57

Audio Interconnect Performance: Claims Versus Laboratory Measurements

by

Robert A. Cooper

Submitted to the Department of Electrical Engineering and Computer Science

in Partial Fulfillment of the Requirements for the Degrees of

Bachelor of Science in Electrical Science and Engineering

and

Master of Engineering in Electrical Engineering and Computer Science

at the Massachusetts Institute of Technology

May 22, 1998

Author ______________ 5/20/98
Department of Electrical Engineering and Computer Science
May 22, 1998

Certified by ______________ 5/20/98
Byron M. Roscoe
Thesis Supervisor

Accepted by ______________
Arthur C. Smith
Chairman, Department Committee on Graduate Theses

Audio Interconnect Performance: Claims Versus Laboratory Measurements

by
Robert A. Cooper

Submitted to the
Department of Electrical Engineering and Computer Science

May 22, 1998

In Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Electrical Science and Engineering and
Master of Engineering in Electrical Engineering and Computer Science

ABSTRACT

With advancements in high fidelity home audio and theater, many claims, theories, ideologies, and products concerning the improvement of sound in high fidelity audio systems have hit the market, regularly confusing consumers. Often, in the quest for better sounding audio systems, audio enthusiasts succumb to false or unresearched claims of ways to improve sound quality, and in doing so, often spend a lot of money. As an example of an unresearched area, companies exist that charge hundreds to thousands of dollars for a "specialized" power cord that connects an audio component (e.g. amplifier) to the AC-line, and purports to offer improved bass response, increased dynamic range, and greater transient-delivering capability.

Another area in the high fidelity audio market that has seen relatively little research is audio component interconnects. These cables are used to connect audio components together in order to transfer the signal from one to another, such as for sending the signal from a CD player to a preamplifier. For many years, simple coaxial cable (RCA/phono connectors on both ends) was used to accomplish this task. However, in recent years, companies have surfaced that have technologies (some of which are patented) which tout improved dynamic range, imaging, clarity, or other audible quality enhancement over the simple coaxial cable.

The goal of this thesis, and the research presented in it, is to determine whether these audio interconnects have any measurable qualities which would affect the audible sound quality of an audio system. Specifically, the intent is to show whether interconnect quality/construction has an impact on sound quality and to what extent price and performance are correlated.

Thesis Supervisor: Byron M. Roscoe
Title: Technical Instructor; Director of Undergraduate Teaching Labs

Acknowledgments

Thanks are due to various people who helped me gain the idea for this thesis and who helped in the completion of it by offering guidance, assistance, equipment or just moral support.

First and foremost, I should recognize Ron Roscoe, my thesis advisor, who helped lock down the idea for this thesis and got the project going. In addition, it was he who provided the equipment that I used to conduct my tests and measurements, personal contacts to whom I went for guidance and advice, and the many references that I used for the thesis.

Secondly, I must acknowledge Dave Smith, my senior year roommate, whose many trips to the hi-fi audio store (and quest for better sound) planted the idea for this thesis. In particular, it was his desire to buy expensive interconnects and speaker wire that led me to wonder if the short length of interconnects could possibly have any audible effects on the performance of an audio system.

I wish to thank Monster Cable Products, Inc., of San Francisco, CA, for lending me all of the Monster Cable products that were tested for this thesis. Without their support, obtaining an adequate number of cables to test for an extended period of time would have been very difficult.

Thanks and love go out to my fiancé, Sharonda Bridgeforth, for the encouragement she gave me while writing my thesis and while trying to finish my final year at MIT. She is a wonderful blessing, and I look forward to our future together.

Finally, I have to thank Bryan Bilyeu and Phillip Rowe, my two roommates who not only helped me proofread this thesis, but who provided often needed distraction from all the stress of academia, and Shahram Tadayyon, who drove me all over the place whenever I asked, especially to the golf course.

Table of Contents

List of Figures & Tables

Chapter 1

Introduction

1.1 Background

In the audio industry, a noteworthy debate exists in the area of audio component interconnects (hereafter referred to as interconnects or cables). These interconnects carry the audio signal from one piece of audio equipment to another, and some assert that they affect the sonic performance of the audio system. Often, when a compact disc player or other piece of audio equipment is purchased, a pair (one for each of right and left channels) of basic interconnects is packaged with it. These interconnects, if purchased separately, are relatively inexpensive – costing two to three dollars. Their construction is simple: typically a one-meter coaxial design with a 20 – 24 gauge, multi-stranded center conductor, a braided or wrapped copper shield/ground, and RCA/phono plugs on each end.

