BELDEN
SENDING ALL THE RIGHT SIGNALS

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SPEAKER CABLE DESIGN BRIEF

Speaker cables are a very different animal than high input impedance interconnecting cables. A speaker cable connects to an extremely inconsistent 2-32 ohm (or even lower and higher!) reactive load created by the speaker. RCA and XLR interconnect cables see a much more consistent and resistive high impedance load making their electrical measurements far easier to predict. The speaker cable also suffers from the audio band's velocity of propagation non-linearities seen in the interconnect, but also has to figure out a way to be LOWER in impedance to better match the speaker load, while the velocity of propagation is going DOWN, and this naturally increases the cable's impedance. How is all this managed as best we can? This paper is a walk through on how ICONOCLAST™ speaker cable addresses some of these issues.

SOUND DESIGNS CREATE SOUND PERFORMANCE™

SPEAKER CABLE DESIGN BRIEF

1.0 Conductors.
  1.1 Copper Size.
2.0 Dielectric material(s).
3.0 Dielectric geometry.
4.0 Shield material and design considerations.
5.0 Jacket design and material considerations.

1.0 Conductors

For speaker cables, the first issue that has to be decided is how much CMA (Circular Wire Area) you need based on the application. This isn't always an exact science as the cable length and speaker type will change your calculated answer. The speaker cable becomes part of the cross-over network in the speaker. The amplifier sees BOTH components as *one* load.

Since the cable is seen as part of the speaker, it is easy to understand that the "reactive" relationship is between the speaker plus speaker cable and the amplifier. Speakers vary by design so the overall speaker component back EMF portion of this load into amplifiers varies. Amplifiers of differing design react to the back EMF and the overall performance can be hard to predict. The goal is to "remove" the cable as best we can between the amplifier and speaker. Cables should not be tone controls, but that's the goal of EVERY component!

The analysis below looks at the calculations that have been made to settle on the total CMA area for benign reactions to the frequency response of a typical set of loudspeaker loads. And yes, these are NOT real time resistive loads but as always, an approximation.

The general rule of thumb is that you want the total speaker cable resistance to be less than 5% of the speaker impedance PLUS the cable resistance value to avoid speaker frequency response interactions;

VOLTAGE DIVIDER FORMULA
Vout = Vin x R2 / (R2 + R1)

ICONOCLAST™ total CMA size mitigates appreciable calculated frequency response changes, and stopped at 9600 CMA (10 AWG).

VOLTAGE DIVIDER FORMULA
Vout = Vin x R2 / (R2 + R1)

EXAMPLE OF A VOLTAGE DIVIDER SPEAKER CIRCUIT
Here is an example with a typical 2 to 16-ohm swing with a 1.5-ohm resistance speaker lead.
Vout = Vin x 16.0 / (16.0 + 1.5), Vin x 0.914
Vout = Vin x 2.0 / (2.0 + 1.5), Vin x 0.5771
A 58% change in the output factor.

Change the wire to one-third the resistance;
Vout = Vin x 16.0 / (16.0 + 0.5), Vin x 0.969
Vout = Vin x 2.0 / (2.0 + 0.5), Vin x 0.800
A 21% change in the output factor.

So lower resistance (it matters HOW you get low resistance, though) is better but at some point the factor becomes inaudible (**consider the resistance of an eight foot set of leads!**).

Looking at it from an, "I can see the data" standpoint shown above, let's consider ICONOCLAST™ (1.00-ohms / 1000 feet). We have to go there and back, and assume we run a 15 foot speaker lead (about as long as recommended for L and C);
(1.00/1000) * 15 * 2 = 0.030 ohms

Vout = Vin x 16.0 / (16.0 + 0.030), Vin x 0.99812
Vout = Vin x 2.0 / (2.0 + 0.030), Vin x 0.98522
A ~1.31% change in the output factor, which is very small.

For most practical applications of 0 to 35 feet, 9600 CMA per polarity should work well to be resistively invisible to the speaker, or amplifier. We want the load to be the speaker, not the cable.

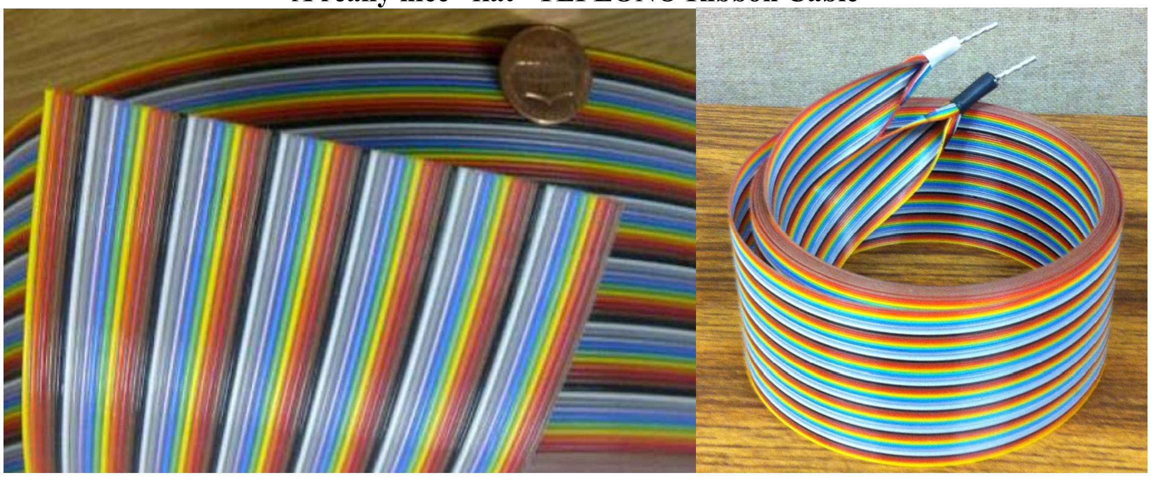
HOW we get to the approximate 9600 CMA per polarity is the hard question. For those that want the easy way out we have one, 1313A. If we want to see if we can DESIGN a better MEASURING cable let's see what can be done with Belden technology.

