Effects of Cable, Loudspeaker, and Amplifier Interactions*

FRED E. DAVIS

Engineering Consultant, Hamden, CT 06517, USA

Loudspeaker cables are among the least understood yet mandatory components of an audio system. How cables work and interact with loudspeaker and amplifier is often based more on presumption and speculation than on fact. The literature on loudspeaker cable behavior and effects is minimal. Measurements were made with 12 cables covering a variety of geometries, gauges, and types. The measured data indicate distinct differences among the cables as frequency-dependent impedance, subtle response variations with loudspeakers, and reactance interactions between amplifier, cable, and loudspeaker. In some cases the effects of the amplifier overwhelm the cable's effects. Mathematical models that provide insight into the interaction mechanisms were constructed and compared to the measured data.

0 INTRODUCTION

A variety of specialty loudspeaker cables can be found advertised in almost any audio magazine from the last 10 years. All promise the same result—better sound—yet they span the gamut of electrical characteristics, geometries, and materials. How loudspeaker cables work is often based more on presumption and speculation than on fact. Few articles are published exploring the behavior of these mandatory components in journals [1] and popular magazines [2]–[6]. Debates continue on computer network newsgroups on audio [7]. "White papers" available from manufacturers (but otherwise unpublished) are frequently more marketing than science [8]–[11].

Using a simplistic view of how loudspeakers and cables work, conventional wisdom would suggest that since loudspeakers exhibit a low impedance (nominally 4–8 Ω), then the cable should have even lower resistance. As a result, "monster" cables were introduced. Then a more complex view of cables emerged, suggesting that loudspeaker cables would perform better with less capacitance or more inductance, or the skin effect, phase shift, and dispersion were veiling high frequencies, or they behaved like transmission lines. These factors are the essence of 'high-end' cables. Greiner addressed some of these issues in his papers [1]–[3]. In short, he proposes that loudspeaker cables are not transmission lines (audio frequency wavelengths are much too long compared to the length of the cables); phase shift and dispersion effects are too small to be audible (typically less than 0.3 deg/m at 20 kHz, and differences of less than 60 ns/m for most cables between 100 Hz and 10 kHz); and the skin effect has only a small effect on heavy conductors (skin depth in copper at 20 kHz is 0.5 mm).

It is no secret that loudspeakers offer a complex load to the amplifier [12]–[13]. While an isolated loudspeaker is predominantly inductive, the complex impedance of most loudspeaker systems with multiple drivers and passive crossover networks exhibits both negative and positive phase angles at given frequencies, indicating capacitive reactance as well as inductive reactance.[1] Otala and Huttunen [13] show that given complex waveforms, commercial loudspeakers require up to 6.6 times more current than an 8-Ω resistor for the same waveform, suggesting a dynamic impedance as low as 1.2 Ω.

The ideal loudspeaker cable should transfer all audio frequencies into any loudspeaker load with flat voltage response. Real cables will always show some loss due to resistance, but better cables will both minimize this loss and still transfer all frequencies unscathed. The acoustical result will depend on many factors, but the electrical interaction of loudspeaker, amplifier, and cable forms an essential foundation. This engineering

* Manuscript received 1990 August 21; revised 1990 December 24.

[1] Some issues of *Audio* that illustrate Nyquist plots of loudspeakers' complex impedances are vol. 74, p. 100 (1990 Nov.); vol. 74, p. 94 (1990 Aug.); vol. 73, p. 111 (1989 June); vol. 73, pp. 88, 108 (1989 Sept.).

report examines the mechanisms for this interaction and shows how it can affect the response of the system.

1 SAMPLE OF CABLES TESTED

The sample of cables gathered for this test represents a variety of commonly and uncommonly available wire. Most of the samples were 3.1 m in length. Some are *very* expensive (over \$419 per meter), others cheap (\$1.91 per meter), and some are not loudspeaker cables at all. This is not an exhaustive examination of every loudspeaker cable available. The following is a brief description of each type with sample numbers as they appear in Figs. 1–3. They are presented in order of ascending resistance per meter. When known, the organization of the strands is shown in parentheses as (quantity*gauge). Unspecified gauges were estimated from conductor diameter and resistance.

1) *Levinson HF10C*. Many very small copper strands in two parallel conductors (each about 6.4 mm in diameter) spaced about 12.7 mm apart (between centers of the conductors). Approximately 3 AWG. Extremely flexible for such a heavy conductor.

2) *Auto Jumper Cables*. Literally from the garage. Two thick parallel (9.5-mm diameter) conductors of approximately 7 AWG (19*20).

3) *Krell "The Path."* Independent wires of about 15.9-mm diameter, each of complex layer construction. The conductor is 4.8 mm in diameter, the remainder is insulation. It has several groups of tightly twisted very thin enameled wires wound in helices around heavier enameled wires. (This construction is similar to Music Interface Technologies' "Vari-Lay" and Monster Cable "Time Correct"). All conductors are soldered together at each end with heavy, crimped terminations. Approximately 5 AWG. They are labeled "transconductant speaker cable."

4) *AudioQuest Green "Litz."* Six conductors (approximately 10 AWG) of many small enameled copper wires, lightly twisted over a stranded plastic core, altogether about 12.7 mm in diameter. Equivalent to about 6 AWG.

