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-

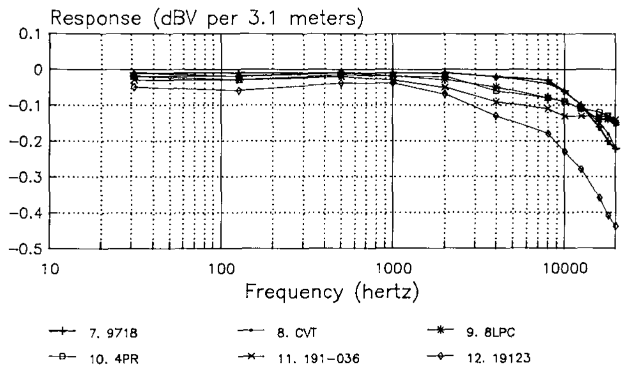


Fig. 10. Measured cable response with loudspeaker A for cable samples 7–12.

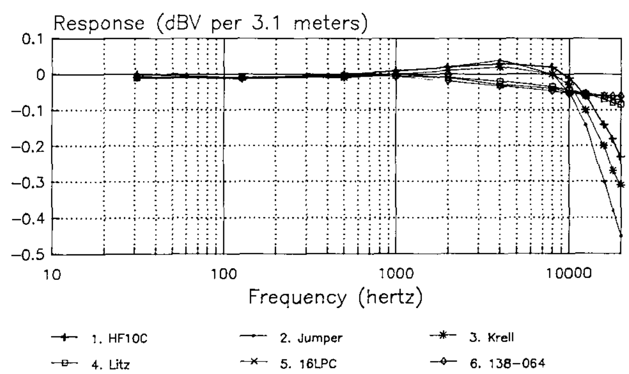


Fig. 9. Measured cable response with loudspeaker A for cable samples 1–6.

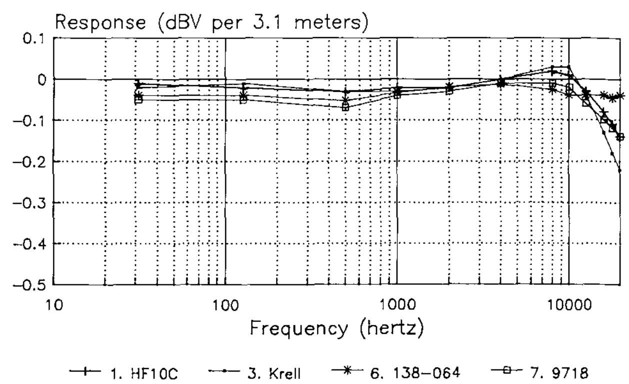


Fig. 11. Measured cable response with loudspeaker B for cable samples 1, 3, 6, and 7.

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-

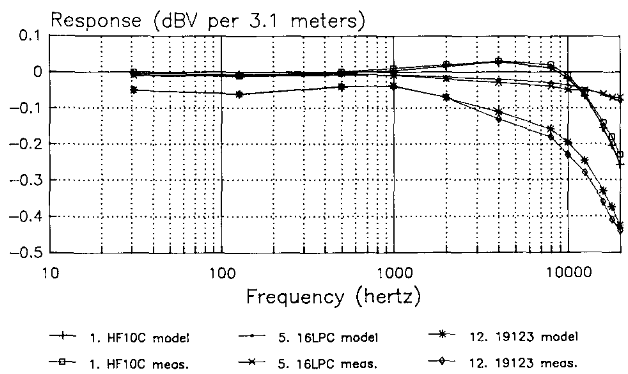


Fig. 12. Modeled and measured response with loudspeaker A for cable samples 1, 5, and 12.

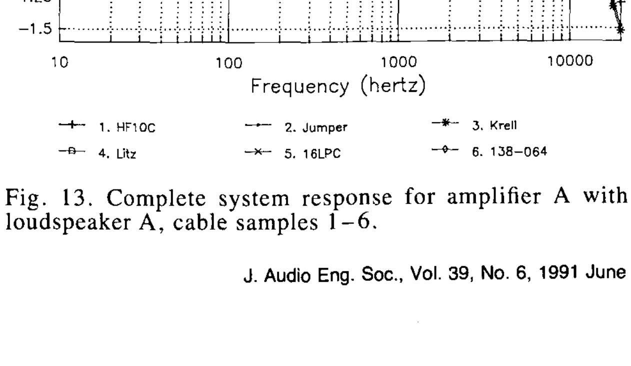


Fig. 13. Complete system response for amplifier A with loudspeaker A, cable samples 1–6.