In order to figure out what best to do, I looked at things that indicate what NOT to do. We all know by now, that multiple smaller wires (to a point!) are better than one fat 9600 CMA solid or stranded wire. The operative here is, to my ear, TIME based issues at audio. You want the signal to be most uniform through the wire for improved current coherence (more identical frequency arrival times). To make that happen, we decrease the wire size so that the skin depth penetration goes deeper into the wire, evening out the differences in current magnitude with respect to frequency. This technique better aligns the signal speeds through the wire. I said "better" as there is no perfect way to do this. But we can certainly be better. The depth is calculated based on frequency and material. The wire size does not change the penetration, it DOES change the minimum current found in the center of the wire. The smaller the wire, the closer the center current magnitude matches the surface current as signal frequencies go up.

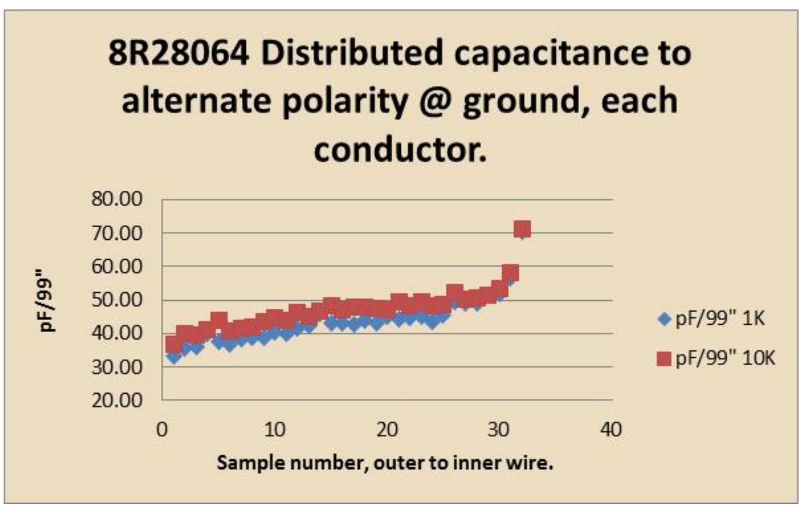
Studies were made on various geometries that would hint at what type of conductor to use, and how many. What various design limitations be “inside” the ~9600 CMA resistive box we want to be within?

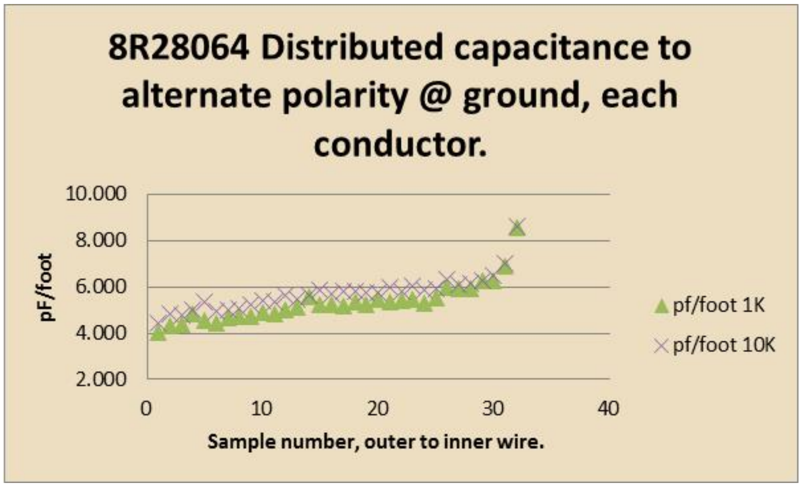
Probably the easiest approximation for a cable with multi-sized wires is a flat design. Yep, line those wires up and stop when you reach the proper AWG size. The parallel wire tested issues lead (pun there?) me away from this simple design. Why? I looked at our TEFLON® ribbon cable for that answer.

A really nice “flat” TEFLON® Ribbon Cable



Above is a TEFLON® ribbon cable I used to test polarity symmetry, and capacitive symmetry WITHIN each polarity. The two tables below graph the capacitance from the outer edge wire to the opposite polarity, all opposite polarity wires grounded together.