5) *Kimber 16LPC*. These are 16 independent wires, woven together in a flat cable, Teflon insulation. Each individual wire is equivalent to 19 AWG, and is composed of seven strands of variable gauge from 31 AWG to 24 AWG. Equivalent to 7 AWG.

6) *Spectra-Strip 843-138-2601-064 Ribbon Cable*. Abbreviated 138-064. Made of 32 twisted pairs of 26 AWG wire (7*34), arranged in a flat ribbon. Intended for high-speed differential digital data transmission. Equivalent to about 8 AWG.

7) *Belden 9718*. Belden's 12 AWG (65*30) loudspeaker wire with clear PVC insulation and parallel construction, like "zip" cord (sample 12).

8) *Music Interface Technologies' CVT*. A large 18-mm diameter cable using MIT's Vari-Lay construction (multiple conductors of different gauge and length). The manufacturer claims this will permit "all frequencies to travel through a given length of MIT cable at exactly the same rate of speed," hence the name constant velocity transmission (CVT). Two groups of three Vari-Lay bundles form the two main conductors, with a coaxial cable connected in an unknown fashion (due to potting compound) inside a proprietary coupler at the amplifier end. At \$419 per meter, the most expensive cable tested. Equivalent to 12 AWG.

9) *Kimber 8LPC*. Very similar to sample 5, except eight independent wires, woven in a flat cable, Teflon insulation. Each individual wire is equivalent to 19 AWG, and is composed of seven strands of variable gauge from 31 AWG to 24 AWG. Equivalent to 10 AWG.

10) *Kimber 4PR*. An unusual cable made from eight independent wires of 23 AWG (7*31) braided together, PVC insulation. Equivalent to 14 AWG.

11) *Spectra-Strip 843-191-2811-036 Ribbon Cable*. Abbreviated 191-036. Made of 36 wires of 28 AWG (7*36), arranged in a flat ribbon; intended for digital interconnections. The least expensive cable tested at \$1.91 per meter. Equivalent to about 15 AWG.

12) *Belden 19123*. 18 AWG (41*34) "zip" (lamp) cord. Brown PVC insulation, parallel construction.

2 ELECTRICAL PARAMETERS OF CABLE SAMPLES

The standard electrical parameters of the cables were measured with an ESI model 252 impedance meter and normalized to 1 m. The results are shown in Figs. 1–3. It is resistance, capacitance, and inductance that will decide the performance of the cable, since exotic materials and layer geometries can only affect these fundamental characteristics.

Cable resistance in milliohms per meter is shown in Fig. 1 (remember that this includes the resistance of both conductors). Resistance is not a major factor in cables of reasonable length. Based on resistance alone, it would require about 23.4 m of 18 AWG cable to show −1 dBV drop with an 8-Ω load. 12 AWG seems more than adequate even for demanding systems, high

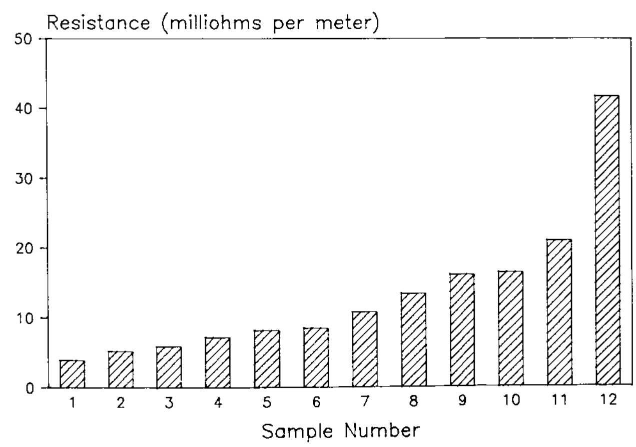


Fig. 1. Cable resistance in milliohms per meter. 1—HF10C; 2—jumper; 3—Krell; 4—Litz; 5—16LPC; 6—138-064; 7—9718; 8—CVT; 9—8LPC; 10—4PR; 11—191-036; 12—19123.

power levels, and reasonable lengths. The maximum current for 12 AWG wire with PVC insulation in an ambient temperature of 30°C, allowing for a 50°C temperature rise, is 36 A. This seems fine for audio applications, since 36 A into 8 Ω is greater than 7 kW rms (1.8 kW rms into 2 Ω).

Fig. 2 shows the cable capacitance. As expected, flat cables show the highest capacitance (samples 6 and 11), multiconductor cables less (samples 4, 5, 8, 9, and 10), and two-conductor cables the least (samples 1, 2, 3, 7, and 12).

Fig. 3 shows the cable inductance. Cables with only two separated conductors show the highest inductance, while most multiwire cables show the lowest inductance. An exception is Music Interface Technologies' CVT due to its construction.

3 CABLE IMPEDANCE VERSUS FREQUENCY

The impedance of a cable across the audio spectrum shows the influence of reactive and skin effects. Better cables will have a low impedance that remains constant with frequency which permits flatter voltage response.

A current of 1 A at a given frequency will cause a voltage difference equivalent to the magnitude of the cable's impedance in ohms at that frequency. For this test, a resistive load of 1.0 Ω (with approximately 0.06-μH inductance) was driven at a current of 1.0 A rms at 12 frequencies between 30 Hz and 20 kHz. All measurements were made with a Fluke 8050A digital voltmeter and waveforms monitored on a Tektronix 2215 oscilloscope. The amount of current was determined by driving the amplifier until the voltage across the load was 1.000 V rms at each frequency and for every cable, thus removing frequency response variations from signal source, attenuator, and amplifier. The voltage difference from the output of the amplifier to the load was then measured and recorded, and the impedance calculated.

