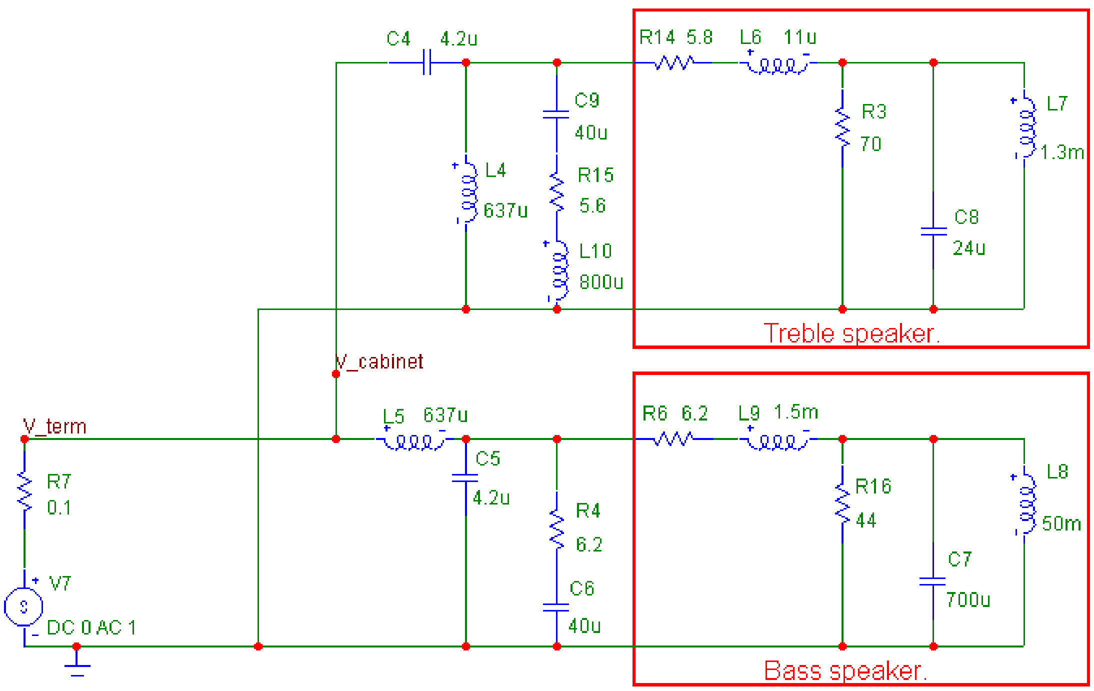
Cables, Amplifiers and Speaker interactions.   part 1.

Final version.

Cyril Bateman investigates a cause of audible distortion and amplifier failures.   *In confidence, not yet published.*

Many people claim to hear audible differences with change of speaker cable, so having five quite different cables to hand, covering a range of self capacitance, inductance and RF impedance, I decided to see whether any measurable change in distortion did occur when changing cable types while driving into a representative loudspeaker load. I have two quite different distortion meters, one which measures conventional 1kHz second and third harmonic distortion, down to 1ppm or -120dB, see reference 1, the other, intermodulation distortion as a 4kHz amplitude, using test frequencies of 8kHz and 11.95kHz, the TDFD or Total Difference-Frequency Distortion method proposed by A. N. Thiele in 1975.

For test amplifiers, I had pairs of the D. Self "Blameless" bi-polar 50 watt class B amplifier and the popular Maplin 50 watt Hitachi lateral mosfet designs. My usual listening system comprises an Acoustic Research 40 watt bi-polar amplifier driving a pair of two way horn loaded cabinets with crossover around 250Hz, via very low resistance 100Ω RF impedance cables. To minimise man-handling of these weighty cabinets into my workroom, I assembled a "replica" of the published ESP two way crossover, using a Kef T27 tweeter and bass driver. This ESP schematic was chosen because it had previously been simulated using Spice standard L, C, R components and the results published on web sites. I wanted to clarify the true behaviour of my cables with this crossover network using measurements of an actual assembly, to compare with values also measured using my horn loaded speakers.   Fig 1.



These distortion tests would require several quite noisy hours so to save my ears, I measured this ESP_replica assembly, for impedance and phase angle from 1kHz to 10MHz. At 1kHz this speaker system measured as 4.89Ω impedance with an inductive +11.3° phase angle. To approximate this 1kHz impedance I decided to use a 4.7Ω aluminium clad power wirewound resistor in series with a suitable aircored inductor, a value of 152.5µH would produce that phase angle. I had available a range of aircored inductors, 25µH, 54µH, 110µH and 250µH manufactured by Falcon Electronics, as supplied to UK speaker makers. For the initial experimental measurements, used a less reactive, more easily driven test load, the 25µH inductor with the 4.7Ω resistor, resulting in a modest +1.92° phase angle at 1kHz.

To ensure the amplifier and test rig performed correctly and obtain a baseline distortion reference using a D. Self amplifier, I measured distortion driving 1kHz at 3 volts into my 8.2Ω non-inductive test load, direct, no speaker cable. Second harmonic distortion was -95dB and third harmonic -98dB, while using the TDFD method, intermodulation distortion measured -87.1dB, or 0.004%. Using each test cable in turn to connect this 8.2Ω resistive load, produced almost identical results. Less than 1dB distortion difference between the "with cable" and the "no cable" results.

At 3v with no cable the 4.7Ω/25µH reactive test load measured rather worse, -89.5dB second -97.3dB third harmonic. Connected via 4.9metres (15ft) of 79 Strand zip-wire cable, my lowest capacitance test cable with 71pF/metre, similar distortions were measured, -89.5dB second -97.5dB third harmonic, while 4.9metres of the medium capacitance, 203pF/metre, Supra 2.0 cable, produced identical results, -89.6dB second and -97.5 dB third harmonic. The TDFD analyser intermodulation distortions measured -82dB, -81.6dB respectively for these two commercial cables. With no measurable distortion differences for these commercial cables, time now to measure using a rather higher capacitance cable. **Appendix 1**.

I had available three 4.9metre long development cables having nominal RF impedances of 30Ω, 16Ω and 14Ω. I selected the 14Ω impedance, my highest capacitance cable, labelled as #55 made using Raychem 55A0111 wire. With 440pF/metre, it has slightly more than double the Supra 2.0 capacitance, perhaps that might produce a measurable distortion difference. This 440pF/metre presents a very modest capacitance compared to some commercially available cables which have more than 1500pF/metre.

With this cable and 3 volts 1kHz drive into the 4.7Ω/25µH test load, something was clearly wrong. Distortions increased almost 30 fold to now measure some -60dB second and third harmonic, so immediately switched off the power supply, but too late, both power supply rail 4A fuses blew as the amplifier disappeared in smoke. The output devices, several small signal devices, PCB tracks and five of the small signal section resistors were destroyed. The 100nF capacitor and 10Ω resistor in the Zobel network and the output inductor, when removed and measured, were undamaged.

This dramatic amplifier failure, driving less than 2 watts into this representative speaker test load, reminded me of a past failure of my Acoustic Research amplifier while auditioning several speaker cables. Comparing my standard 100Ω impedance cable in the left channel with this "#55 cable" in the right hand channel, the right channel of that amplifier too had overheated and failed.

I had failed to find any difference in amplifier/cable distortion driving into my 8.2Ω resistive load, but having now broken two quite different amplifiers, driving into an inductive load, time to revise my plans.

Failed Amplifier Investigation.

Using my HP4815A impedance meter, I measured this 4.7Ω/25µH load for impedance and phase angle from 500kHz to 10MHz direct, no cable. Impedance increased up to resonance at 5.7MHz, reducing to 475Ω and -86° at 10MHz. I also measured the 4.7Ω/110µH and 4.7Ω/250µH loads over the same frequencies. The 4.7Ω/110µH resonant frequency mimicked that measured for the ESP_replica assembly and the 4.7Ω/250µH matched my two way horn loaded speaker resonance.

Measured via the 79 Strand cable the resonant impedance peak of the cable and 4.7Ω/25µH load became 3600Ω at 1.8MHz, then reduced to a 5.8Ω low at 8.5MHz. With Supra cable this load measured 1600Ω at 1.185MHz falling to a 4.1Ω low at 7.8MHz. With my #55 cable, peak impedance was 1400Ω at 720kHz falling to a very low 1.1Ω at 7.65MHz, clear illustrations of how a cable can transform a mismatched, terminating load impedance. Similar resonant frequencies and high impedances could reasonably be expected when driving many speaker systems using 4.9metre long speaker cables.

To minimise the risk of damaging my sole remaining D. Self "Blameless" bipolar amplifier, I decided to monitor inside the amplifier using a pair of very high impedance, very low capacitance differential oscilloscope probes to input Channel B set at 20mV/cm, to observe any difference between the input and feed back differential input pair transistor base voltages. Channel A would monitor the amplifier output waveform using a conventional oscilloscope probe. I would again measure 1kHz output distortion but now using amplifier output voltages from 1v to 5v, in 1v steps.

Driving into this 4.7Ω/25µH test load using 4.9metre lengths of the 79 Strand, Supra and my 30Ω RF impedance, 164pF/metre PTFE cable, made with 19*0.45mm PTFE insulated wire, these combinations all supported a 5 volts amplifier output with almost identical distortions and no sign of any amplifier distress, either on the differential input bases, output voltage oscilloscope traces or measured distortion.

Changing now to my second lowest impedance, the 16Ω RF impedance, 406pF/metre #44 cable, made with Raychem 44A0111 wire. With 1 and 2 volts output all was well, with almost identical distortions to those of the previous cables. At 2.5 volts amplifier output, high frequency RF bursts of voltage became visible on channel B, monitoring the amplifier input/feedback pair transistor bases. Commencing slightly later than the output positive signal peak, this initial RF burst lasted for some 100µs. Any further, small increase in drive level produced much larger amplitude, longer duration, bursts of RF. The output trace then exhibited similar high frequency bursts, with rapidly increasing distortion measurements.

Selecting an oscilloscope sweep speed of 10µS and using 10 times X trace width expansion, 2.5 cycles of RF occupied 1 cm of screen width, suggesting a 2.5MHz RF frequency.