Particularly in the last five to ten years, a handful of interconnect manufacturers have made a name for themselves by offering interconnects that are supposedly superior to basic interconnects in construction, design, and performance. The manufacturers patent their cables as the result of a new method of wire winding technology or because their design employs exotic insulation. For example, Monster Cable Products, Inc., which is a well-known interconnect and speaker cable manufacturer, produces the M550i. In addition to winning awards and top reviews[1], this product boasts "greater overall clarity, extended frequency response, lower noise floor and extended dynamic range, and improved reproduction of imaging, soundstage and depth". The advertised characteristics of the M550i include a 100% copper foil shield, 24k gold contacts, special dielectric insulation, two conductors with "multiple-gauge wire networks", and heavy duty construction that is capable of withstanding years of use.

One group of devout audiophiles suggests that cable construction and quality has a large effect on the quality of sound produced by an audio system. On the other hand, another group insists that these supposedly higher-quality interconnects do nothing more than add cost to the audio system; they believe that the cables negligibly affect the signal being passed through them. In other words, they contend that interconnects do not affect the signal enough to alter quality of the sound. While both sides have convincing and compelling points, gray areas still exist in both arguments. The side advocating the benefits of cable quality often cites listening tests in which subjects decided which cable(s) made the overall system sound better in comparison to others. However, this group has no measurements or anything else concrete to support the listening test results. Those who do not believe that interconnects affect system performance insist that because of the short length of the cables and the small frequency range of audio, the parasitic elements – series inductance and resistance and shunt capacitance – of the interconnect are of no noticeable consequence.

[1] The M550i was the winner of the Hi-Fi Grand Prix Award from AudioVideo Magazine International and was given a "unanimous, unequivocal top rating" by Home Theater Magazine.

1.2 Previous Work

Much of the work done thus far in audio component interconnection has been in the area of speaker cables. Various audio magazines have conducted tests on speaker cables, as has the Audio Engineering Society in more than one issue of their journal[2]. These magazine articles, as well as basic engineering knowledge, make it clear that it is best to be cautious when buying speaker cable. Despite the fact that people still disagree as to which type of cable is best, it is clear that the lengths of cables used to connect speakers to amplifiers – often between 15 and 30 feet in today's surround sound systems – are significant. Therefore wire should be chosen that is sized to handle the current involved in driving a speaker, low enough in resistance to avoid wasting a significant amount of power, and low enough in capacitance to avoid attenuating high frequencies or causing power amplifier instability.

The main motivation for this thesis came after reading Brent Butterworth and Al Griffin's article, "String 'Em Up", in the August 1997 issue of *Home Theater*. In this article, the authors present the results of a supposedly single-blind listening test (the listeners did not know which cable was connected to the system). The article states that, "Each panelist ranked the cables in three groups, roughly corresponding to 'OK', 'good', and 'great', and each panelist also picked a favorite." This rating scheme seems acceptable; however, in the authors' final results, there were numeric quantities for the interconnects' performance, build quality, ergonomics, features, value, and overall rating, leading one to wonder from where the numbers came. The source of the numbers is never explained, and the qualifications of performance are a bit arbitrary. For example,

[2] See Reference section for Audio Engineering Society publications concerning speaker cable tests.

in the review of AudioQuest's "Turquoise" product, "edgy" was a word used by one listener to describe the sound, while another said, "The percussion had a nice, full sound, with lots of drive." These descriptions and classifications are not at all scientific and are indeed subjective opinion. It is, therefore, the goal of the work conducted in this thesis to show scientific measurements and test results which determine whether these interconnects have any perceptible effects in audio systems.

1.3 Objective

The objective of this thesis is to evaluate various models of interconnect cables in order to determine the impact of their electrical characteristics and performance on the rest of the audio system. In particular, 11 different models of interconnect were tested and evaluated based upon their lumped parameter values, impedance, amplitude and phase response, and total harmonic distortion, crosstalk, and intermodulation distortion performance. An approximately 15-year-old Tandy Corporation interconnect was used as a reference to which all of the other cables will be compared.