The results of these measurements are shown in Figs. 4 and 5 as cable impedance versus frequency, where the value of impedance reflects the contribution of both conductors. Cables with the most constant impedance were the flat cables with higher capacitance (Fig. 4, 138-064; Fig. 5, 191-036). Other multiconductor cables such as Kimber 16LPC and AudioQuest Green Litz (Fig. 4, 16LPC and Litz) and the lighter gauge Kimber 8LPC and 4PR (Fig. 5, 8LPC and 4PR) display a small impedance rise. Of the two conductor cables tested,

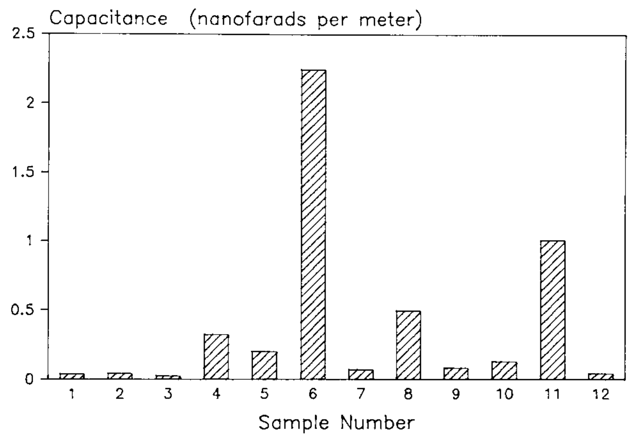


Fig. 2. Cable capacitance in nanofarads per meter. 1—HF10C; 2—jumper; 3—Krell; 4—Litz; 5—16LPC; 6—138-064; 7—9718; 8—CVT; 9—8LPC; 10—4PR; 11—191-036; 12—19123.

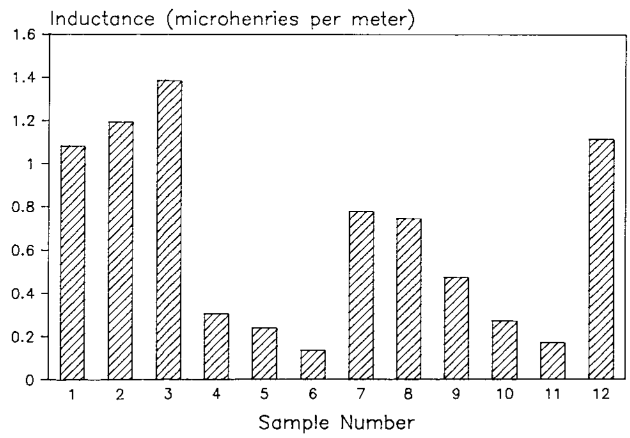


Fig. 3. Cable inductance in microhenrys per meter. 1—HF10C; 2—jumper; 3—Krell; 4—Litz; 5—16LPC; 6—138-064; 7—9718; 8—CVT; 9—8LPC; 10—4PR; 11—191-036; 12—19123.

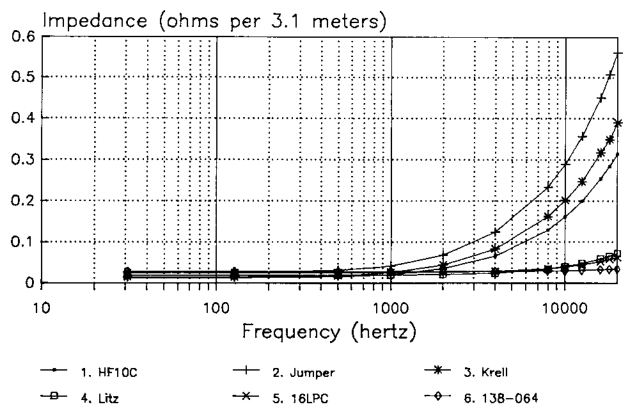


Fig. 4. Cable impedance versus frequency for cable samples 1–6.

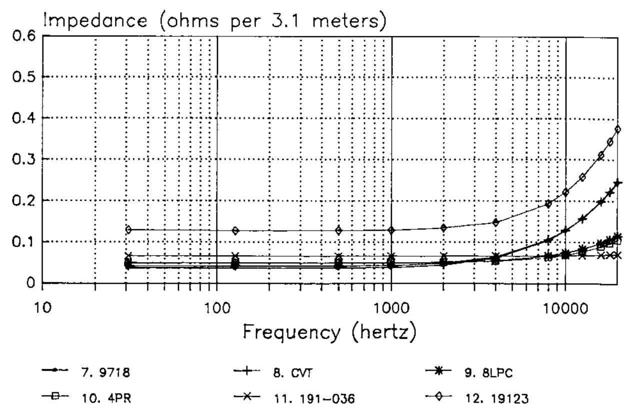


Fig. 5. Cable impedance versus frequency for cable samples 7–12.