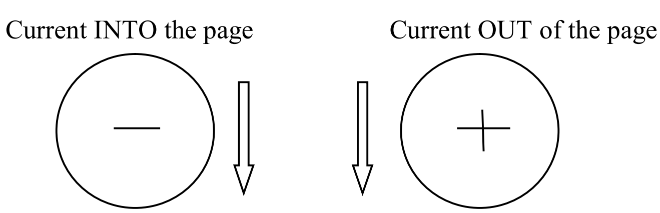
	1 KHz	10 KHz
AVG (pF) =	5.333	5.730
STD DEV=	0.862	0.761
Tolerance =	5.33 pF (+/- 2.59 pF) @ 1 KHz	

The data says that the CONSISTENCY of FLAT cable is not perfect. The closer each wire gets to the opposite polarity, the higher the capacitance. The GROUND reference is more robust the closer we get, and the less distance between two wires, all else the same, the higher the capacitance. We have EACH and every wire, for all intents and purposes, acting like a different wire. ANY cable with more than ONE wire per polarity will have this issue to contend with. How can we do better on capacitance control in each polarity?

For the answer to that we need to turn to inductance. When you separate the two polarities in a flat design, inductance is seemingly well controlled. Each parallel wire has current going in the exact same direction in each polarity half so the magnetic fields CANCEL one another. The closer to the inside polarity separation zone you go, the more the opposite polarity's different current direction upsets the SYMMETRY of the inductive cancellation process. There is non-linearity through the "flat" polarity, too, but it is worse near the edges of each polarity where the "design" changes.

Two wires with the SAME current direction next to each other cancel some of the fields' gauss density between them, and two wires next to each other with opposite polarities reinforce the magnetic field lines.

Below are two close proximity wires. Notice that the current direction "adds" between the wires with the magnetic field flux lines in the same "reinforcing" direction. If we FLIP the current direction of one of the wires, the currents cancel but now we have two of the same polarity to get the cancellation effect. This is the problem with ZIP cord. We can get low capacitance, but it is not practical to get the lowest inductance.



REDUCE LOOP AREA TO REDUCE FIELD COUPLING.

To prove a point, a single bonded pair used in ICONOCLAST measured by itself is 12.5 pF/foot and 0.196 uH/foot inductance, about what 1313A reference zip cord is (chart below). This isn't the best reactive variable balance of L and C for a premium current delivery cable.

	Results				
				Impedance	
	Ls	Rs	Cp	Mag.	Phase
Units:	µH/ft.	mΩ/ft.	pF/ft.	ohms	degrees
Freq. (Hz)					
100	0.125	2.27	17.13	460.63	-43.57
1000	0.155	2.27	16.94	152.64	-33.36
2500	0.154	2.30	16.87	112.22	-21.70
5000	0.154	2.40	16.80	100.93	-13.16
7500	0.153	2.57	16.77	98.06	-9.71
10000	0.152	2.78	16.74	96.85	-8.00
15000	0.150	3.31	16.69	95.49	-6.46
20000	0.147	3.90	16.66	94.49	-5.80
50000	0.136	7.30	16.57	90.61	-4.68
100000	0.127	11.67	16.53	87.81	-3.97
200000	0.121	18.35	16.58	85.43	-3.28
500000	0.114	31.78	16.43	83.95	-2.40
1000000	0.111	49.24	16.40	82.15	-1.96
	Loop DCR (milliohms/ft.)		2.27		

In the tested flat design there are inconsistent ground plane issues that have to be resolved, AND there are inconsistent electromagnetic field cancellation properties, too, through the "flat". The problems are locked-in by the geometry of this cable specimen, same as the issues with zip-cord.

What is GOOD about a flat cable that and can we use those positive attributes and mitigate the bad aspects? The answer to that question lies in a BONDED pair used at RF frequencies. To get to the answer for speaker cable, we need to re-invent what a BONDED pair does at audio. Re-designing a bonded pair for audio leads to what size and count wires we can manage in forward processes. We STILL don't have the conductor size or quantity question answered after all this.

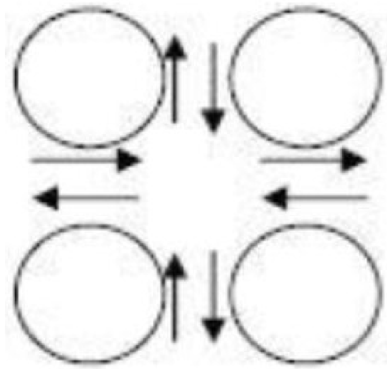
What is a bonded pair? A BONDED pair is two co-joined wires. A super geometrically consistent zip cord design with superior adjacent wire BOND technology. The precision C-C of each wire controls impedance at RF to incredibly small variation.

BONDED PAIRS

A zip cord removes a lot of symmetry complexity for poor magnetic field cancellation properties. Adding wires to the zip cord to make it a FLAT cable just adds to the capacitive and inductive "cable in a cable" issue as every wire becomes its own drummer. Coherence is improved with more small wires that add to the same CMA, but we don't really have "one" like polarity for each signal anymore.

Tests show the inconsistent capacitance in a FLAT arrangement. Tests can also show the INDUCTANCE issues with zip- cords. A single bonded pair is 0.196 uH/foot inductance. This value is far too high for the state of the art R, L and C cable that is the intent of the project.