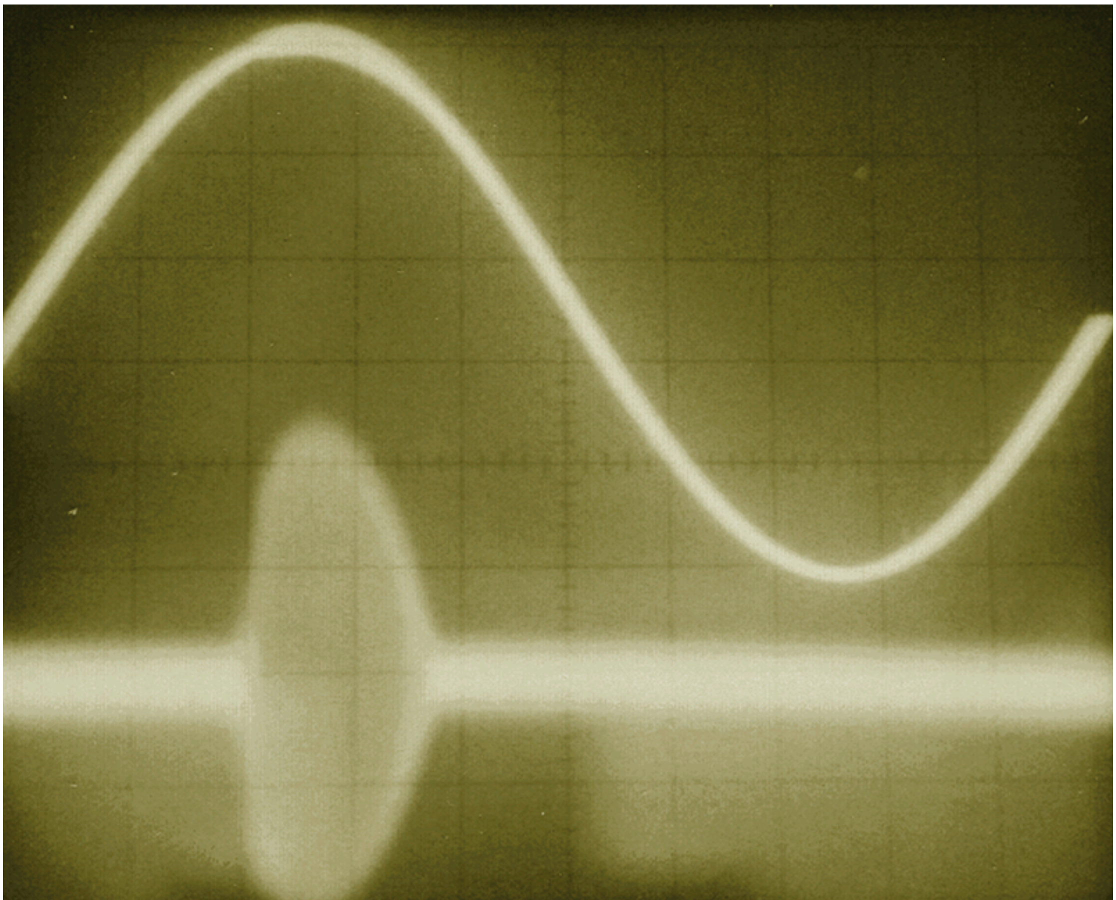


Figure 2. Replacing this #44 cable by my #55 cable, the same high frequency bursts were seen, but now occurring at lower voltage, at just 2.1 volts drive.

Channel B sensitivity was 20mV/cm.

As far as I could measure, these RF oscillations occurred at 2.5MHz with both cables.

With small increases in drive voltage these RF oscillations increased in amplitude and remained visible for more of the cycle. With this particular amplifier, oscillations always initiated slightly after the peak of the positive output waveform but with increased drive then also appeared near the negative output peak, eventually becoming near continuous throughout the waveform. Compared with the Supra cable my #44 and #55 cables were both low impedance types but were not identical, so I had hoped to find a measurable difference in RF oscillation frequency, with change of cable.

Plotting the measured impedance and phase angles of this ESP_replica assembly together with values measured for my horn loaded speakers, initially direct with no cables then with each cable type in turn would illustrate the effect a change in cable has on load impedance with frequency. I used a Spice "one-port" or "Z_block", containing tables of measured values of impedance and phase angle for my speakers, to be displayed on screen or be used with other components, in Spice simulations. Fig 3.

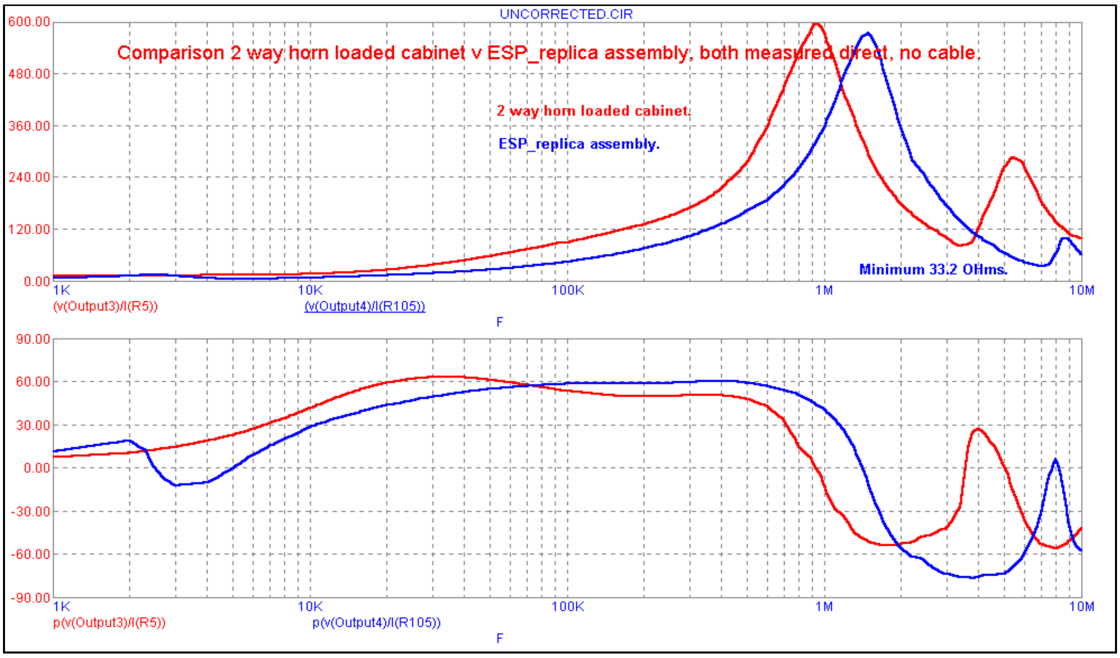


Figure 3. At 600Ω full scale, shows "no cable" values of impedance and phase angle as measured for my horn loaded & ESP_replica speakers. The Z_block model is used here as a display aid only.

Simulations would require a cable model usable from audible frequencies to say 10MHz. Cables are described using four frequency dependant AC parameters, series resistance R, series inductance L, shunt capacitance C and shunt conductance G. Cable Z0 = $\sqrt{\dfrac{R+j\omega L}{G+j\omega C}}$ **Equation1**. The Spice3 transmission line model accepts only fixed values and only three of these four parameters so cannot be used, instead we are forced to use a number of "lumped" four component model stages. Many writers try to use quite small models, but to simulate to 10MHz, multiple stages are essential. I developed realistic Spice models using 201 frequency dependant four component nodes or stages, for each of my test cables. With these and the "Z_block" model I could now simulate the affect each cable had on my speakers.

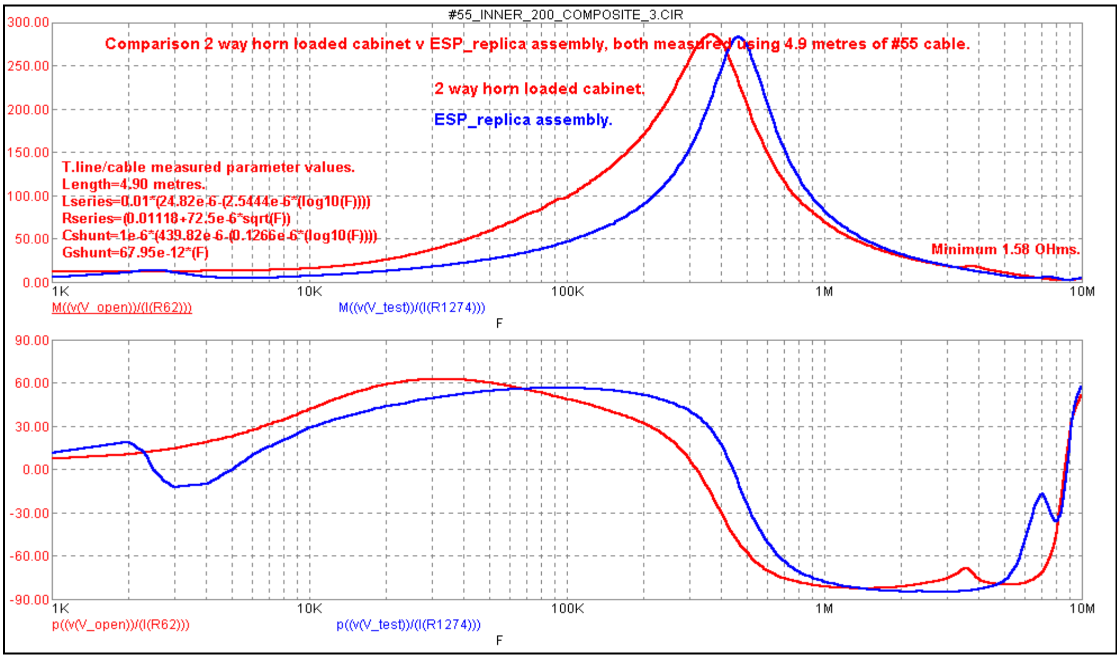


Figure 4. Now scaled 300Ω. With no cable the lowest HF impedance of both speakers measured as 33.2Ω. Using the #55 14Ω impedance cable we now find a 1.58Ω impedance is presented to the amplifier terminals at high frequency.