12 AWG wires (Fig. 5, 9718 and CVT) performed the best, since both heavier and lighter gauges showed greater high-frequency impedance. The complex layer construction of the CVT cable has duplicated almost exactly the impedance characteristics of the 12 AWG Belden 9718 (Fig. 5, CVT and 9718; coefficient of correlation = 0.997).

The effect of inductive reactance in this sample of cables is far more significant than the skin effect. For example, 3.1 m of the largest diameter cable sampled, Levinson HF10C (sample 1), will show a 3.42 times increase in resistance at 20 kHz due to the skin effect, but the inductive reactance will be 9.8 times greater than resistance at that frequency. When driving 8 Ω at 20 kHz through 3.1 m, the skin effect alone would produce a drop of −0.044 dBV relative to 20 Hz, while the combined reactance and skin effects would produce a drop of −0.43 dBV.

Higher cable capacitance will tend to reduce the combined reactive component of the cable, thus lowering cable impedance at high frequencies and improving the high-frequency response. This effect is contrary to the popular belief that high frequencies will be attenuated more with higher cable capacitance [5], [8]. Such conclusions are drawn from a cable model consisting of series resistance and shunt capacitance, but no series inductance. Spectra-Strip 138-064 (sample 6) showed the highest capacitance (6.847 nF for 3.1 m), lowest inductance, and flattest cable impedance. Well designed amplifiers are not affected by this amount of capacitance, but some amplifiers may become unstable.

4 TEST LOUDSPEAKER AND AMPLIFIER CHARACTERISTICS

The impedance and phase characteristics of loudspeakers A and B used in these tests are shown in Figs. 6 and 7, measured at the same frequencies used in the cable impedance test. Please note that the lines connecting the data points in these graphs are intended to simplify reading the plot and do not reflect valid data between the sampled frequencies. Loudspeaker A is a three-way design with an acoustic suspension woofer, three dome midrange drivers, and three dome tweeter drivers. It exhibits mostly capacitive reactance (negative phase angle) at the frequencies sampled between 127 Hz and 12 kHz, with its lowest impedance of 4.8 Ω above 8 kHz. Loudspeaker B is a two-way system with a bass reflex enclosure and dome tweeter. It shows much more inductive reactance (positive phase angle) than loudspeaker A around 1 kHz, and a capacitive reactance peak around 8 kHz. Its lowest impedance is 5.8 Ω around 500 Hz.

Amplifier frequency response and damping factor are shown in Fig. 8. Amplifier A exhibits more significant frequency response variations and a large drop in damping factor above 1 kHz. Amplifier B has a flat frequency response and a high, almost linear damping factor. In Secs. 5 and 6, the effect of the amplifier is factored out, showing only the cable and loudspeaker interactions. In Sec. 7, amplifier effects are included with loudspeaker and cable effects for a total system response.

5 CABLE RESPONSE WITH LOUDSPEAKER LOADS

Obviously, a loudspeaker can only perform to the quality of the electrical input to its terminals, so the best cable will show the flattest frequency response

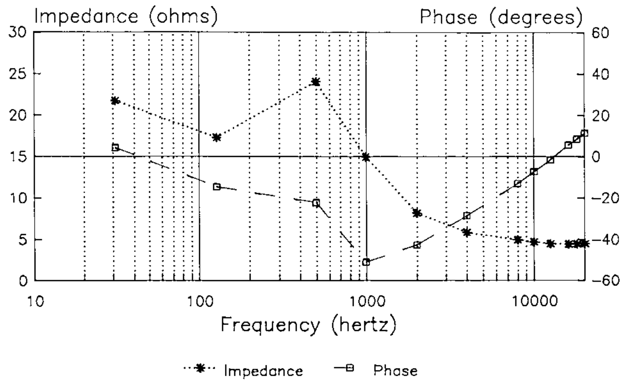


Fig. 6. Impedance and phase response of loudspeaker A. Note that frequencies are sampled and lines connecting data points do not reflect valid data.

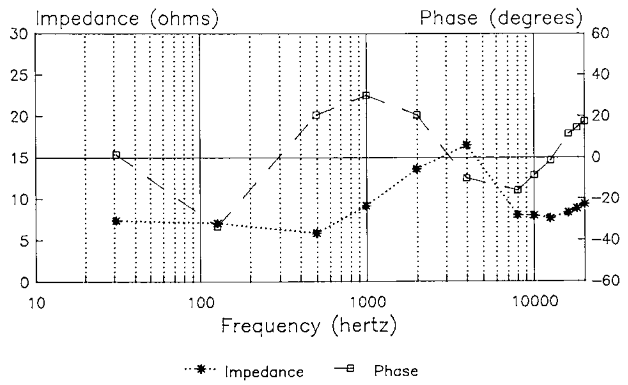


Fig. 7. Impedance and phase response of loudspeaker B. Note that frequencies are sampled and lines connecting data points do not reflect valid data.

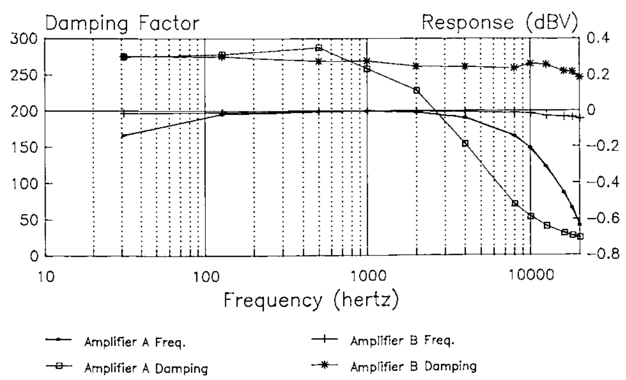


Fig. 8. Frequency response and damping factor for amplifiers A and B.

despite loudspeaker impedance or phase angle. The cable electrical response was measured using two commercial loudspeakers as a load.

