notice length also adds to plate surface area, which is why excessively long cable runs are to be avoided. It is not practical to separate the positive and negative conductors so far that field effects are non existent since this will severely compromise the cables "self-shielding" or noise rejection capabilities (in a balanced line). Therefore, a crucial feature of all our cable designs is a balanced impedance between polarities. This ensures identical reactive forces at each axial point between both polarities and is especially important for balanced amplifiers that depend on phase cancellation of any noise picked up by the cable through common mode noise rejection. In all our designs, single ended or not, the strategy is to first reduce the strength of distortion inducing field effects then ensure the fields are equal between polarities which greatly reduces their susceptibility to external interference.

Thus, the worst possible design for line level interconnects would be two excessively long, large gauge, completely parallel conductors placed very close together.

Inductance

Now we come to inductance, which can also be thought of as a type of resistance since it opposes changes in current direction and/or magnitude. Luckily, inductance is much less of a problem with interconnects than with speaker cables since the voltage to current ratio is much higher. When a signal changes direction or magnitude as it does in our interconnect cables, self-inductance tries to resist this change which is the origin of the skin effect. Conductor size is a crucial component of self-inductance.

Mutual inductance refers to one conductor's effect on the other and is also magnetic in nature, a function of current. The current moving in one conductor produces an electromagnetic field that tries to couple with and produce current flow in the opposite direction in the other conductor. This is the principle behind the electric motor hence the term EMF (electromotive force). Again, geometry becomes important. Steep angle crossing of opposite polarity conductors is the best way to weaken this coupling effect.

Why Silver Instead of Copper?

Technicalities aside for the moment, properly designed Silver audio cables are found supremely pleasing for their lush, vivid, and above all, natural presentation. Pure Silver wiring harnesses and even transformers are the choice of many cost no object amplifiers and loudspeakers. However, just because Silver is used as a conductor does not, unfortunately, make a cable a good performer. As explained earlier, Silver is more prone to phase shift than copper due to skin effect problems as a result of its different magnetic permeability and ironically, its greater conductivity. Therefore, it is crucial to use even thinner conductors than one would with copper to nullify this limitation.

An important benefit to the use of Silver is freedom from the diode-like, energy storing and distortion producing effects of its oxide (compression and other non-linear effects). This is because Silver Oxide itself is such a superior conductor. Copper Oxide on the other hand, is a semi conductor, a material a rectifier could be made of! Copper Oxide occurs at the molecular level and is the reason behind the fanatical effort expended to attempt to make "OFC" (oxygen free copper) which is not 100% possible. Copper Oxide only gets worse with age especially with repeated bending and twisting.

Cables as Tone Controls and What Measurements Tell Us

The good news is the sum of all the above mentioned sonic evils won't really produce a cable that sounds absolutely awful. It will instead produce one without the superior resolution and tonal purity that characterizes the world best audio cables. Typical lesser quality cables usually sound "warm" (because of rolled off/phase shifted high frequencies) but with grainy, strident tonalities and compressed imaging and dynamics. It is common practice to use cables that are known to be "warm" and "laid back" for instance in a system that suffers from excessive brightness. Attempting to "patch up" such a system with a warm (rolled off) sounding cable type will ultimately lead to disappointment since cables lacking frequency extension will inevitably produce a loss of other desirable qualities such as three dimensional imaging and ambience. Unfortunately, the only proper way to correct a system with a flawed tonal balance is to change one or more of the components responsible for the problem. One should be also be conscious of excessive high frequency emphasis (distortion) in modern recordings and re-masterings, a relatively recent Hollywood mixing habit and chronic complaint among audiophiles that confounds all too many listening evaluations.

Because of DC and AC resistance, the "sound" of a cable is really more a function of altering the interaction between the source and load components. AC resistance (impedance) is the result of both capacitive and inductive effects (reactance) and is far more relevant than DC resistance however. AC resistance is perhaps the main source of the "voodoo" of audio cables since a given cable design will in principle cause different audio equipment to "behave" differently due to the substantial variation in both input and output impedance's of preamplifiers, power amplifiers, and front end units.

The "voodoo" reputation of audio cables is worsened by the apparent irrelevance of typical steady state measurements. Educated "cable cynics" are fond of pointing out that calculated frequency effects (3db down!) of the capacitative and inductive values of any normal audio cable at normal lengths are much higher than any audible frequency. This simplistic argument implies that that such delicate, complex and highly variable sonic qualities affected by different audio cables (or amplifiers for that matter) such as sound stage depth, image focus and ambience could be completely explained by simple frequency attenuation. While the "first order" effects of LC influenced frequency attenuation may be well characterized, indirect effects of their time delay components on our perception of the more subtle aspects of playback are not.

The fact that different audio cables do affect system performance differently would be especially challenging to defend if all audio cables had identical LC measurements. Luckily, this is not the case, as different interconnect and speaker cable designs result in easily measurable variations in capacitance and inductance respectively. Placed into the big picture of impedance, seemingly modest differences in LC measurements calculate to substantial differences in impedance (frequency variant) and characteristic impedance (frequency invariant) especially with speaker cables. Measurable differences in amplifier damping (which produces a rainbow sonic aberrations to the listener) have been easily demonstrated with different speaker cable designs, all of whose direct effects on frequency response alone should have been inconsequential! Furthermore, with the exception of digital cables, no audio interconnect or speaker cable can be terminated in their exact characteristic impedance, a condition that theoretically results in 100% power transfer (zero power loss). Therefore, all audio cables create varying degrees of so called "mismatch reflections" between source and load. It is then reasonable to assume that audio cable designs that happen to come closer to an ideal impedance should in principle reduce these distortions, as is the case in the RF world. While the degree of harm caused by these mismatch reflections at audio frequencies may be hotly debated, their existence cannot be!

Other possible distortion effects invite examination as well. These include the effects of inter-modulation distortions caused by varying susceptibilities of different cable designs to low frequency interference and the nature of unique "beat frequencies" generated when higher frequencies react against lower ones (heterodyning). The former is strongly a function of geometry since conventional shielding alone cannot block very low frequency EMI. The latter is especially appealing since most exotic audio cables measure differently enough that their response to ultra-sonic frequencies (generated as harmonics of amplification stages themselves) would vary substantially as well.

When the complexity of each of these phenomenons alone are considered against the staggering complexity of a real musical signal at the "quantum level", it is clear we are a long way from being able to truly understand the electronic behavior of any audio equipment under "real life" conditions. Thus the effects of high performance audio cables remain among the purest demonstrations of the limitations of the study natural science; which is the disparity between the naturally occurring phenomenon and the simplistic, measured, simulated version of reality.

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