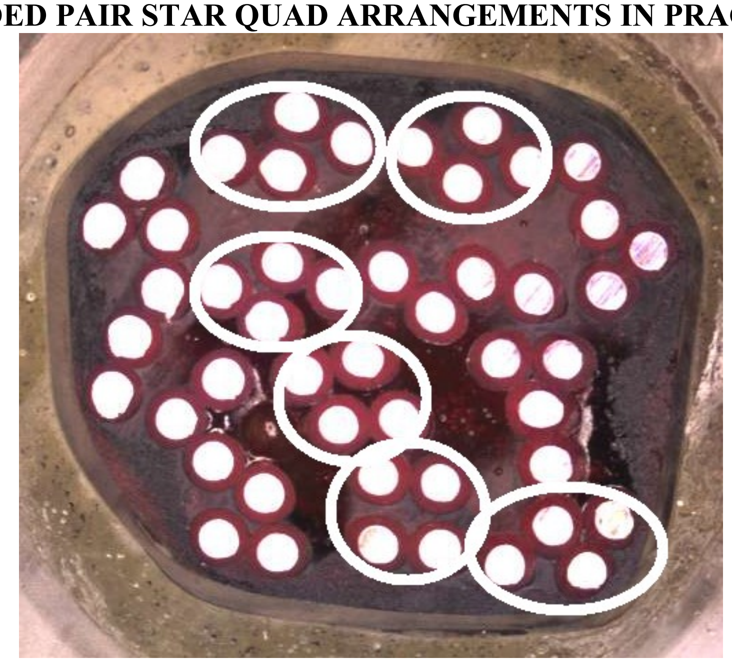
How is using another bonded pair zip cord component going to fix this mess? The answer is in the XLR cable. We need to build STAR QUAD arrangements of BONDED pairs! Visualize the currents using the right hand rule;



Like the XLR, two BONDED pairs in a QUAD arrangement show ideal field cancellation with LIKE polarity current all in the same within the same polarity. This field cancellation property of star quads tells us fundamentally we need two polarities using many wires in a star quad arrangement. There isn't an answer as to how, yet, just that a true star quad is a key element we need to keep.

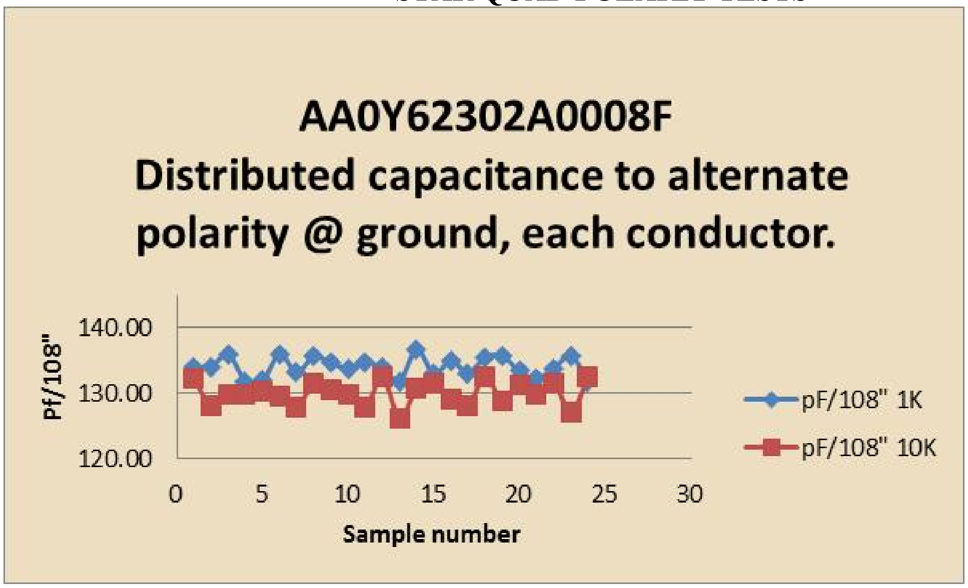
The solution was a compromise, as is usually the case in audio cables. The design devised a way to create star quads THROUGHOUT a process that varied between near perfect, and slightly imperfect. It was done with 100% consistency within each polarity so every wire measured the same inductance and capacitance to the opposite polarity, and made significantly lowered inductance with only a moderate rise in capacitance. The capacitance was increased on purpose, I might add! More on why I did that later.

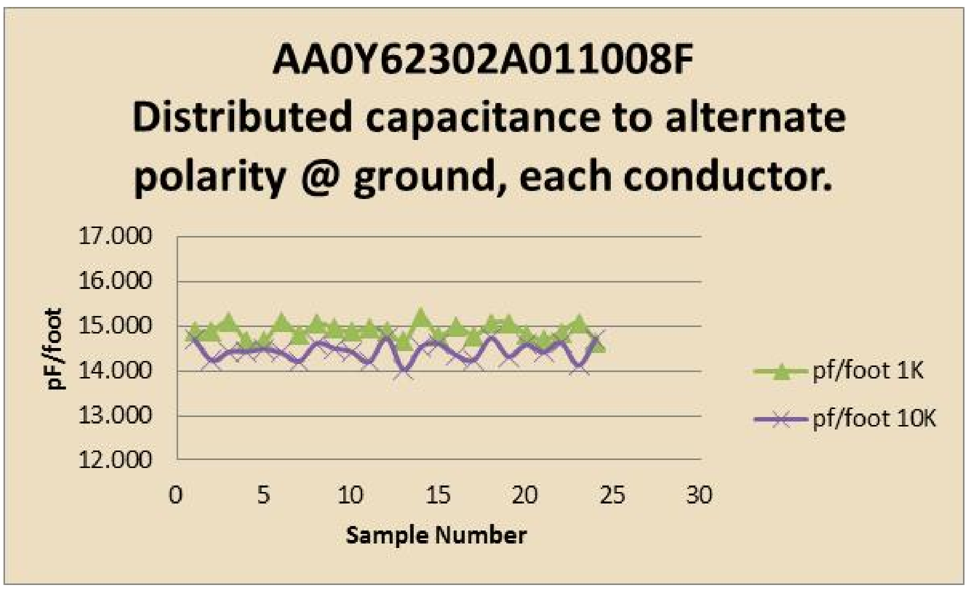
BONDED PAIR STAR QUAD ARRANGEMENTS IN PRACTICE