A constant amplifier output of 1 V (0.00 dBV) was used at each frequency to remove any variations due to amplifier or signal source. The amplitude of the voltage at the loudspeaker terminals was measured in dBV and recorded.

The low-inductance multiconductor cables show the most linear response (Fig. 9, Litz, 16LPC, and 138-064; Fig. 10, 8LPC, 4PR, and 191-036). Also note the relatively flat response of the 12 AWG cable with both loudspeakers (Figs. 10 and 11, 9718) when compared to other two-wire cables (Figs. 9 and 11, HF10C and Krell). Another common effect is the high-frequency loss with the higher inductance two-conductor cables.

Fig. 9 also shows the interaction of a cable's inductive reactance with loudspeaker A's capacitive reactance where the level rises above 0 dBV in the 1-kHz to 10-kHz region. At this point the loudspeaker terminal voltage has exceeded the amplifier's output. The cause of this will become apparent with the loudspeaker cable model introduced in Sec. 6.

Four cables representing a variety of types were tested with loudspeaker B (Fig. 11). Loudspeaker B shows inductive reactance and low impedance between 300 Hz and 3 kHz and the response dips. When the reactance of loudspeaker B becomes capacitive around 8 kHz, it shows the same rise with the more inductive cables (HF10C and Krell).

6 LOUDSPEAKER CABLE MODEL

Expressions for transmission lines (such as characteristic impedance, impedance matching, reflections) do not fit audio applications, since the cable lengths involved are minute fractions of the shortest audio wavelength (about 16 km at 20 kHz in copper). This is discussed thoroughly in Greiner [1]–[3].

Therefore, cable and loudspeaker should be treated as lumped-circuit elements. The cable response model in this engineering report is simple and is based on the ratio of the vector sum of the loudspeaker's resistive and reactive components to the vector sum of both loudspeaker and cable resistive and reactive components together. The cable is modeled at each frequency as a resistance in series with an inductive reactance using the measured values of resistance and inductance. The skin effect was calculated and applied to the resistance where appropriate. The capacitive component of the cable is too small to have much influence at audible frequencies, and is thus omitted from the model. The loudspeaker is modeled at each frequency as a resistance in series with a reactance that can be either inductive or capacitive. The expression for the cable response at the loudspeaker terminals for a given frequency is

$$V_s(f) = V_a(f) \frac{\sqrt{R_s^2 + X_s^2}}{\sqrt{(R_w + R_s)^2 + (X_w \pm X_s)^2}}$$

where

$V_s(f)$ = voltage at loudspeaker terminals at frequency f
$V_a(f)$ = voltage at amplifier output at frequency f
R_w = cable resistance, including skin effect, at frequency f
X_w = cable inductive reactance at frequency f
R_s = loudspeaker resistance
$\pm X_s$ = loudspeaker reactance at frequency f, inductive (+) or capacitive (−).

The response in dBV was found by taking the log-

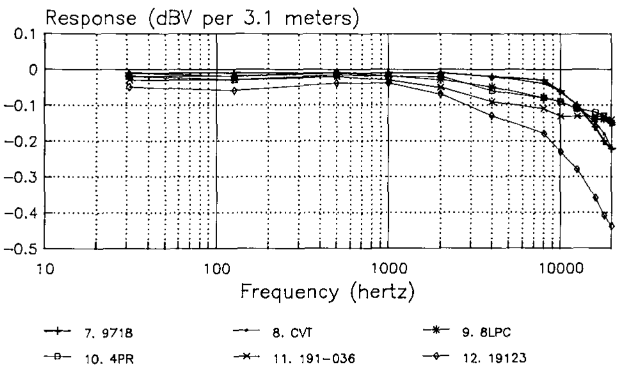


Fig. 10. Measured cable response with loudspeaker A for cable samples 7–12.

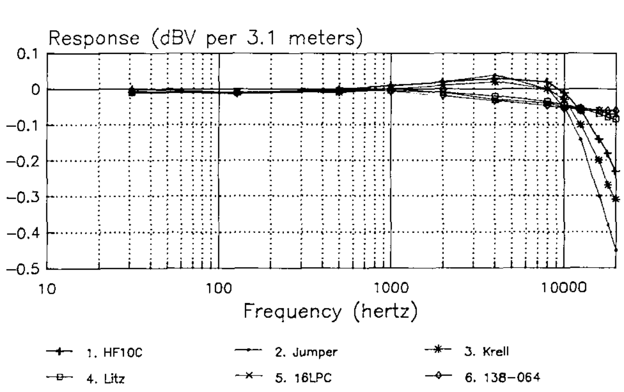


Fig. 9. Measured cable response with loudspeaker A for cable samples 1–6.

