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To: Kurt Denke, Bob Howard

From: Galen Gareis

Subject: What Cable Variables Are Most Important?

BACKGROUND: The common "wisdom" in the audio circles is that all that matters when selecting, or just understanding, a speaker cable is DCR, and not L or C. Let's look at this assumption and see what really matters most and is hardest to mitigate.

BODY: It is true that an amplifier's damping factor is the amplifier's output impedance divided into the load impedance (cable + speaker). This is very easy to optimize with simple DCR, and with a value that is sufficient for good damping factor numbers. Short cables and/or higher AWG is all that is needed. Damping factor is an indication of the amplifier's ability to control the driver electromagnetically for tighter and/or more accurate bass dynamics. It translates to a time based improvement.

Damping Factor = Z(load) / Z(out)

A speaker driver is both a generator of energy and a receiver of energy. We want to mitigate the generation of energy, sometimes refereed to as back EMF, or electromotive force. Lower output impedance numbers all allow an amplifier to best handle this unwanted back EMF that is distorting the primary applied signal. Most tests consider a damping factor value over 100 to be "solved", and it is pretty easy to manage with larger aggregate AWG size cables. Typical ten foot cables with 11 AWG or more are adequate to solve this property to values over 100.

We're done then, yes? But what happens to L and C when we just consider DCR and damping factor? Since damping factor is so easy to solve and understand, bigger AWG is better, we can just ignore L and C?

How a cable derives L and C impacts the way an analog signal travels down the cable with respect to time. Resistance is not a time based variable to the APPLIED signal, although a poor damping factor allows the drivers to generate unwanted information out of time to the applied signal, and this in the end is also a time based issue. Our ears are very sensitive to time over frequency base distortions.

A thorough research paper , THE HUMAN AUDITORY SYSTEM AND AUDIO, written by Milind N. Kuncher in 2023 points out that the human ear is many, many time better discerning time based distortion than we give it credit for. The ear's NEP (Neural Excitation Pattern) can resolve one part in 10^{40}. Exactly how did they calculate that? In the research paper it explains why the human ear is sensitive enough to detect a basilar-membrane amplitude at the level of a picometer, or about a hundred times smaller than atom. This study is available to anyone who wishes to review this vastly technical presentation as it applies to audio.

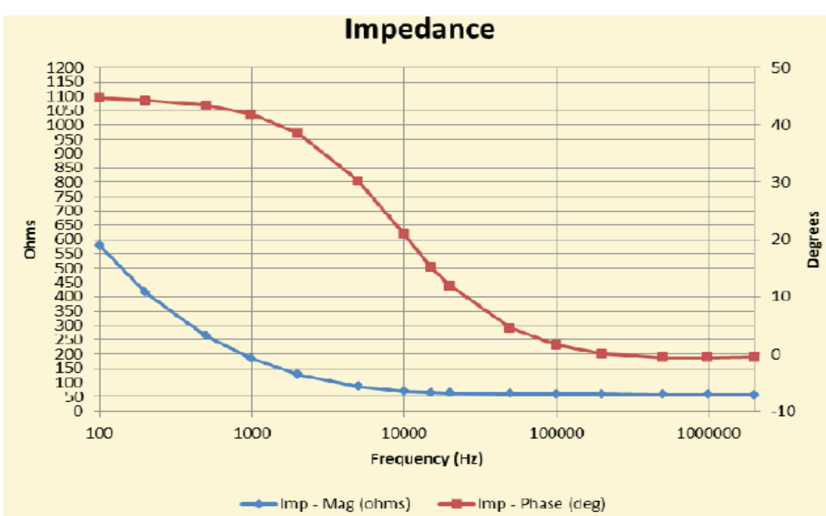
The crux of the matter, is that the human ear is an amazing TIME sensitive instrument. This is why the cable's DCR does impact what we hear indirectly. The DCR value allows the signal amplitude to be better controlled by the amplifier's damping factor and thus to control what we hear based on the applied signal, and not the speaker's voice coil generating back EMF time based distortion, and we can hear those distortions. The DCR by itself is a passive and inaudible factor, but it impacts the damping factor that is time based, and thus the transfer function becomes audible. But this isn't all that alters the analog signal.