The above illustration shows the variation in the STAR QUADS between like bonded pairs in a polarity. The question is does it work; capacitance measured 45 pF/foot between polarity wires and inductance measured 0.08 uH/foot. Capacitance variation, and the electromagnetically tied inductance variation, is superb.

STAR QUAD POLARIY TESTS





The difference in reactive stability between each wire in a single polarity, and BETWEEN each polarity can measures significantly better in ICONOCLAST.

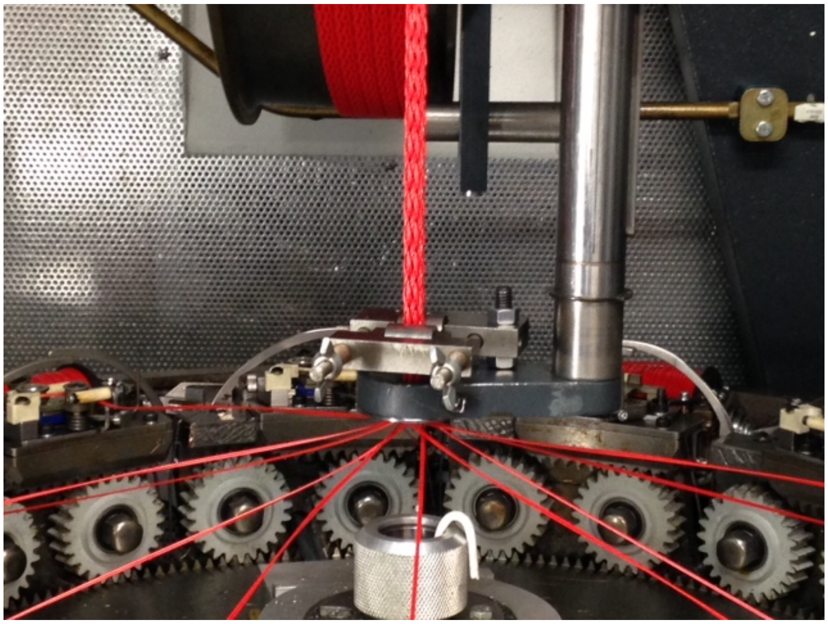
	1 KHz	10 KHz
AVG (pF)	14.893	14.441
STD DEV	00.166	00.202

Tolerance is +/- 0.5 pF @ 1 KHz or more than 5 times tighter variation than the 8R28064 flat cable.

What was done was to BRAID, on a GHz capable braider, the needed wires to arrive at the 9600 CMA DCR requirement. The braider needed a symmetrical arrangement so an even number of bobbins was chosen, 12. This is 24 wires per polarity. 9600 CMA / 24 = 400CMA per wire, or a 0.020” 24 AWG wire.

The braid DESIGN is not forthcoming, so the balance of electricals has to be understood. Several, several design iterations were trialed before I froze the design around the proper braid relationship to arrive at a suitably balance reactive cable measurement.

BRAIDED POLARITY



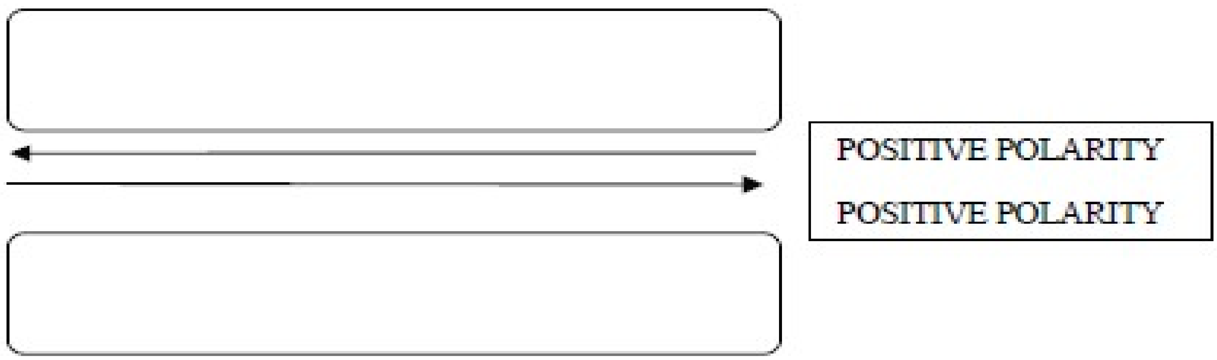
People will "guess" that ICONOCLAST is a BONDED pair ETHERNET cable, and it is not. The REASONS and the DESIGN are not the same at all. All that is the same is the coincidence of a 24 AWG solid copper wire common to Ethernet.