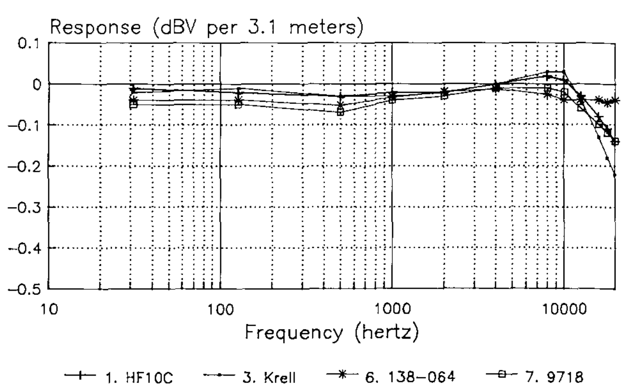


Fig. 11. Measured cable response with loudspeaker B for cable samples 1, 3, 6, and 7.

arithm of the ratio of the response at a test frequency and the 1-kHz response,

$$V_s(f)_{\mathrm{dBV}} = 20 \log \frac{V_s(f)}{V_s(1\ \mathrm{kHz})} .$$

Three different styles of cables are modeled and compared to measured values in Fig. 12. The model gives a very good approximation to the measured responses (coefficient of correlation = 0.999, 0.948, and 0.997 for HF10C, 16LPC, and 19123, respectively). The results are for the full 3.1-m length of the cable since they are not directly scalable to other lengths.

The rise above 0 dBV in the measured responses occurs when the combined magnitude of the impedance of loudspeaker and cable (as seen by the amplifier) is lower than the loudspeaker's impedance alone. This results when the reactance of the loudspeaker is capacitive and subtracts from the cable's inductive reactance. The result is a lower total reactive component, which reduces the magnitude of the impedance seen by the amplifier. Since the amplifier output is held at a constant voltage for the cable impedance test, the current through the loop is higher than the loudspeaker's impedance alone would require. This higher current results in a voltage across the loudspeaker terminals that is higher than the amplifier output. Low-inductance cables will provide a more ideal response since cables whose inductive reactance is much less than the loudspeaker's capacitive reactance will reduce this "hump" effect and present little more than the loudspeaker's complex impedance to the amplifier as a load. When the effective impedance of cable and loudspeaker is lower, it should not prove difficult for a well-designed amplifier because the effect is small with short cables (approximately 0.6% for the worst case in these tests, sample 2, auto jumper cable). The lowest impedance seen by the amplifier and the greatest rise in loudspeaker voltage as a result of this effect occur at resonance, when $X_{\mathrm{cable}} = -X_{\mathrm{speaker}}$. The impedance will then be limited by the resistive components of both cable and loudspeaker. For example, loudspeaker A would require just over 12.4 m of Belden 9718 cable to provide enough inductance to achieve resonance at 10 kHz, where the resistance seen by the amplifier would be about 4.84 Ω.

7 AMPLIFIER EFFECTS

Now that the relationship between loudspeaker and cable is better understood, the effects of the amplifier will be considered. As seen with the cable model, added inductance will cause frequency response deviations due to interactions with the loudspeaker's reactive components. Therefore it would be desirable to minimize reactive effects from the amplifier as well. Most amplifiers include added inductance (typically 0.5–10 μH) paralleled with a resistance (typically 2.7–27 Ω) between the output of the amplifier (generally from the point that negative feedback is taken) and the amplifier's output terminals. This inductance is added to isolate phase shifts due to capacitive loads from causing instability in the feedback loop. Both amplifiers A and B include this network. Obviously, this inductance is in series with the cable inductance, and in some cases can exceed the cable inductance.

The damping factor of an amplifier can also shape the frequency response. The damping factor (and the output impedance of the amplifier) is controlled by the frequency-dependent loop gain of the amplifier, the degree of negative feedback, the impedance of the output devices, and any other components in series between the amplifier output and the output terminals. The amplifier output voltage will be lower where the damping factor is lower or where the load impedance is lower. An amplifier with low damping factor is less able to control back EMF and reactive effects of the loudspeaker.

The responses of all cables were tested with the same loudspeaker, but using two different amplifiers. Figs. 13 and 14 present the responses of loudspeaker A and amplifier A, while Figs. 15 and 16 present the responses of loudspeaker A with amplifier B. These graphs illustrate the combined responses of loudspeaker, cable, and amplifier. Immediately obvious is that the response of amplifier A overwhelms the individual cable effects (Figs. 13 and 14). The damping factor for amplifier A and the impedance of loudspeaker A both drop in the same frequency range, which exacerbates their inter-

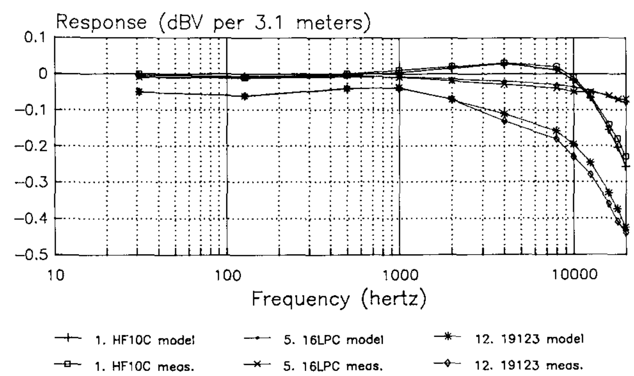


Fig. 12. Modeled and measured response with loudspeaker A for cable samples 1, 5, and 12.