The L and C variables are also time based distortions. Inductance, L, varies current with respect to time and C, capacitance, varies voltage with respect to time. The two are commonly called reactance as each reacts to a signal in a specific time based way. Each has its own equation to map the phase distortion with respect to time and logically they are called inductive and capacitive reactance. The effect of L and C is a distortion versus a pure resistance that does not alter the PHASE of an applied signal. The two equations show reactance go in opposite magnitudes with frequency. We are mostly in the capacitive region with analog audio.

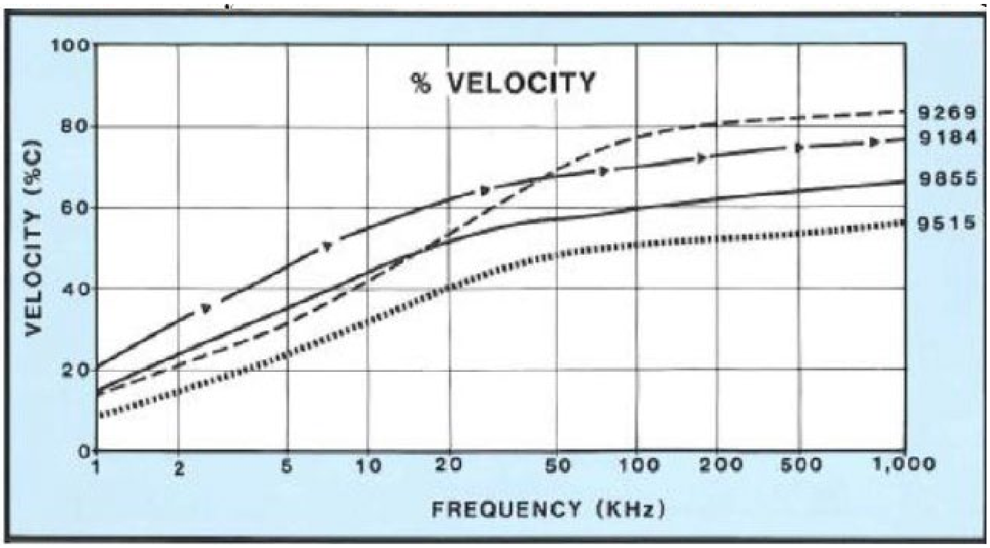
$$X_c = 1/(2*\pi*F*C) \qquad X_L = (2*\pi*F*L)$$

If we approximate our speaker cable by assuming that the DCR is sufficiently low to maximize the amplifier's damping factor, we can essentially say it is “zero”, or so low it doesn't impact the cable performance in a meaningful way. If that's the case, and it is with a suitable and easy to design AWG size, we have reactance that is left and that is a time based distortions the ear is sensitive to. The amplifier sees a capacitor across the terminals with an inductance in series with the signal lead. The resistance is basically invisible.

The reactance and DCR are what give our cable a term called IMPEDANCE, or a ratio of the REAL vector component to the REACTIVE vector component, and our cable has BOTH. An impedance is not just a resistor, and many confuse the issue with that interpretation. It is a VECOR math addition of the two. If R is super small, as it is in our case, than what's left has to be the reactance, and that's also the case. Our impedance is a almost pure reactance, or time based distortion and it does not attenuate the signal, only the resistive component can dissipate energy. What reactance does do is alter the time based information from the originally applied signal.



What we see above is the actual measurement of a typical 10 AWG zip cord. Our cable has a varying phase to frequency and the impedance also changes with frequency, rising as frequency drops. This is a result of the velocity of propagation dropping across frequency. The chart below graphs a few common cable types, but rest assured ALL cable Vp drops with frequency until it hits zero at DC. The cables capacitance and resistance at each frequency influence this curve.