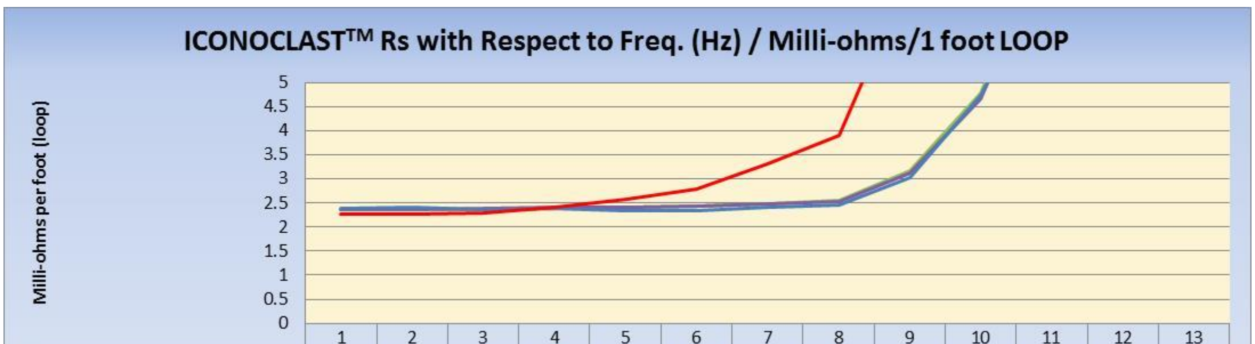
Each polarity is BRAIDED and FLATTENED into a, you guesses it, FLAT shape! We essentially "fold" the flat cable over on itself into ONE polarity. Then, opposite polarities are tightly bound to keep LOOP area to a minimum, critical to inductance as the formula is GEOMETRY controlled, not the dielectric.

TEXTILE BRAID BONDING OF TWO POLARITIES

Measured Rs (skin effect / proximity effects)

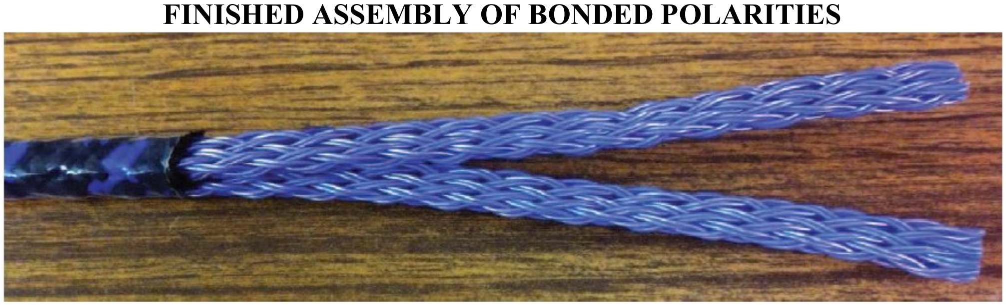
The nature of the magnetic fields can be indirectly MEASURED with an Rs measurement. The flatter the Rs, the better the skin depth / proximity effect are managed. Proximity effect is the currents in each polarity being "pulled" to the inside edge of each conductor, and away from the outside edge. This impacts conductor efficiency.





	1	2	3	4	5	6	7	8	9	10	11	12	13
FREQ. (Hz)	100	1000	2500	5000	7500	10000	15000	20000	50000	100000	200000	500000	1000000
ICONOCLAST SPTPC (0.020")	2.37	2.37	2.37	2.39	2.40	2.43	2.48	2.55	3.17	4.77	8.20	14.51	21.06
ICONOCLAST TPC (0.020")	2.37	2.37	2.39	2.41	2.42	2.43	2.47	2.53	3.12	4.65	8.01	14.04	20.26
ICONOCLAST TPC (0.022")	2.38	2.41	2.35	2.39	2.34	2.34	2.40	2.45	3.03	4.73	7.56	12.49	17.71
1313A	2.27	2.27	2.30	2.40	2.57	2.78	3.31	3.90	7.30	11.67	18.35	31.78	49.24

FINISHED ASSEMBLY OF BONDED POLARITIES



An awful lot of testing was done to identify the weaknesses of various designs. We wanted to avoid;

- Inconsistent capacitance in each wire.
- Inconsistent inductance in each wire.
- Inconsistent ground plane interaction between wires and between polarities.
- Inconsistent wire DCR between all wires.
- Poor polarity DCR values (too high or low total CMA).
- Inconsistent dielectric performance between each wire.
- Poor frequency coherence in each wire.

After all the testing, a 20-mil wire diameter in a 24 wire (12 bonded pairs) woven polarity was created to match the design to the electromagnetic requirements. The final design that drove the final wire size is 100% symmetrical in every measure on every wire.

Woven single polarities achieve class leading performance in polarity-to-polarity and wire-to-wire consistency while also providing exceptionally low reactive variables. The superposition of the magnetic fields drive inductance down from 0.196 uH/foot to 0.08 uH/foot, a 59% reduction in inductance, while holding capacitance to just 45 pF/foot. L and C can be CHANGED based on the woven DESIGN, but was optimized for speaker cable applications.