The resonant peak frequencies have also been significantly lowered in frequency and halved in impedance. The transition from inductive +ve to capacitive -ve phase angle, now occurs at a much lower frequency, well within the power band of many amplifiers. The 100Ω impedance 79 Strand cable has similar but smaller affect on both impedance and phase angle, more noticeably so with the ESP_replica assembly than with the lower resonant frequency horn loaded cabinets. Naturally the Supra and PTFE medium impedance cables produce similar but intermediate effects, between these #55 and 79 Strand test cable extremes. Higher capacitance/lower impedance cables produce even larger changes, noticeably also they increase speaker/cable load impedance at 20kHz.

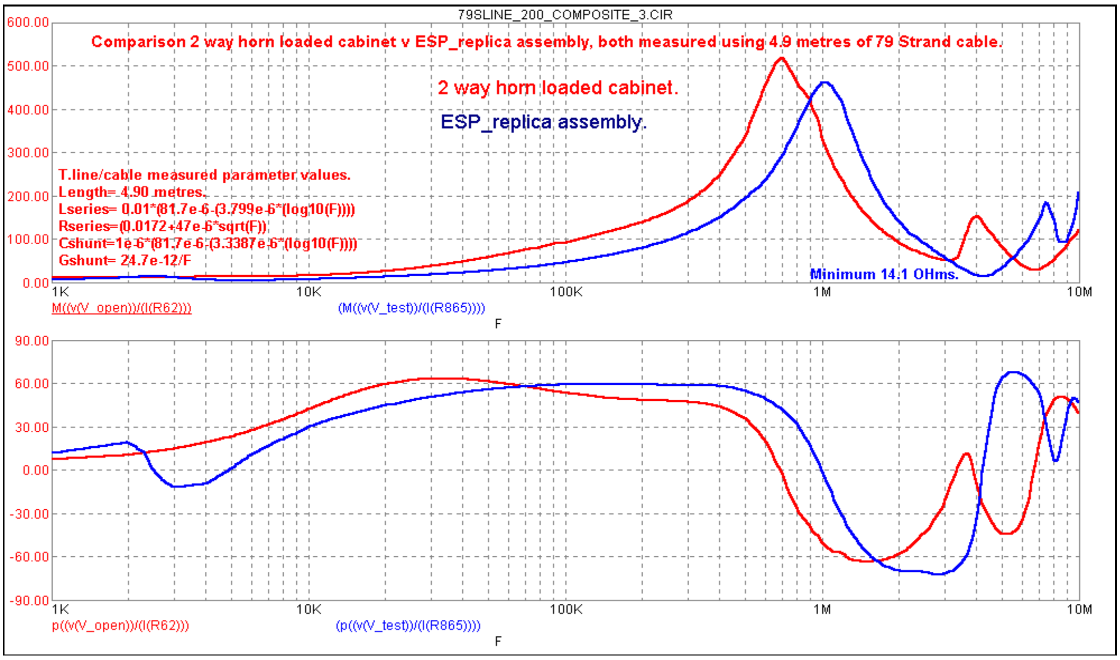


Figure 5.
At 600Ω full scale, even the modest 79 Strand zip-wire cable affects impedance especially at 4MHz where the original minimum load impedance of 33.2Ω at 7MHz has been replaced by a new minimum of 14.1Ω.

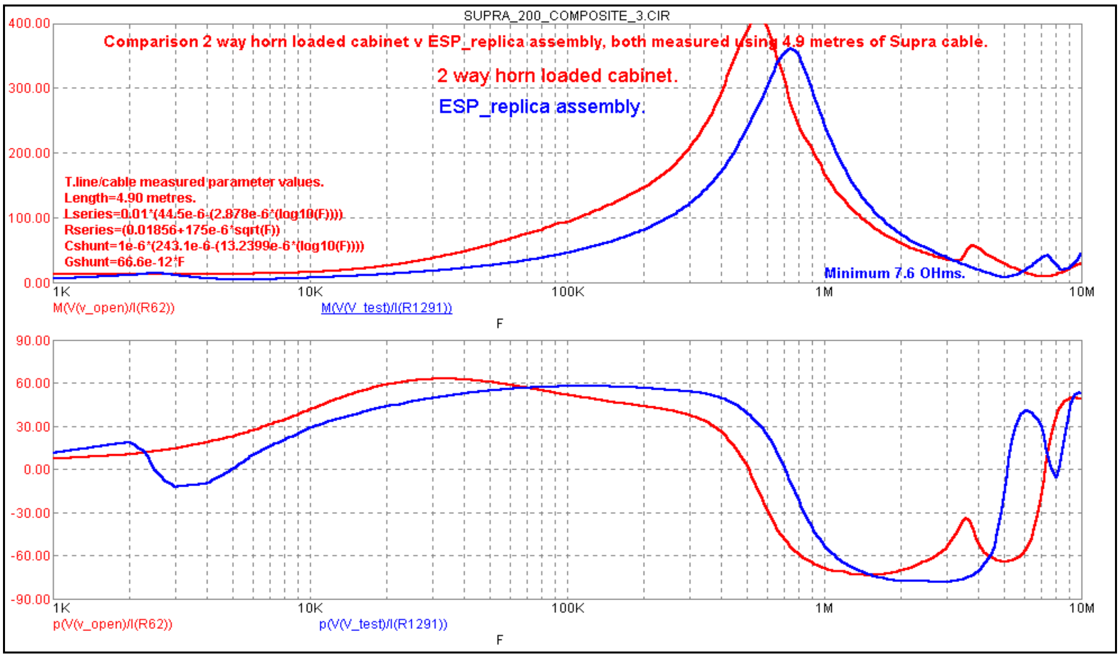


Figure 6.
At 400Ω full scale. The Supra cable has less than half the impedance, inductance and more than double the capacitance of 79 Strand Zip-wire so speaker impedance and resonant frequencies are reduced more.

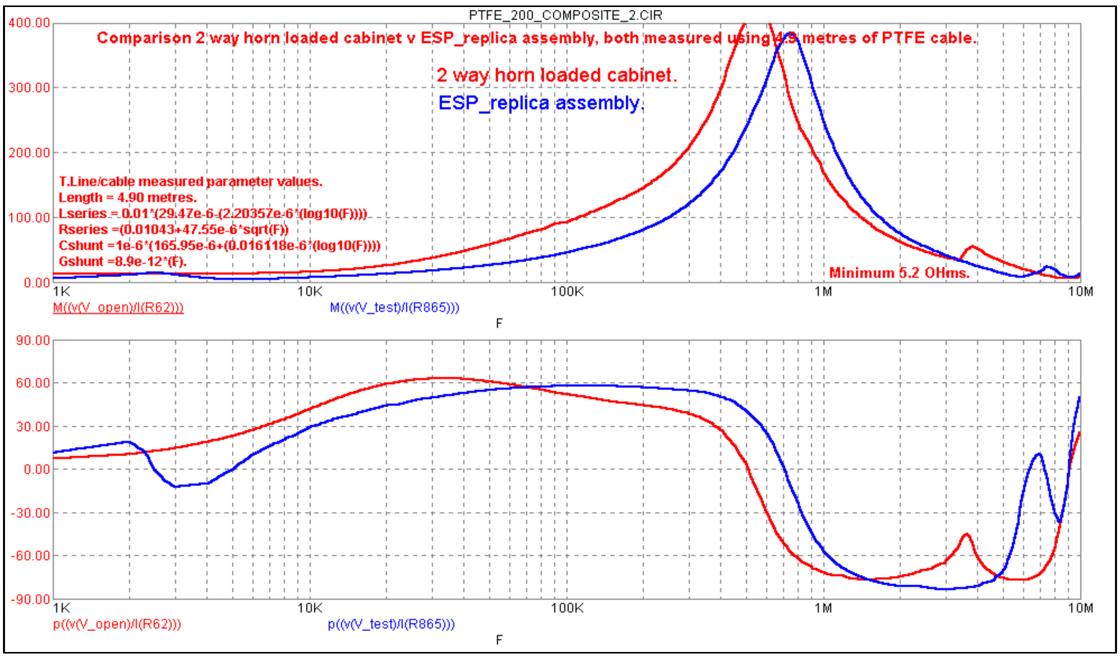


Figure 7.
This very low loss PTFE cable, has 30Ω RF impedance compared with the Supra at 40Ω, but less capacitance and inductance, so similar speaker impedances and resonant frequencies except above 1MHz.

Cable characteristic impedance or Z0.

The characteristic impedance, Z0, of any cable is an AC parameter having a reasonably constant value above 1MHz, but at lower frequencies, Z0 increases rapidly, becoming near infinite near DC. At audible frequencies, characteristic impedance Z0 of any cable is many times higher than its high frequency value. Many audio writers use the much simplified equation Z0 = $\sqrt{\frac{L}{C}}$, an approximation and only relevant at frequencies above 1MHz if using low loss insulators and values for L and C applicable to RF cables. It cannot be applied to any loudspeaker cable used at audio frequencies when values for R and G dominate. The full cable **Equation 1**, Z0 = $\sqrt{\frac{R+j\varpi L}{G+j\varpi C}}$ is essential and is used throughout this paper. All four parameters are frequency dependant. R typically increases by the square root of frequency but even when using very low loss insulators, conductance G must increase rather more than this increase in frequency.

At audio frequencies, because R and G are dominant, not C or L, cable impedance is high but speaker system impedance in comparison is very low. With increase in frequency, speaker system impedance increases to very high values, typically more than 500Ω at resonance, for a speaker with or without a crossover, while speaker cable impedance reduces to a low value, typically rather less than 100Ω.

Speaker impedance increases to a peak of several hundred Ohms around 1MHz before reducing to around 100Ω by 10MHz. Between 1 and 10MHz it is usual to find at least one, lower impedance peak. Matching cable, amplifier and speaker system impedance at audible frequencies is not possible, but at high frequency we can explore the possibility and benefit, of improved high frequency matching.

Regardless of it's actual physical length, any cable matched or terminated by its characteristic impedance at that frequency, appears infinitely long, All energy entering the cable is absorbed and none reflected.