Does the speaker cable look like a giant near 600-ohm resistor at low frequencies like the charts shows? No, the reactance is what drives the impedance up, not the DCR resistive component. We can't use a classic RF resonance method for low frequency analog. A test called an open-short test, the best way to measure low frequency cables where the wavelength is many, many orders of magnitude longer than the cable, will show the following;

1313A (9 ft)	Impedance			Phase		
Freq (Hz)	Open (Ω)	Short (Ω)	Imp (Ω)	Open (°)	Short (°)	Phase (°)
20	4.81E+07	2.96E-02	1193.141	-90.4698	0.3563	-45.057
50	2.00E+07	2.18E-02	660.023	-90.3453	1.1852	-44.580
100	9.82E+06	2.82E-02	526.722	-90.3686	1.8263	-44.271
250	3.92E+06	2.83E-02	332.688	-90.0467	4.5145	-42.766
500	1.98E+06	2.68E-02	229.994	-89.9460	9.6386	-40.154
1000	9.90E+05	2.75E-02	165.054	-89.7825	18.9478	-35.417
2500	4.07E+05	3.02E-02	110.789	-89.7190	47.6699	-21.025
5000	2.01E+05	5.04E-02	100.582	-89.6549	61.9023	-13.876
7500	1.34E+05	7.08E-02	97.334	-89.6116	69.5925	-10.010
10000	1.00E+05	9.37E-02	97.020	-89.5907	70.3138	-9.638
15000	6.67E+04	1.35E-01	95.010	-89.5655	75.0060	-7.280
20000	5.06E+04	1.76E-01	94.445	-89.5846	77.0976	-6.244
50000	2.03E+04	4.09E-01	91.098	-89.5782	80.3490	-4.615
100000	1.08E+04	7.70E-01	91.197	-89.5977	82.0787	-3.760
500000	2.04E+03	3.42E+00	83.573	-89.6801	84.4757	-2.602
1000000	1.02E+03	6.65E+00	82.348	-89.7118	82.5675	-3.572
2000000	5.07E+02	1.29E+01	80.761	-89.7418	84.8804	-2.431

Look at the LENGTH of the test. We do not need a miles long piece of cable to characterize the cable's influence across frequency. You would if you want to try to use a resonance method! The impedance is a RATIO so if one reactive vector changes, so does the other one and the impedance will be the same. Does the open-short test work? Each test, open and short has a MAGNITUDE and a PHASE associated with it. Let's examine this table and see.

The characteristics of the R, L and C are evident in the collected values. This chart is very informative as to how each variable behaves across frequency. Let's go through each section of the chart one at a time and see if theory matches how they work when measured.

IMPEDANCE OPEN(Ω) / PHASE OPEN(°)

The Impedance Open(Ω) column is the cable under test with no load at the end or "open". This sees the cable as a long capacitor and the associated Phase Open(°) column shows this with a -90 degree phase angle. We are measuring a capacitor. The capacitive reactance of a capacitor changes how the cable behaves as frequency rises. At near DC the reactance to an AC signal is very high (4.81E7). We all know a capacitor will pass AC, but not DC. Do we see this effect? Yes, the reactance at 2MHz is 1.29E1, far lower and looks more like a short, or just a small resistance / reactance to AC signals. The capacitive impact is following the theory under measurement and reactance decreases as frequency rises

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IMPEDANCE SHORT(Ω) / PHASE SHORT(°)

Going to the Impedance Short(Ω) test measures the cable magnitude with the far end shorted. The shorted open-short test captures resistive(Ω) and inductance(°) properties across frequency. The resistive magnitude values are very small at and near DC, 2.96E-2 at 20 Hz and increasing to 1.29E1 at 2 MHz. The swept resistance includes skin effect and proximity effects. There is no doubt resistance changes with frequency. Resistance, and thus damping factor, is not constant.

The second variable we need to look at with the Phase Short (°) test is the associated inductance phase angle. An inductor is often called a CHOKE. Why? If we examine the column Phase Short(°), we see the phase values go from 0.3563, or nearly zero, to 84.8804 phase indicating at higher frequencies we have inductive influences. An inductor resists current at high frequencies and looks like an "open" or chokes off the signal flow as frequency rises. The open-short tests confirm the theory.

IMPEDANCE/IMP(Ω)

The column Impedance / imp(Ω) is calculated by multiplying the open and short impedance magnitudes and taking the square root, this is the VECTOR impedance, it is NOT a resistance. Example at 20 Hz is SQRT(4.81E7 * 2.96E-2) = ~1193.141(Ω). What this means, is at lower frequencies our cable looks like a capacitor across the amplifier terminals with a very high capacitive reactance and a very, very low resistance.