In running the aforementioned tests, the following pieces of N.I.S.T. (National Institute for Standards Technology) traceable equipment were used: Hewlett Packard 4192A Low Frequency Impedance Analyzer, Hewlett Packard 34401A Digital Multimeter, Hewlett Packard 33120A Arbitrary Waveform Generator, and the Audio Precision Portable One *Plus* Analog Domain Audio Analyzer. In addition, various pieces of audio equipment were evaluated for such things as input and output impedances, so that realistic numbers could be obtained for use in frequency and phase response calculations.

1.4 Thesis Organization

This thesis is divided into three major sections. Chapter 2 provides an overview of the different pieces of test equipment, audio equipment, and interconnects that were used or tested in the various experiments. Primarily, this chapter is provided for background purposes in the event that future experimenters intend to reproduce the results presented in this thesis. Chapter 3 lays out the various electrical tests that were run on the interconnects, and finally, Chapter 4 summarizes all of the experimental findings in a qualitative manner and discusses the importance of interconnects in audio systems.

Chapter 2

Overview of Equipment Used

2.1 Audio and Test Equipment

The following audio and test equipment was used in conducting the experiments for research presented in this paper. A brief description[3] of each, with pertinent performance specifications, has been provided for background information in case one desires to reproduce the tests/results that are discussed.

Hewlett Packard 34401A Digital Multimeter: S/N US36047341, Calibrated (NIST traceable) 2/5/98 by HP

- 6½ digit, 15 parts-per-million basic DC accuracy
- AC Voltage Measurement Accuracy: ±(0.06% of reading + 0.03% of range) for 10 Hz to 20 kHz.

Hewlett Packard 33120A Arbitrary Waveform Generator: SN US36018116, Calibrated (NIST traceable) 2/10/98 by HP

- Features sine, triangle, square, ramp, and noise waveforms, a 12-bit, 40 Mega Samples/second arbitrary waveform generator, with sweep and modulation capabilities.
- 6½ digit, 15 MHz synthesized function generator
- Amplitude (into 50 Ω): 50 mV_{p-p} to 10 V_{p-p}
- Accuracy (at 1 kHz): 1% of specified output
- Flatness (sine wave relative to 1 kHz): ±1% (0.1 dB) for frequencies less than 100 kHz.

[3] Descriptions are taken from respective manufacturers data books. Refer to the References section for a listing of these books.

Hewlett Packard 4192A Low Frequency Impedance Analyzer: SN 2830J07258, Calibrated (NIST traceable) 1/28/98 by HP

- Performs network analysis and impedance analysis from 5 Hz to 13 MHz.
- Measures amplitude, phase, group delay, inductance, capacitance, resistance, impedance magnitude, conductance magnitude, etc.
- Capacitance accuracy: 0.15% from 0.1 pF to 199 mF
- Inductance accuracy: 0.27% from 0.01 nH to 1000 H
- Resistance accuracy: 0.15% from 1.00 Ω to 1.00 MΩ

Audio Precision Portable One, Analog Domain: SN P1P-52083, Calibrated (NIST traceable) 3/13/98 by Audio Precision

- A comprehensive two-channel audio test set
- Measurement functions include: level, noise or signal-to-noise ratio, phase, amplitude, impedance, total harmonic distortion plus noise, intermodulation distortion, crosstalk, and AC impedance.
- Since this was the main piece of test equipment used, its spec sheets from the User's Manual have been reproduced in Appendix B.

Teac EQA-220 Graphic Equalizer

- 2-channel, 10-band, ±12 dB boost/cut
- Center frequencies: 30 Hz, 60 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, and 16 kHz
- Input impedance: 47 kΩ at 0.3 V nominal level
- Output impedance: 1 kΩ at 6 V maximum level
- Frequency Response: 10 Hz – 100 kHz, ±1 dB

Apt Corporation "Holman" Pre-amplifier

- Old piece of equipment – specs unknown

Figure 2-1 shows output impedance measurements taken on the Teac EQA-220 equalizer and Apt pre-amplifier.