All 4.9metre long speaker cables become quarter wave resonant, between 8 and 11MHz dependant on the square root of the dielectric constant or "K" value of their insulation, which acts to slow down propagation speed within the cable. Cables longer than 4.9metres become quarter wave resonant at proportionally lower frequency. A quarter wave resonant cable acts to dramatically transform and can even invert the impedance of any "far end" load as measured at the cable's "near" or source end.

At this quarter wave resonant frequency, a cable with an open circuited far end reflects all energy arriving at this open circuit end back to the source, returning in phase with the incident energy. An open circuit can support no current so cannot dissipate any power. At the cable source end, the input impedance of this open circuited cable, now measures as a short circuit at that frequency.

With a short circuited far end, all energy is again reflected back to the source, but now out of phase with the incident energy, the input impedance at the source end of the cable now measures as an open circuit.

At frequencies above and below this resonance frequency, with real speaker loads, more complex impedance transformations now occur, which must be measured or calculated. **see Appendix 1.**

At exactly double this quarter wave resonance frequency, no transformation occurs, so input impedance at the source end of the cable now measures exactly the same as the terminating impedance.

Cable Reflections.

At much lower frequencies reflections do still occur with mismatched terminations, but produce less dramatic impedance changes. Reflections at 10kHz using the Supra cable driving the ESP_replica load are easily measured using a reflection bridge, the basic tool of all RF measurements. The figure shows some 40% of the incident signal has been reflected, equivalent to a VSWR of 2.2:1 and returned out of phase to the source. For this measurement I used my 50Ω HP8721A reflection bridges. Fig 8

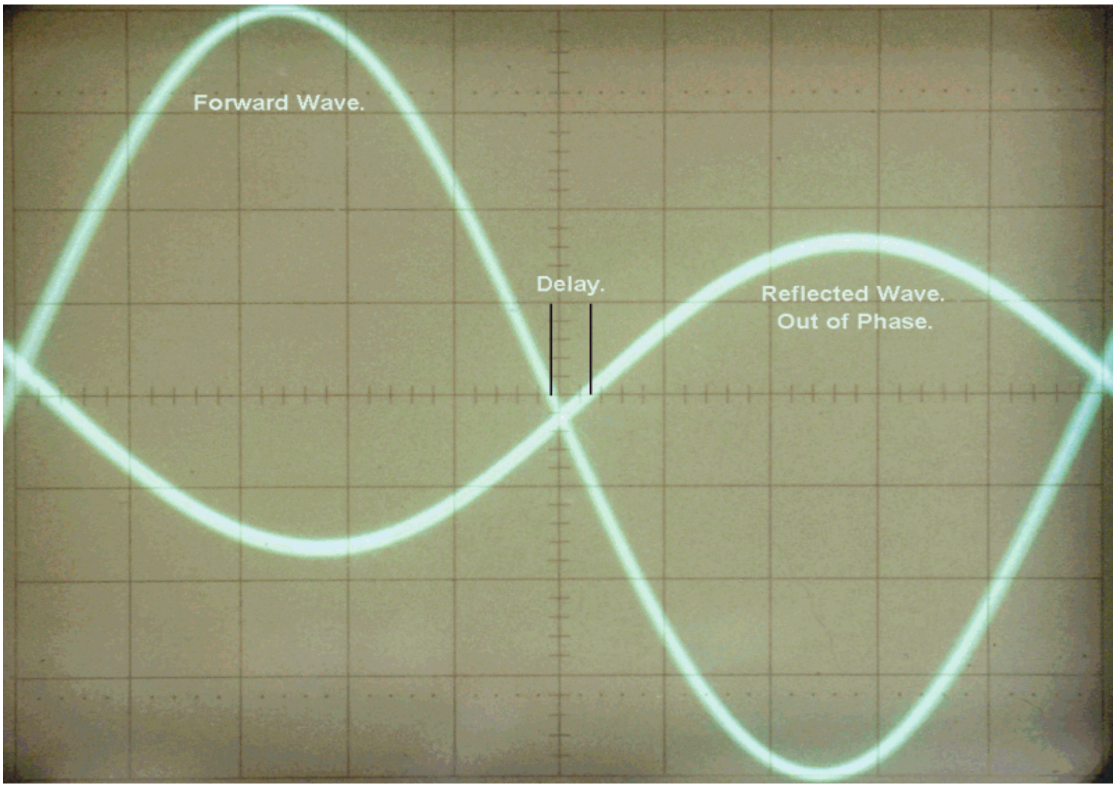


Figure 8. Open and short circuit terminations are extreme conditions. Any non-Z0 termination impedance even at audio frequencies as shown here at 10kHz, results in a reflected wave having an amplitude and polarity dependant on the degree of mismatch.

The ratio of this reflection to the incident signal or $\frac{Vreflection}{Vincident}$ is called the reflection coefficient and calculated as (rho) or ρ = $\left(\frac{ZL-Z0}{ZL+Z0}\right)$ where Z0 is the cable characteristic impedance at that frequency. At 10kHz Supra Z0 is 49.6Ω, ESP_replica speaker approximates 6.6Ω. At audio frequencies, cable/speaker mismatch results in a negative value for ρ. Regardless of cable length, reflections are returned out of phase with the forward signal. It is not possible to reduce these audio frequency mismatch reflections.

With increasing frequency, as speaker impedance increases and cable Z0 reduces, we reach a crossover point with no reflections at that frequency while both impedances remain equal. At higher frequencies speaker impedance then exceeds cable Z0 so reflections are now returned in phase, have the same polarity, as the forward signal at the cable far end. A mismatch of 2:1 or reflection coefficient of 0.33, is generally considered the maximum acceptable level for RF designs.

Ideally our amplifier will not produce any power at these in phase frequencies, otherwise strong oscillations may result. However since the loudspeaker load impedance now exceeds the cable's characteristic impedance, improved matching becomes possible, to minimise high frequency reflections.

We can use Spice to calculate and plot the cable Z0 by frequency, either by inserting the cable's measured parameters into **Equation 1** or by using my frequency dependant, 200/01 nodes, lumped cable model. We can then model the impedance of both cable and speaker to calculate and display reflection coefficients using the above equation for ρ. Unity indicates a 100% reflection, a positive ρ value indicates reflection in phase/same polarity with the forward signal, a negative ρ value indicates a reflection returned out of phase/opposite polarity with the forward signal, at the cable far end.

Starting with the #55 cable we find large, nearly 100%, in phase, same polarity reflections do occur between 700kHz and 3MHz, changing from negative to positive phasing at high audio frequencies. Should the amplifier produce any unwanted higher frequency signals the speaker cable end mismatch will produce an in phase reflected voltage at the amplifier terminals, with amplitude determined by cable losses and reflection coefficient, delayed only by the cable end, load phase angles and cable transit times.

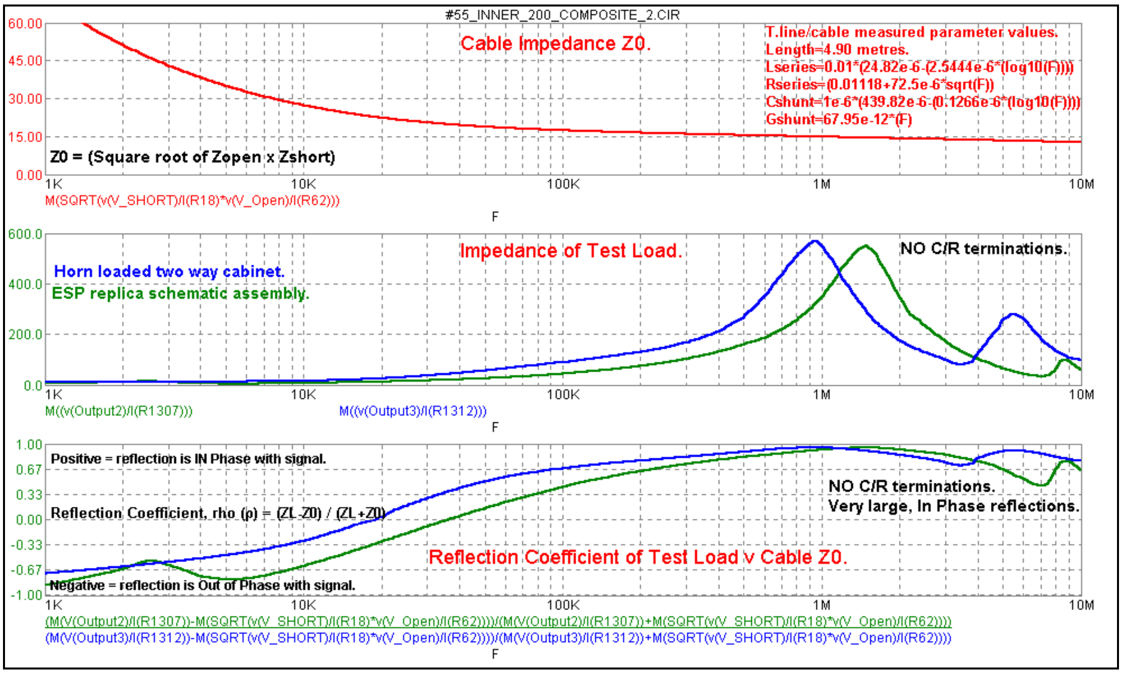


Figure 9. Using 600Ω full scale, the 575Ω ESP_replica peak impedance at 1.5MHz with #55 cable, results in a reflection coefficient of 0.95, reflecting 95% of any incident signal over many frequencies, in phase back to the amplifier.