2.0 Dielectric material(s).

TEFLON® was chosen as it is again, the best solid dielectric there is. I needed a thin wall to bring the wires close together for inductance reduction but capacitance is an issue with 24 closely spaced wires. A capacitor is two parallel conductive plates with an insulator between them. To lower capacitance, I wanted a low dielectric constant plastic, Teflon®. To achieve the required low capacitance, more needs to be done to "thicken" the insulation without increasing loop area effects.

This seems impossible to do, but it isn't with the woven design described above. The final insulation wall was driven by BALANCING capacitive gains with inductive reduction. Dielectric geometry allowed this balance to be accomplished.

3.0 Dielectric geometry.

The requirement to meet capacitance ALSO drove the design to a weave pattern. Each polarity is SEPARATE from one another. There is NO interweaving of same polarity wires.

Some will ask about wires with several AWG sizes. Current will flow along the path of least resistance. This does not mean current won't flow in specific wires, just that the majority of the current magnitude is shifted to the easier path. EVERY wire will have current at ALL frequencies. The magnitude will change and follow ohm's law. Many differing wires sizes and electrical lengths can impact the signal arrival times across the audio band based on physical conductor lengths in composite wire size designs.

If we take two wires with the same exact skin depth (same frequency point being considered) but one wire has twice the surface area, more current will flow into the larger surface area wire. It offers less resistance. But, the lower resistance wire is a larger wire and isn't what we would like if the current across the wire is to be more uniform. Bigger wires are better at lowering resistance at a given frequency because they have the most surface area. We use this at RF with a "skin" of copper to carry the lowest, yet still high, frequencies efficiently. The wire's core under the copper is a material that is "filler" and has no current flow: steel, aluminum, etc.

At lower frequencies the current is diffusion coupled evenly through the ENTIRE wire. So if you send JUST low frequencies, use low a DCR wire as you can get.

Those are the extremes. Audio is weird in that we need to improve current coherence through the wire while it is trying to MOVE to the outside surface. We don't care about attenuation as much at audio since it is negligible. We make the conscious decision to go for forced current coherence with more SMALL wires. This technically violates the practice of more "surface" area for lower attenuation at high frequencies for current coherence. Big wire is more surface area for attenuation while small wire is better current coherence but higher attenuation. If you use one wire (interconnect) the current delivery has to be considered to the load. RCA and XLR cables have near zero current flow into the high impedance load so we can go for signal current coherence and suffer little attenuation. Speaker cables can't use too few wires as there are 20-30 amps coursing through a speaker cable.

Audio is trying to TIME align the low and high frequencies, so the best, and most consistent, way to do this is to use more small wires that add-up to the low frequency DCR needs, and are small enough to FORCE the wire to see more and more cross sectional current usage at higher frequencies. This means several small insulated wire that all need to be the same "single" wire.

The unique woven design does a LOT to reduce inductance and associated capacitance. How is 59% reduced inductance over a single bonded pair achieved?

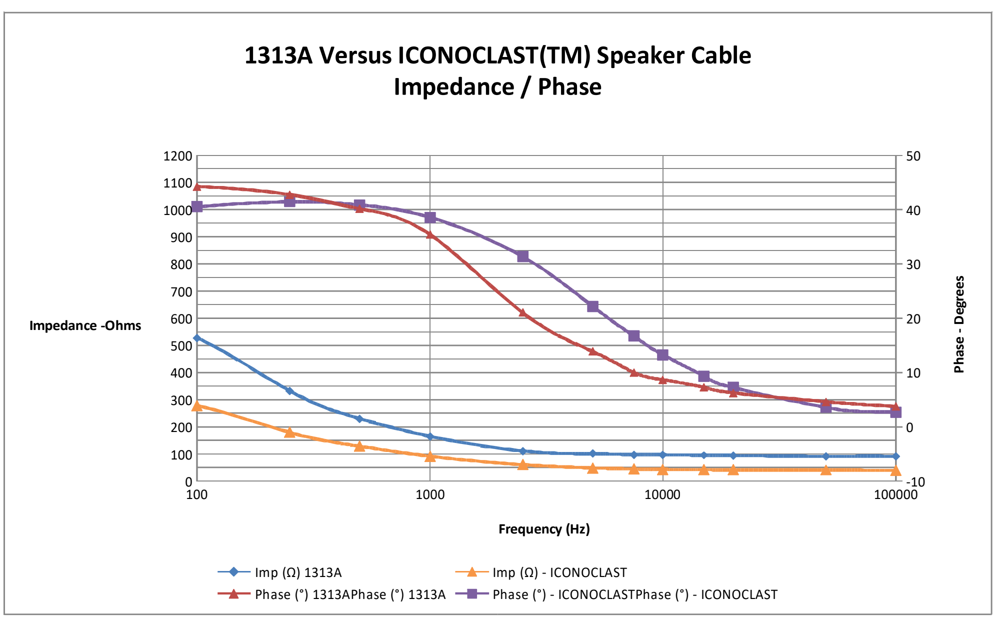
- ELECTROMAGNETIC FIELD CANCELLATION
  - Star quad wire arrangement.
    - Allows ideal geometry for low field strength.
  - Boned pair like polarity wires.
    - Allows star quads to be formed throughout the weave.
  - Separate polarity halve fields are NOT parallel, reduce field reinforcements.
    - Fields between polarities have some cancellation (wires that cross at ninety degrees cancel) since the cross at ANGLES, and not ever parallel.
  - Controlled Proximity effects / Skin effects
    - Measured Rs flat to 20 KHz.