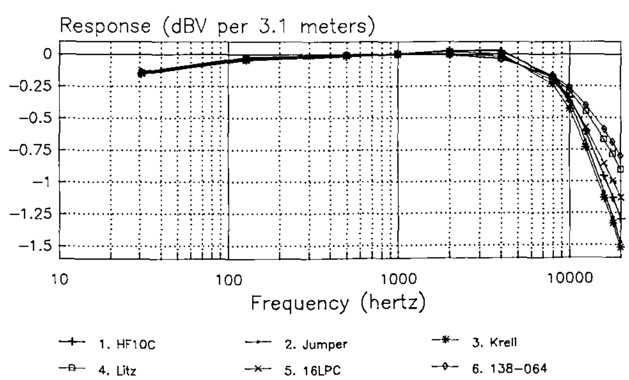


Fig. 13. Complete system response for amplifier A with loudspeaker A, cable samples 1–6.

action. The response with amplifier B (Figs. 15 and 16) closely resembles the response of the cable and loudspeaker alone (Figs. 9 and 10). The high damping factor of amplifier B maintains better control of reactive effects with the more inductive cables, producing a flatter response (Fig. 15).

The effect of the amplifier can be added to the cable response model by including the additional resistance and reactance of the amplifier's output:

$$V_s(f) = V_a(f)' \frac{\sqrt{R_s^2 + X_s^2}}{\sqrt{(R_a + R_w + R_s)^2 + (X_a + X_w \pm X_s)^2}}$$

where $V_a(f)'$ = amplifier voltage at frequency f.

Fig. 17 illustrates the results of this model, using amplifier B's voltage response with loudspeaker A's impedance and phase (converted to dBV relative to the 1-kHz response as before). The model fits well with the measured data (coefficient of correlation = 1.000, 0.997, and 0.999 for HF10C, 16LPC, and 19123, respectively). Because the model is very simple and amplifier dynamic responses are more complex, it does not fit as closely with all amplifiers, especially the ones that have a more complex output reactance (which may include capacitive effects). The model infers that the flattest response will occur by keeping the reactance of the amplifier and cable as low as possible.

8 CONCLUSIONS

If loudspeakers were only simple resistance, then large, low-resistance cables would not be a bad idea. However, loudspeaker systems exhibit a frequency-dependent complex impedance that can interact with the reactive components of amplifier and cable. The best response was obtained with low-inductance cables and an amplifier with low-inductance output and a high, frequency-independent damping factor.

These tests have shown that the best way to achieve adequately low resistance *and* inductance in a cable is by using many independently insulated wires per conductor rather than one large wire. Efforts to reduce the skin effect (such as Litz construction) will help, but due more to the reduction of inductance than the reduction of the skin effect. Inductive reactance is more significant in large cables than the skin effect. If an amplifier does not disagree, larger capacitance in a cable is not significant since this component is comparatively small and reduces amplifier and cable inductive reactance effects.

The best performance was measured with the multiconductor cables Spectra-Strip 138-064, Kimber 16LPC, and AudioQuest Litz. Smaller multiconductor

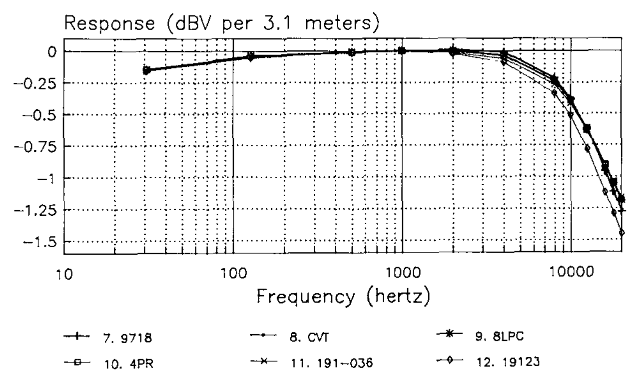


Fig. 14. Complete system response for amplifier A with loudspeaker A, cable samples 7–12.

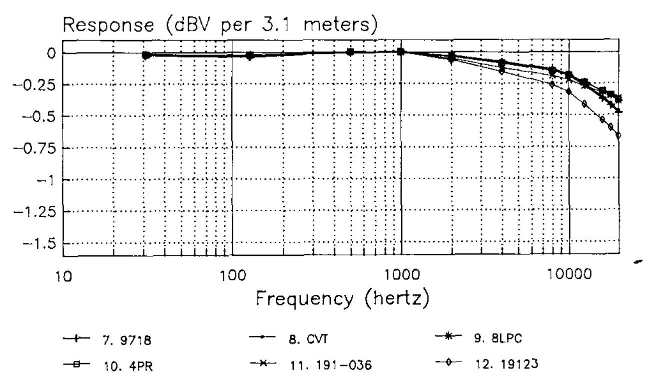


Fig. 16. Complete system response for amplifier B with loudspeaker A, cable samples 7–12.