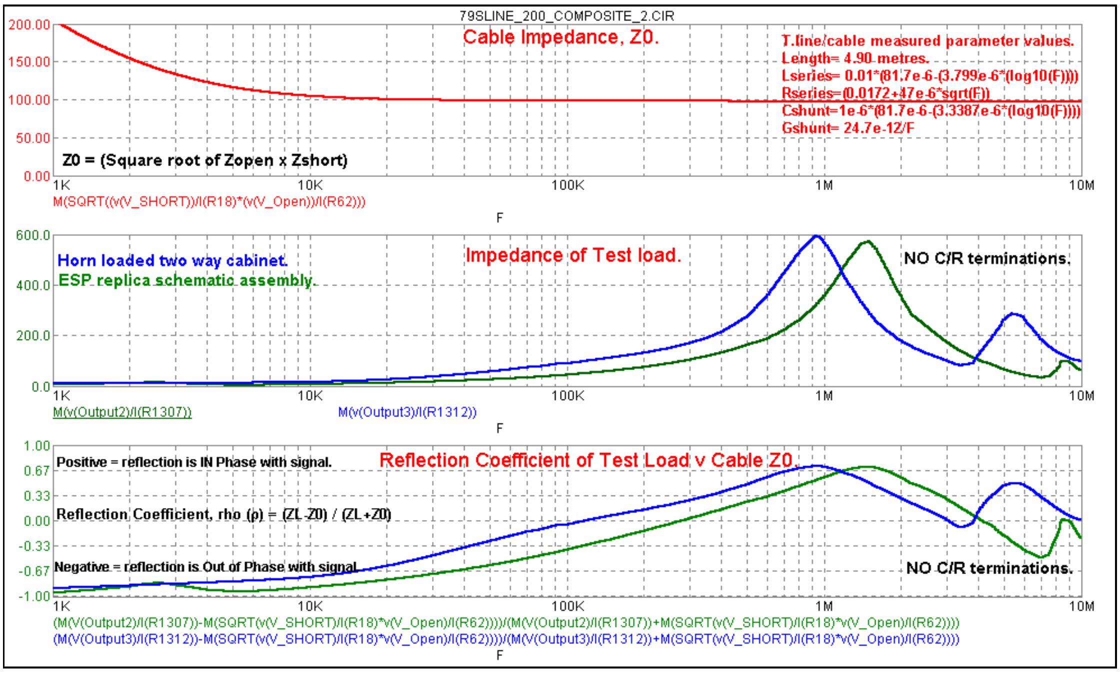


Figure 10. Looking now at the 100Ω impedance 79 Strand cable we see this cable is much better behaved with both our speakers. Maximum in phase reflections are less than 80% and over fewer frequencies.

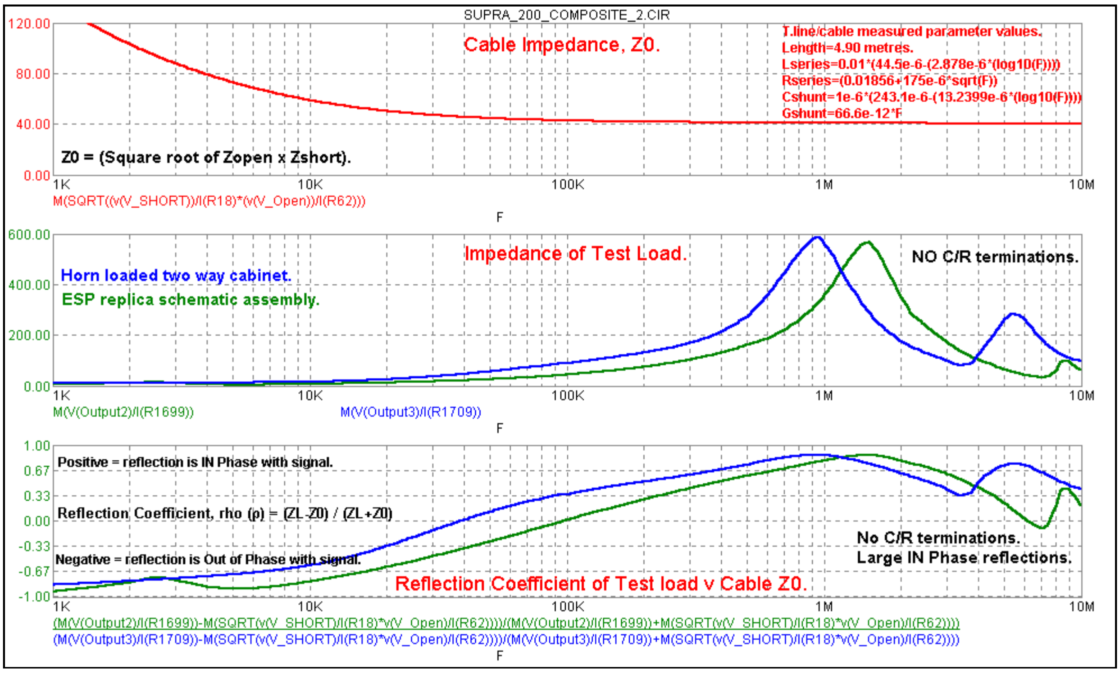


Figure 11. With the medium impedance Supra cable we find reflection coefficients midway between these two cable extremes.

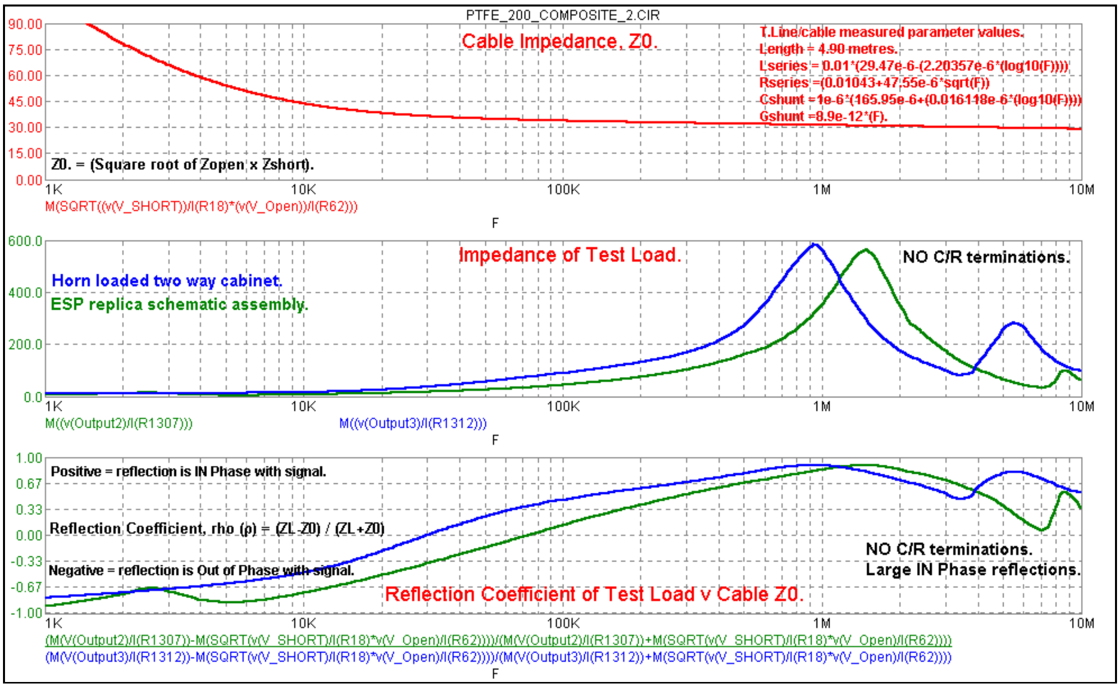


Figure 12. Major in phase reflections of 85 to 90% using the PTFE cable but again over fewer frequencies, more like the 79 Strand than the low impedance #55 cable frequency pattern.

After allowing for the two way cable losses and transit delays, a large, near 100% in phase signal reflection will appear at the amplifier output terminals. It remains to be seen later, how well or badly the amplifier Zobel network, output inductor and amplifier output impedance at 1MHz and above, combine to prevent these undesired reflections from entering inside the amplifier.

So far we have only simulated these in phase RF reflections and not proven them by measurements. But accepting that these reflections do occur, can anything be done to minimise in phase reflections. Let us now see how we may improve the high frequency cable speaker matching, to reduce in phase reflections at high frequencies. At 1MHz self inductance of resistors and capacitors matters and cannot be ignored.

We could add a resistor across the speaker terminals to set a limit on the speaker maximum impedance, but to be effective that resistor would have to absorb significant audio frequency power and be non-inductive at high frequency, a difficult almost impossible choice, wirewound types exhibit far too much self inductance. Using a small value series capacitor to reject the audio power allows using a 1-2 watt, low inductance, film resistor. We can explore the effect of using terminating resistance slightly larger and smaller than the cable RF impedance, using the Spice "stepping" function.

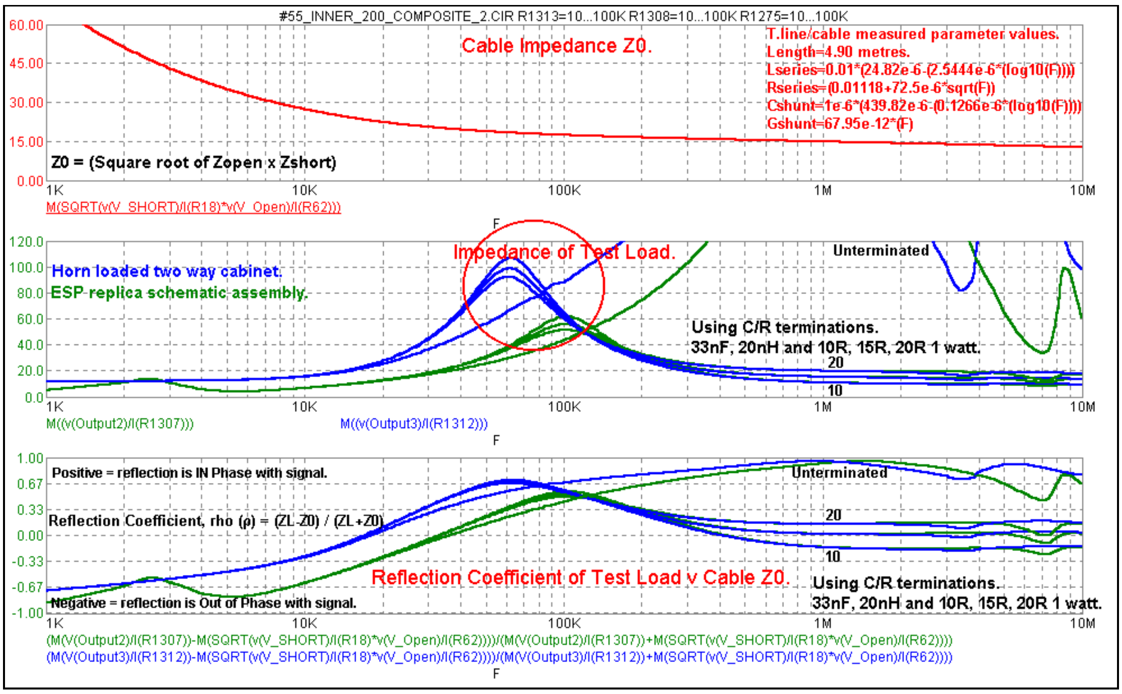


Fig 13 Using a 33nF capacitor and resistor to remove these high frequency reflections we find increased cable/speaker impedance commencing at high audio frequencies. Some writers have advocated using a 100nF capacitor, but that seriously degrades treble response.