- CAPACITIVE REDUCTION
  - Low dielectric constant plastic.
    - Thinnest possible C-C with the lowest cap.
  - Woven pattern averages out the wire-to-wire distances significantly.
    - Woven pattern separates the wires and "tricks" the bulk capacitive value to be far lower.

The last point on the capacitive reduction is also what we like in a FLAT design, but it is inconsistent. Average distance between any two wires in a braided polarity and thus between polarities is far more consistent. The weave moves all the wires evenly, and consistently, to a closest proximity position and a max proximity position throughout the weave. Capacitance and inductance DO vary, but they are exactly the "same" wire and at the same time as every other through the weave. The fattened weave holds overall capacitance to an unexpectedly low value of 45 pF/foot in a cable with such high conductor count.

Low inductance leverages the same current direction in the bonded pair's combined with the star quad wire geometry periodicity (end view photo above). And finally, the TIGHT textile weave between polarity halves force a low loop area and with wires never being parallel, further reducing inductance.

The overall reactance of the cable is shown in the graph below.



The chart illustrates a significant drop (yellow trace) in cable impedance compared to 1313A (blue trace). We know all we need to know to figure out why this happened. The velocity, although variable, is nearly the same at each SPECIFIC swept frequency point. We need to look at frequency by frequency calculations. The capacitance is linear across the entire audio band so that's a set value.

We have a set value of capacitance, and a nearly set value of velocity (there will be slight variation) at a given frequency. What is CHANGING is fundamentally the capacitance between cable designs for "impedance" characterization.

The impedance equation is influenced by the change in capacitance and thus lower measured impedance as the capacitance shows up in the denominator of the impedance equation. Increasing capacitance from ~16 pF/foot to ~45 pF/foot decreases ICONOCLAST cable impedance. Speaker cables require low inductance and to get there without shooting capacitance through the roof. DESIGN is the overriding requirement, and materials alongside unprovable theory, are second.

Now we know why ICONOCLAST has the capacitance it does, as I can balance the inductance to industry leading values AND keep cap low, yet not so low as to increase impedance too high relative to the input requirement (impossibly low speaker impedance 8-ohms ideal). Cables go UP in impedance as you drop in frequency, the opposite of what we want. Listening test have to decide if the superb inductance or impedance matching with much higher cable capacitance is ideal. Quick calculations will show capacitance problems with 8 ohm cables at audio once an amplifier is attached.

Don't ignore the reactive time constants of L and C. We want an 8-ohm cable with NO L and C and zero resistance and you can't do that. Getting cable "impedance" reasonably low is more reliably safe for amplifiers and TIME based distortions (lower L and C).

4.0 Shield material and design considerations.

I kept this topic here on purpose. Some may already know that low impedance cables signal levels negate the need for a shield. And that's a good thing because a shield over a speaker cable is darn near ALWAYS a bad thing for two reasons;

- A shield will always increase capacitance of the cable. The question is how much.
- To mitigate the capacitance increase, the shield must be moved significantly AWAY from the core polarities, increasing the size of the cable.

Shields are ONLY beneficial if the environment demands them. Shields inhibit the performance of cable in most cases. Coaxial cables being an exception as the shield defines the cable's natural IMPEDANCE. The ground plane proximity and uniformity are vitally important with short wavelength RF cables. Coaxial cables do just that. Audio is not RF, and these shields are more FUD devices than actual benefits, especially in speaker cables that have signals orders of magnitude over the background noise. Incidentally, the woven pattern in ICONOCLAST has a built-in immunity to RF not that that RF immunity is evident in the use of the cable.

View a SHIELD as a rain coat; great if you have water flying around but a major hindrance if you don't. Audio seldom needs shielding on low impedance cables and here is why;

Magnetic fields decay rapidly with distance; ratio of 1/x^3. The best defense is to MOVE the low frequency electromagnetic cables away from one another. The foil and even braid shields are higher frequency shields that are ineffective at much below 1 MHz. Magnetic fields lines need low permeability shield material (something a magnet will stick to) to route flux lines away from sensitive devices. A faraday cage is an example you can put something into to do this. Low permeability metallic shields are a pain to use (stiff and heavy). DISTANCE is the best remedy.

For EMI and RFI, the foil and braid shields used on Interconnect cable will be fine for RFI ELECTRIC field issues, but NOT 20Hz-20KHz magnetic fields. Interconnect cables MAY have wide band input op-amps that can be needlessly hampered by RFI on the line. Speaker cable signal levels are many, many orders of magnitude above the RF and ICONOCLAST speaker cables aren't a good RF conductor due to the weave pattern in the design.

5.0 Jacket design and material considerations.

All ICONOCLAST cables use FEP as the jacket to reduce UV sensitivity, plasticizer migration and chemical resistance. The cables are designed to last decades.

SUMMARY – Little has been left to chance in the design of ICONOCLAST cable. All the products are born from strict measurements and the management of known electrical parameters. Belden's philosophy is to make as low and R, L and C cables as technically capable. The improvement to some may be unimportant. To others, and using different systems, they can be significant. The closer we manage the knowns, the better the tertiary elements will move along with those improvements.

All cables "react" differently. ICONOCLAST is designed to offer the most benign interaction possible between your amplifier and speaker by leveraging high speed digital design principals to the much more complex audio band.