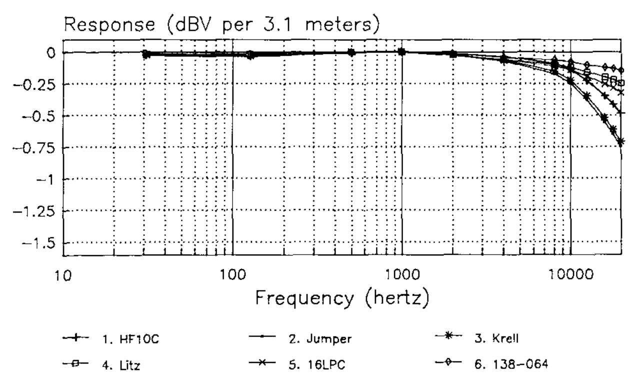


Fig. 15. Complete system response for amplifier B with loudspeaker A, cable samples 1–6.

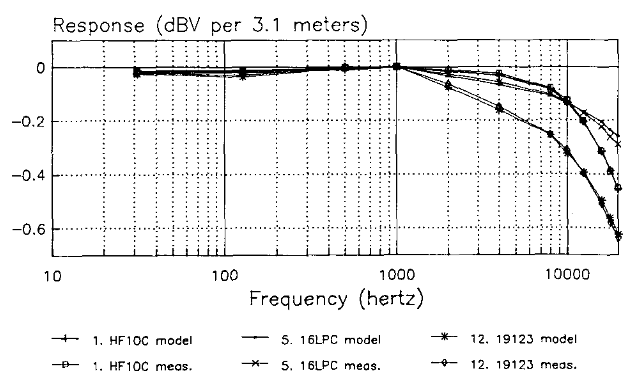


Fig. 17. Model of complete system response for amplifier B with loudspeaker A.

cables such as Kimber 8LPC, Kimber 4PR, and Spectra-Strip 191-036 also performed well.

Of the two-wire cables, 12 AWG provided the best performance with reactive loads, while both smaller and larger gauges (3–7 AWG and 18 AWG) showed greater high-frequency drop and interaction with capacitive reactance in a load. 12 AWG seems more than adequate, even for demanding systems, high power levels, and reasonable lengths.

The effects of 3.1-m cables are subtle, so many situations may not warrant the use of special cables. Low-inductance cables will provide the best performance when driving reactive loads, especially with amplifiers having low damping factor, and when flat response is critical, when long cable lengths are required, or when perfection is sought. Though not as linear as flat cables, 12 AWG wire works well and exceeds the high-frequency performance of other two-conductor cables tested. By the way, keep the auto jumper cables in the garage!

9 ACKNOWLEDGMENT

The author would like to thank Robert A. Pease for his invaluable suggestions on measurement techniques, Dave Sales for his amplifier and exotic cables, and Brian Converse, Dr. Robert Milstein, and Dianne Davis for their support and suggestions.

10 REFERENCES

[1] R. A. Greiner, "Amplifier–Loudspeaker Interfacing," *J. Audio Eng. Soc.*, vol. 28, pp. 310–315 (1980 May).

[2] R. A. Greiner, "Cables and the Amp/Speaker Interface," *Audio*, vol. 73, pp. 46–53 (1989 Aug.).

[3] R. A. Greiner, "Another Look at Speaker Cables," *BAS Speaker*, vol. 7, no. 3, pp. 1–4 appended (1978 Dec.); addenda, vol. 7, no. 6, pp. 6–7 (1979 Mar.).

[4] C. Ward, J. Thompson and M. Harling, "Speaker Cables Compared," *BAS Speaker*, vol. 8, no. 7, pp. 25–29 (1980 Apr.).

[5] R. Warren, "Getting Wired," *Stereo Rev.*, vol. 55, pp. 75–79 (1990 June).

[6] D. Olsher, "Cable Bound," *Stereophile*, vol. 11, pp. 107–118 (1988 July).

[7] B. Jones, "Speaker Cable Electrical Tests," ACSnet/UUCP: brendan@otc.otca.oz 1990; a series of discussions and rebuttals can be found referencing ⟨1857@otc.otca.oz⟩, newsgroup: rec.audio.

[8] D. Salz, "The White Paper on Audio Cables," Straight Wire Inc., Hollywood, FL (1988).

[9] B. Brisson, "How Phase Shift in Audio Cables Influences Musical Waveforms," Musical Interface Technologies, Auburn, CA (undated).

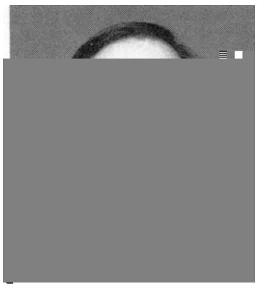
[10] "Cable Design, Theory Versus Empirical Reality," AudioQuest, San Clemente, CA (1990).

[11] "Sumiko Reports: OCOS—The Formula," Sumiko, Berkeley, CA (1989).

[12] J. H. Johnson, "Power Amplifiers and the Loudspeaker Load," *Audio*, vol. 61, pp. 32–40 (1977 Aug.).

[13] M. Otala and P. Huttunen, "Peak Current Requirement of Commercial Loudspeaker Systems," *J. Audio Eng. Soc.*, vol. 35, pp. 455–462 (1987 June).

THE AUTHOR



Fred E. Davis is currently a consulting electronics engineer, and previously has been director of engineering for machine vision and optical data storage companies. He has worked with biomedical electronics, audio, recording studio and video electronics, industrial controls, portable instrumentation and tools, computer hardware design and software, and consumer electronics. Besides a passion for music, his interests include photography, books (especially old and rare science books), and film.