Comparing this result with figure 9, using a 33nF capacitor with 10Ω, 15Ω, 20Ω resistors and self inductance estimated at 20nH we see an immediate benefit at high frequencies. The original near unity reflection has been replaced by near zero reflections above 250kHz. However this capacitance value now reacts with the cable and speaker impedances resulting in increased impedance and reflections at high audio frequencies. Combined with a typical 1-1.5µH amplifier output inductor, results in a measurable loss of treble, especially so for my horn loaded cabinets. The effect of using any larger capacitance C/R such as 0.1µF would be audible with many speaker systems. For some years, following my Acoustic Research amplifier damage, I adopted a similar C/R termination on the horn loaded speakers. My ears were too old to notice, but this reduction in high end treble was remarked on by my musician son.

Can reduced high frequency reflections be obtained without impacting on audible frequency load impedance ? Suppose we use a shunt resistor say ten times larger value than the speaker impedance at audio frequencies, we could try using say 100Ω. That resistor would then only be subject to one tenth of the audio power, say 5 watts maximum. On its own that would not provide sufficient improvement at high frequency so we still need to use the C/R technique. Would we now need to use a larger value resistor to compensate for the shunting effect of this added 100Ω device ?

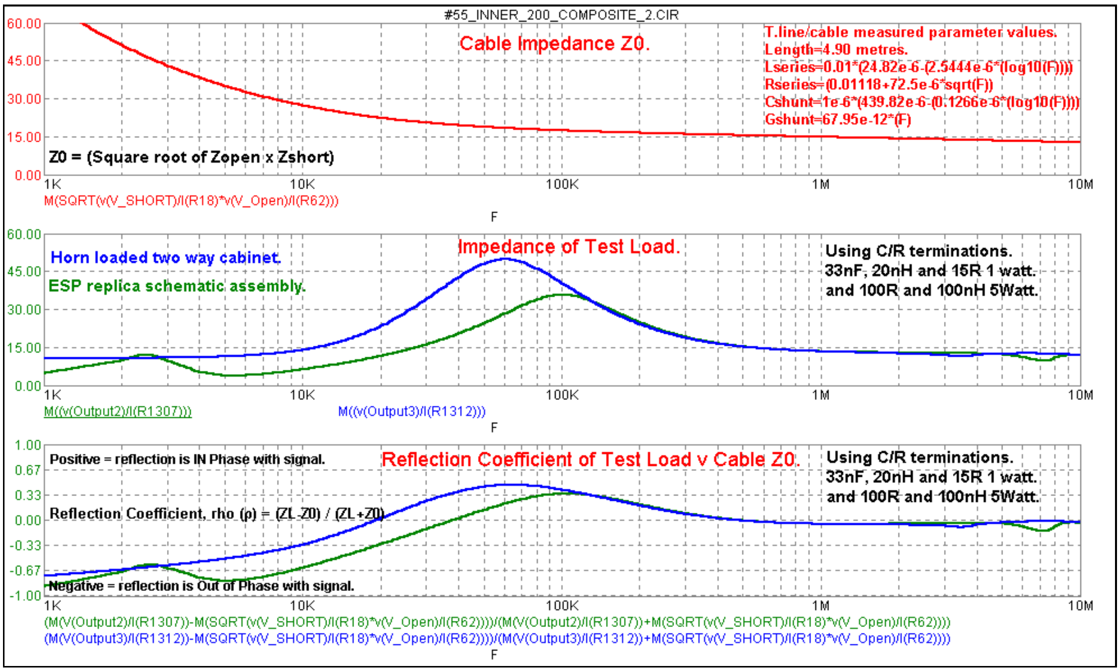


Figure 14. Including a non-inductive 100Ω resistor with no series capacitor has dramatically reduced the impedance peak between 20kHz and 100kHz to less than half. Impedance at high audible frequencies is not affected.

Using the original 33nF capacitor and 15Ω resistor with 20nH self inductance (2.5cm leadwire), together with a 100Ω shunt resistor having less than 100nH self inductance has eliminated high frequency reflections with both speaker systems and halved the previous horn loaded cabinet/cable low frequency impedance hump from 100Ω down to 50Ω without influencing impedance at high audible frequencies or treble response. In addition it has reduced the ESP_replica impedance hump and reflection coefficient of 0.55 at 100kHz, shown in figure 13, to a near reflection coefficient of 0.33, for a 2:1 mismatch.

Does any 5 watt capable resistor exist which is sufficiently non-inductive - well yes. Some time ago I needed a 100Ω non-inductive 5 watt resistor. The solution was to use one of the new TO220 packaged 1 watt resistors which can support up to 20 watts when mounted on a suitable heat sink. When I measured Farnell part no 551-594, its resistance value remained at 100Ω at 1MHz.

Can this technique be applied to other cables, yes apart from the 79 Strand and similar high impedance cables which need only use a 10nF capacitor with a 100Ω film resistor. Reflections from the Supra 40Ω impedance cable were minimised by using an 18nF capacitor with 68Ω resistor C/R network and this shunt 100Ω resistor, while for the PTFE 30Ω impedance cable I choose an 18nF capacitor and 42Ω resistor, again used with the 100Ω shunt resistor. Figs 15, 16 17.

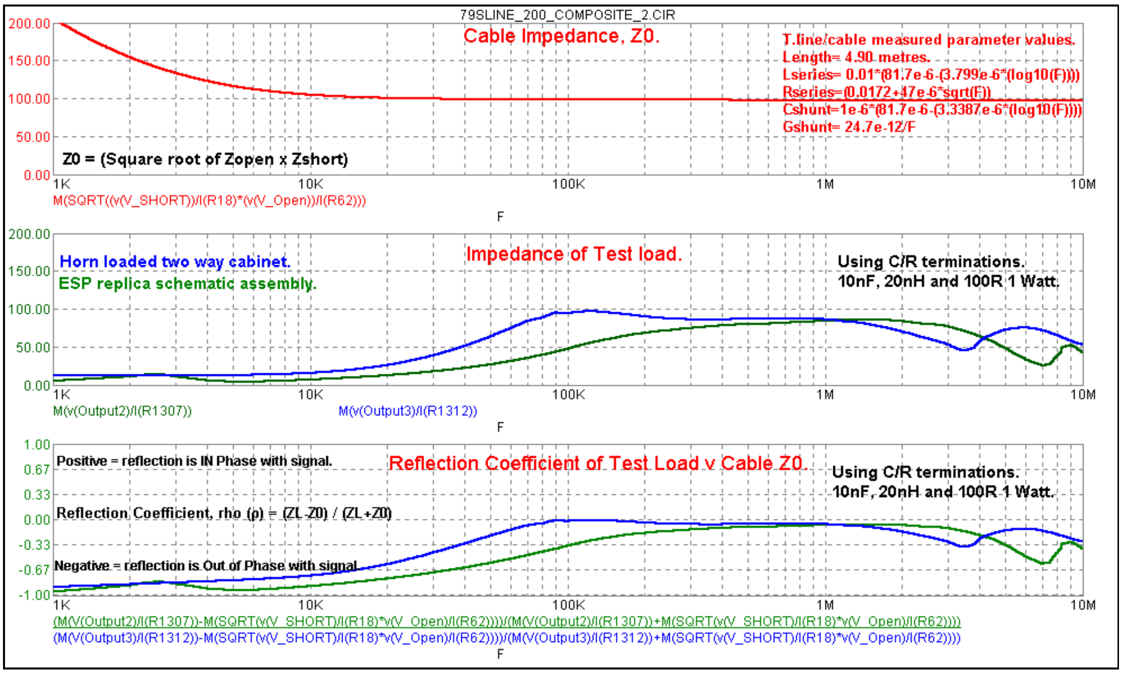


Figure 15. Because the 79 Strand cable is 100Ω Z0 at RF we need only use the 10nF/100Ω C/R network. That works far better than using the 100Ω resistor on its own and no C/R. No in phase reflections at any frequency.

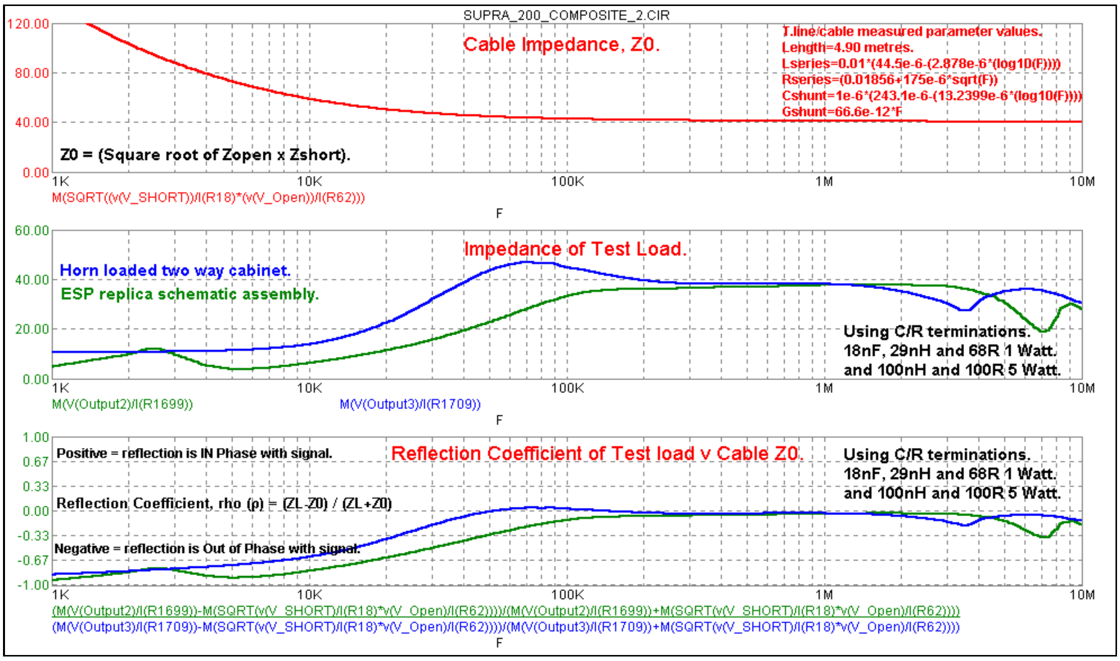


Figure 16. With medium impedance Supra cable, the combination of a parallel 100Ω resistor, with an 18nF 68Ω C/R combination provides the desired control of reflection coefficient at all frequencies.