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

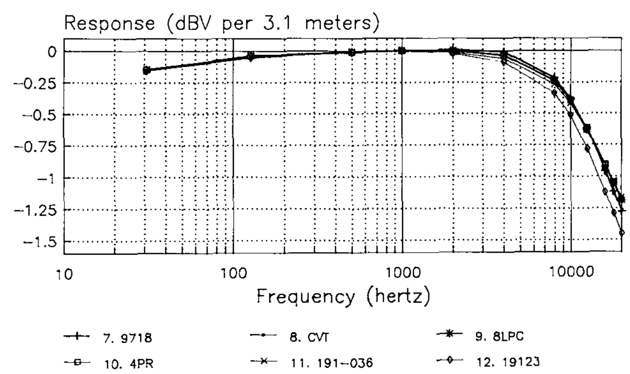


Fig. 14. Complete system response for amplifier A with loudspeaker A, cable samples 7–12.

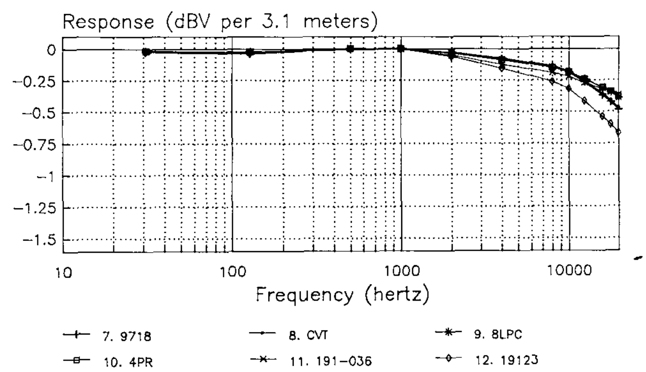


Fig. 16. Complete system response for amplifier B with loudspeaker A, cable samples 7–12.

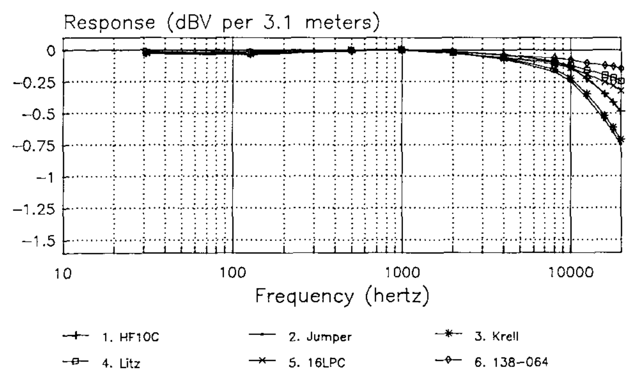


Fig. 15. Complete system response for amplifier B with loudspeaker A, cable samples 1–6.

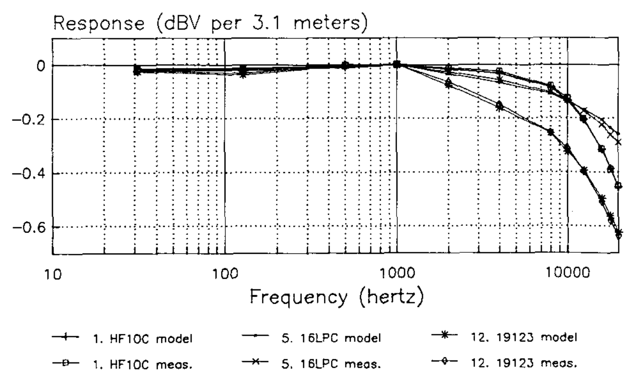


Fig. 17. Model of complete system response for amplifier B with loudspeaker A.

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).

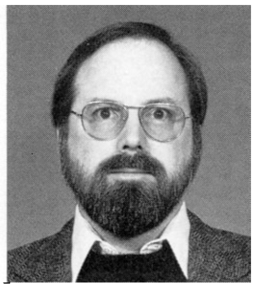
[10] "Cable Design, Theory Versus Empirical Reality," AudioQuest, San Clemente, CA (1990).

[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.