PHASE / PHASE(°)

The superposition of the resultant Phase(°) is the two phase values added and divided by two. An example at 20 Hz is (-90.4698 + 0.3563) = -45.057 or a capacitive element. At RF it goes to a -2.431 or near zero phase as a capacitor looks like a short at RF, and that resistance has no phase across it. That all makes sense. At RF, we can use just the L and C magnitudes and ignore the phase as it is "zero". Zo=SQRT(L/C) works fine. At lower frequencies every spot on the curve exhibits a changing reactance to the amplifier and thus, how it's damping factor and linearity behave. It is more complicated than just DCR.

The above all describes how the reactances are derived and why our cable really looks like a reactance across the amplifier. We don't want reactance, but there it is. How the reactances are derived is also shown to impact the Vp's properties across frequency. Not all cables exhibit the same impedance, swept DCR or Vp properties and that is why we need to include these issues and not just DCR. More important, the reactance contributes to what we hear as it is time based, and as we also see, the damping factor is also a time based problem, too. We just think low DCR but why? There is a good reason for that but there is also a good reason for the reactance to be considered. If I put a reactance across an amplifier and left the room, you'd be likely right to remove it!

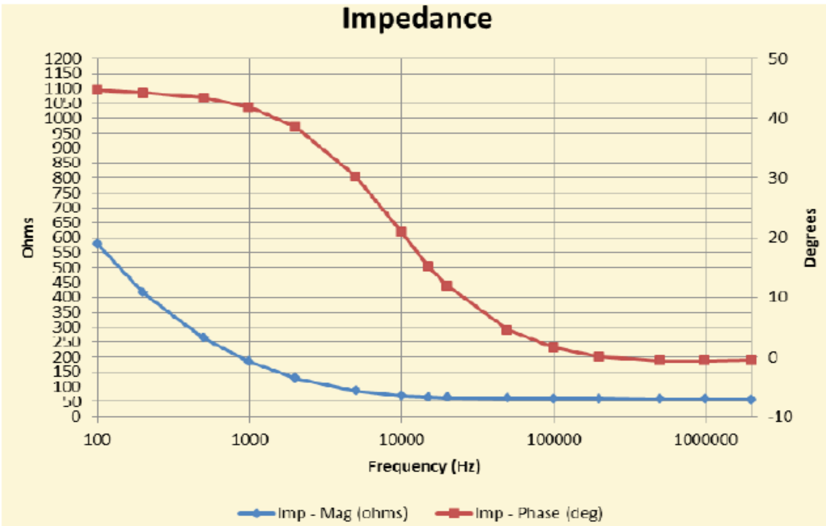
There are ZOBEL networks that approximate the anticipated reactance of a network and apply an equal and opposite reactance to mitigate phase as much as possible and make the load more resistive (resistance has no impact on phase). But, these networks are handled better elsewhere than the cable.

GRAPH ANALYSIS

If we go back to the earlier impedance and phase graph, shown again below, we can now understand what we see.

The cable is capacitive at low frequencies following the red curve which shows a -45 degree capacitive phase. At DC we have essentially a capacitor, not a cable. The blue curve reactive impedance (~575 Ω in this data set) is a result of that high reactance. We take the SQRT of the OPEN+SHORT for the impedance.

At RF, the red curve phase of the L and C slowly cancel thus we see the red curve go to zero phase at RF. We take the average of the two phase at each frequency. The blue impedance curve drops as Vp drop as frequency drops as well as the Capacitive reactance and the inductive reactance goes up. The impedance again is the resultant magnitude of the OPEN reactance and SHORT inductance and swept DCR. Phase follows the larger magnitude of the L and C across frequency.



SUMMARY – There is good reason to manage DCR in a speaker cable since it correlates to a time based distortion, and there are just as compelling reasons to consider reactance and how it impacts a cable's analog “distortions” as reactances are time based too. Our ears hear all the insults, one added to the next, through the chain. Suggesting just DCR being important is missing half the message, reactances and how they are derived are also important.