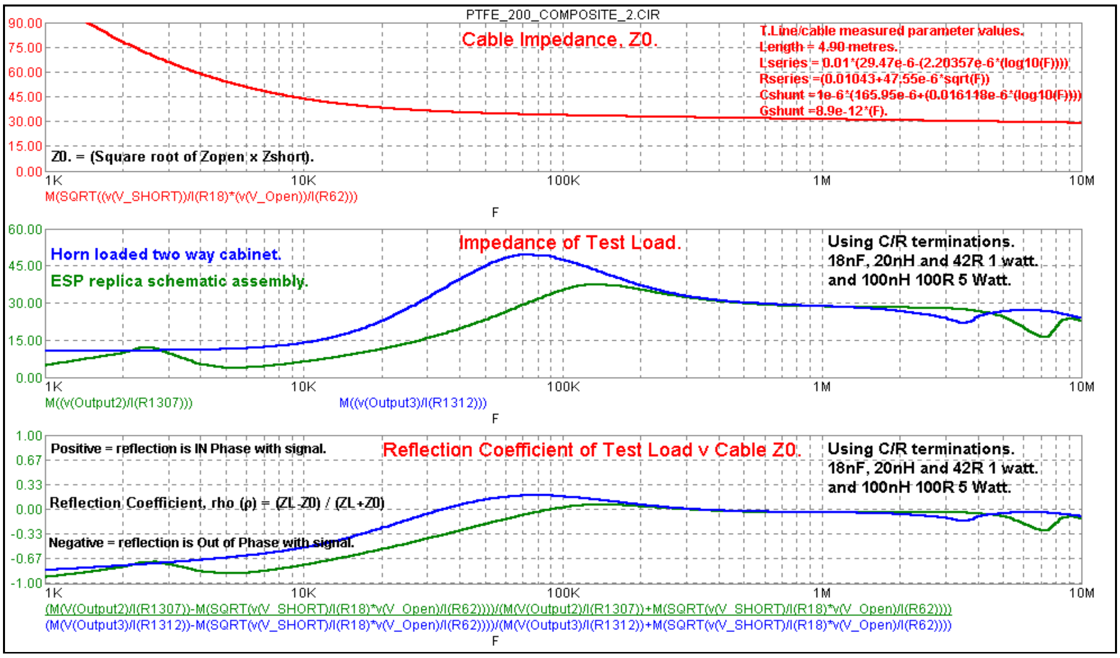


Figure 17. We can now select optimum capacitance and resistor values needed for high frequencies, without impacting on the above audible frequency performance. In this case 18nF/42Ω with the 100Ω.

Clearly the lowest speaker end cable reflections, best high frequency match occurs when using the 100Ω shunt resistor in parallel with a C/R network, for cables having less than 100Ω RF impedance, when this network in parallel with 100Ω and the speaker high frequency impedance, approximates the cable high frequency impedance, Z0.

I said earlier that at audible frequencies, because the cable impedance was so much higher than the speaker impedance, out of phase reflections would be returned back to the amplifier output terminals from the speaker and that nothing could be done to prevent this. Do these audible frequency reflections matter. ?

At audible frequencies, the amplifier output impedance presents an exceptionally low load impedance compared to the cable Z0. These out of phase reflections will not enter the amplifier but will be reflected and phase inverted, becoming in phase with and absorbed in the amplifier output signal, delayed by twice the cable transit time plus any load phase angle.

Assuming our typical 4.9metre length cable, this two way transit time will approximate 50nS equivalent to just 0.36° at 20kHz, or 0.018° at 1kHz.

So much for the theory and simulations, time now in part 2, to try out these solutions in practical measurements, using both the Self bi-polar and the Maplin mosfet amplifiers, my test cables, the ESP_replica assembly and reactive test loads, with output voltages from 1 to 5v in 1v steps.

ref.1 Capacitor Sound, C. Bateman Electronics World July 02, September 02 thru January 03.

Appendix 1. Modelling Audio Cables.

Earlier when discussing the cable **Equation 1**, when Z0 = $\sqrt{\frac{R + j\varpi L}{G + j\varpi C}}$ I stated that all four AC parameters, G, R, L and C were required when modelling cables at audible frequencies, yet many writers have used the much simplified, constant value, RF expression for Z0, Z0 = $\sqrt{\frac{L}{C}}$ at audible frequencies. At frequencies of 1MHz and above this simplification works pretty well provided we use low loss dielectric cable insulation, such as PTFE or Polythene with the typical capacitances used for RF cables, e.g. 50 or 75pF/metre. At 1MHz, L and C then dominates over the contribution made by G and R.

At low audio frequencies and especially using lossy dielectric cable insulation such as PVC and much larger capacitance values, this simplification does not apply. G and R now dominate over L and C giving a simplified low audible frequency expression, Z0 = $\sqrt{\frac{R}{G}}$ for mathematical proof see Line Communications vol.1. p.738.
N.B:- G is the cable AC conductance, measured in Siemens and not its DC insulation resistance.

Z0 is easily found for any frequency simply by measuring the cable's impedance with far end open circuit, for Zopen, then with far end short circuit, for Zshort, when Z0 = $\sqrt{Zshort \times Zopen}$.

Measured Z0 for my cables at 100Hz ranged from 600Ω for 79Strand, 350Ω for the Supra 2.0 cable to 200Ω for my lowest impedance #55 cable. At 1MHz, these three cables were measured as 97.2Ω, 41.6Ω and 13.5Ω respectively. At audible frequencies calculating Z0, using Z0 = $\sqrt{\frac{L}{C}}$ is clearly not valid. Most writers emphasise the affect skin resistance has on cable resistance at high audio frequencies, increasing typically according to the square root of frequency. More important however is G, which even using the most perfect insulation, must increase at least by the increase in frequency. We are all familiar with the use of ESR with capacitors, the small value of resistance in series with a capacitor, used to account for the capacitor phase angle being less than the theoretical 90° due to the imperfect dielectric insulation used. This same phase angle can also be represented as a very large value resistor in parallel with the capacitor. When calculating cable parameters it is usual to use the reciprocal value of this shunt resistance, now called conductance G and measured in Siemens (1/Ω), measured at AC and not DC.

Capacitance, resistance and inductance also vary with frequency, depending on the cable insulation and wire dimensions used. As a result to model from audible frequencies to 1MHz and above we are forced to use all four parameters, each being frequency dependant, so cannot use the Spice3 transmission line model. Perhaps some example measurements made with two of my cables will clarify these points:-

			Supra					PTFE		
Freq.	GμS	R	Cpf	LμH	Z0	GμS	R	Cpf	LμH	Z0
1kHz	0.298	0.0926	994	1.8	114.6	0.0047	0.060	804.3	1.1	91.5
10kHz	3.76	0.0937	905.2	1.78	49.6	0.05	0.0636	801.5	1.04	40.5
100kHz	42.7	0.17	820	1.78	45.6	1.67	0.123	800.0	0.88	33.3
2MHz	651.5	2.07	780	1.46	41.6	87.0	0.6	820	0.72	29.5

All cable models used for these simulations used 201 R, L and 200 G, C stages, based on the above values divided by 201 or 200 respectively and frequency dependant equations.

While Z0 can be calculated from the above table, it is much easier to copy the cable makers method. Measure cable impedance with far end open circuit, then short circuited, when Z0 = $\sqrt{Zshort \times Zopen}$.

Cable measurements/models.

Cable Equations used in Spice simulations, each 201/200 nodes, in order of RF Z0.

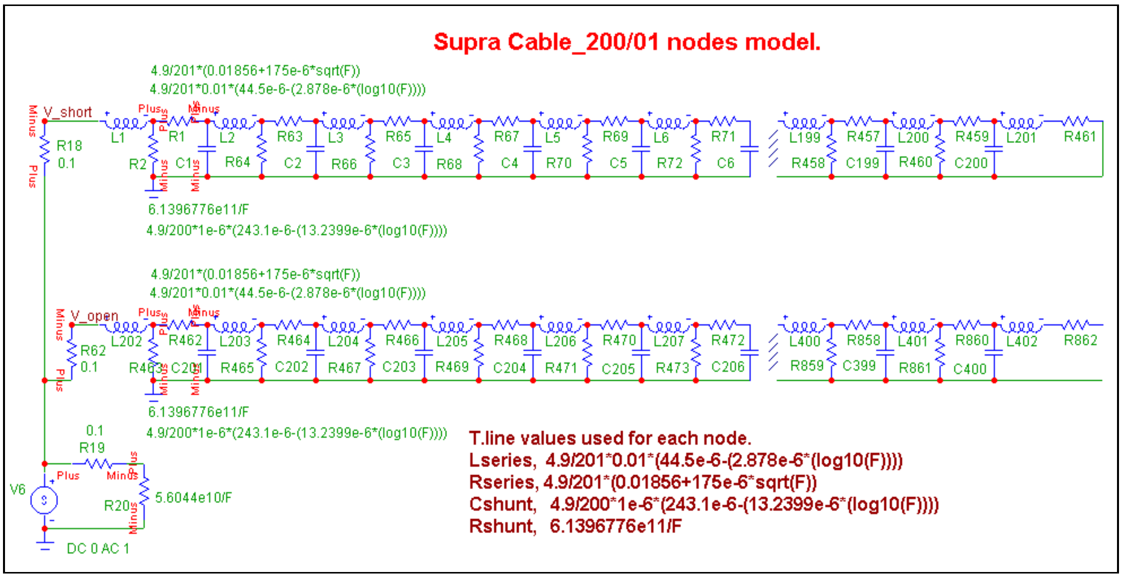
79Strand*0.2mm Zip-wire, 84.2mΩ DCR (Z0 178Ω @ 1kHz, 103.6Ω @ 10kHz, 97.2Ω @ 1MHz,)
T.Line values used for each node.
Lseries, 4.9/201*0.01*(81.7e-6-(3.799e-6*(log10(F))))
Rseries, 4.9/201*(0.0172+47e-6*sqrt(F))
Cshunt, 4.9/200*1e-6*(81.7e-6-(3.3387e-6*(log10(F))))
Rshunt, 1.6525e12/F

Supra 2.0 cable 120*0.15mm, 91.3mΩ DCR (Z0 114.6Ω @ 1kHz, 49.6Ω @ 10kHz, 41.6Ω @ 1MHz)
T.Line values used for each node.
Lseries, 4.9/201*0.01*(44.5e-6-(2.878e-6*(log10(F))))
Rseries, 4.9/201*(0.01856+175e-6*sqrt(F))
Cshunt, 4.9/200*1e-6*(243.1e-6-(13.2399e-6*(log10(F))))
Rshunt, 6.1285775e11/F

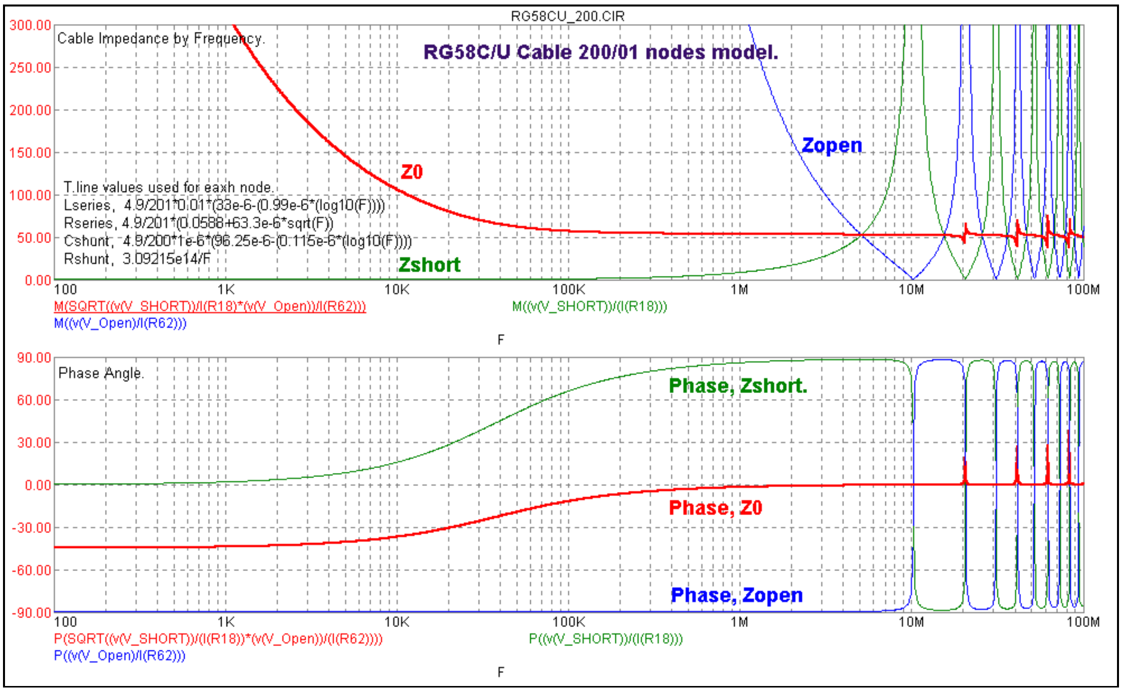
PTFE cable 19*0.45mm, 51.1mΩ DCR (Z0 91.5Ω @ 1kHz, 40.5Ω @ 10kHz, 29.5Ω @ 1MHz)
T.Line values used for each node.
Lseries, 4.9/201*0.01*(29.47e-6-(2.20357e-6*(log10(F))))
Rseries, 4.9/201*(0.01043+47.55e-6*sqrt(F))
Cshunt, 4.9/200*1e-6*(165.95e-6+(0.016118e-6*(log10(F))))
Rshunt, 2.90508e12/F
PTFE cable made using commercial PTFE insulated, 19*0.45mm silver plated wires.

#44 cable 37*0.32mm, 53.8 mΩ DCR (Z0 63.5Ω @ 1kHz, 25Ω @ 10kHz, 15.6Ω @ 1MHz)
T.Line values used for each node.
Lseries, 4.9/201*0.01*(25.878e-6-(2.5789e-6*(log10(F))))
Rseries, 4.9/201*(0.0109796+72.6e-6*sqrt(F))
Cshunt, 4.9/200*1e-6*(412.2e-6-(2.12989e-6*(log10(F))))
Rshunt, 4.00317e11/F

#55 cable 37*0.32mm, 54.8 mΩ DCR (Z0 61.7Ω @ 1kHz, 24.1Ω @ 10kHz, 13.5Ω @ 1MHz,)
T.Line values used for each node.
Lseries, 4.9/201*0.01*(24.82e-6-(2.5444e-6*(log10(F))))
Rseries, 4.9/201*(0.01118+72.5e-6*sqrt(F))
Cshunt, 4.9/200*1e-6*(439.82e-6-(0.1266e-6*(log10(F))))
Rshunt, 6.00682e11/F
#44 used Raychem 44A0111-14 and #55 Raychem 55A0111-12 same wires, different insulation.

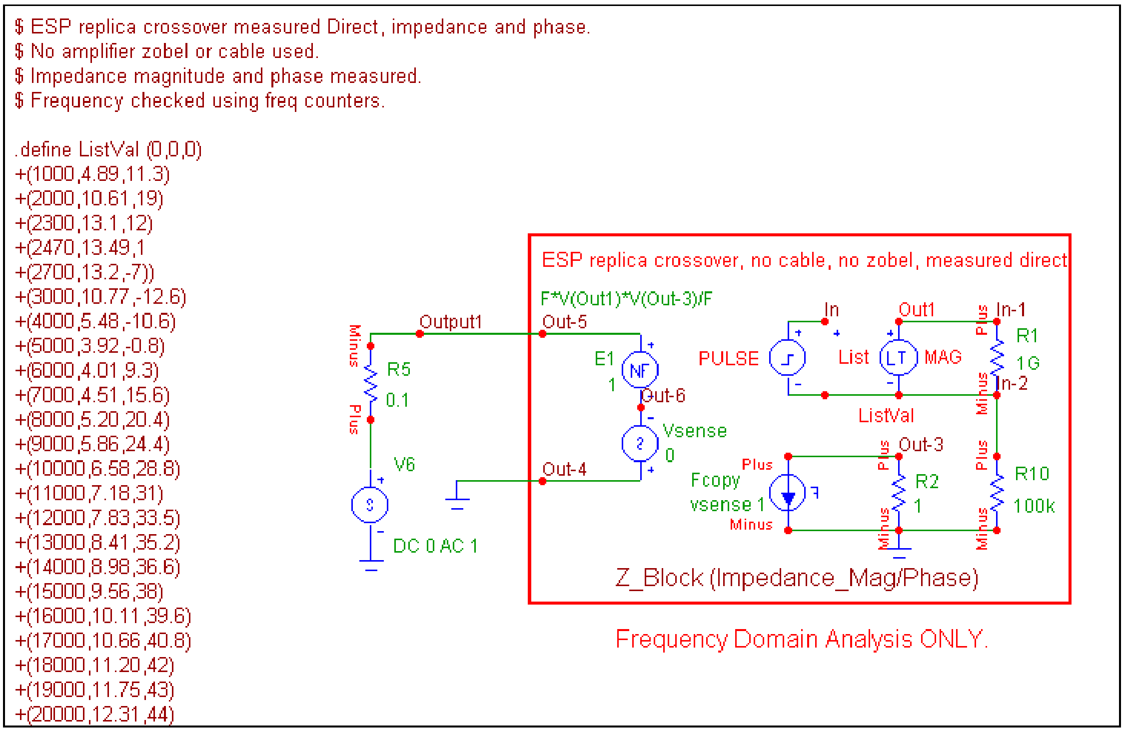


Cable A. Schematic used to develop cable models to R, L, C and G measurements, Z0 and quarter wavelength resonant frequency. For speaker simulations, use one only of these two lines.



Cable B.
To prove this 201/200 node model was valid up to 10MHz, it was initially used to model against 4.9metre of pre-measured RG58U coaxial cable, checking for Z0 by frequency also quarter wave resonance impedance and frequency.

Spice "One Port" or "Z_block" model subcircuit as used in simulations.



This Z_block model allows a CSV listing of measured frequency, impedance and phase angle parameters, to be displayed on screen or used together with other components in Spice simulation.

You may wonder why I choose to use the above Z_block to represent both my test speakers, why not simply model their schematics using Spice ? At audible frequencies that can work quite well, however at higher frequencies every component used, whether inductor, resistor, capacitor and especially so the speaker drivers, for accuracy must use complex, multicomponent models, to match resonant frequencies. Every inductor or speaker voice coil includes significant self capacitance and resonant frequency peaks and troughs. Simplistic Spice simulation of this schematic, shows impedance continually increasing with frequency quite unlike the measured values resonant peaks and troughs, so leads to false conclusions.

Accurately measuring both speaker systems and inputting measured values of impedance and phase angle by frequency into the Z_block as shown, is quicker, simpler and most important, is error free. Combined with my proven cable models, then produces the most accurate simulations possible, for this complex speaker with cable, behaviour. Clearly as figures 3 through 12 have shown, speaker cables do comply with established transmission line behaviour.