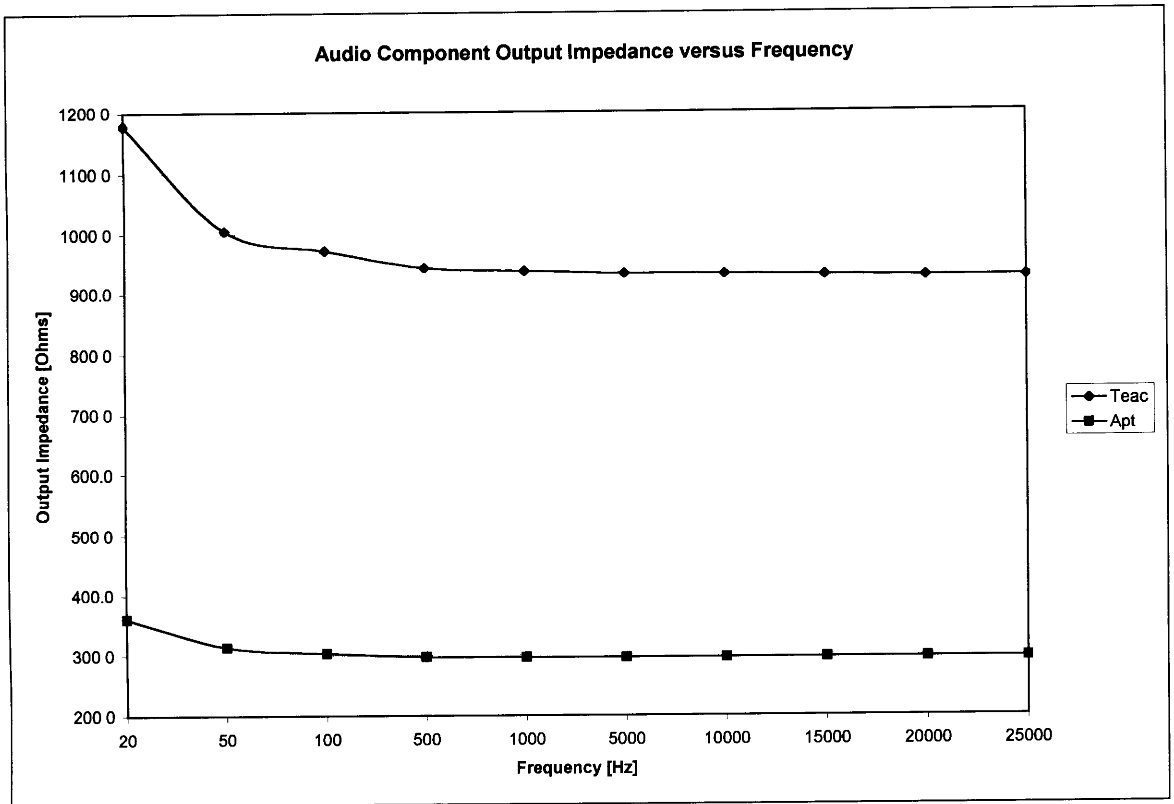

Figure 2-1: Audio Component Output Impedances Versus Frequency

The output impedance measurements were measured using the HP34401A DMM, the HP33120A AWG, and a resistor selector box. The open circuited (unloaded) output voltage was taken (using a set input), and then the output was loaded with a known value of resistor using the resistor selector box. Then, a loaded output voltage measurement was taken. The resulting output impedance was found by using the following equation:

$$R_{out} = \frac{R_{load} \cdot V_{out-unloaded}}{V_{out-loaded}} - R_{load} . \qquad \textbf{(2.1)}$$

2.2 Audio Interconnects

The audio interconnects tested varied somewhat in geometry, but greatly in price. For example, the "reference" interconnect was similar in construction to those included with audio equipment, costing a couple of dollars. This reference cable was about 15 years old, with basic nickel- or zinc-plated connectors that were somewhat dirty and oxidized. Likewise, the wire was of a basic coaxial design – the center conductor was a small gauge and the return was a braided or wrapped copper shield return with no EMI foil shielding (foil shielding is found in most of the interconnects tested).

The top of the line product that was tested was the Monster Cable M1000i, one of Monster's elite audiophile cables, selling for $129.95 per two-meter pair. The M1000i was constructed of two identical, twisted-pair conductors (for signal and return), a 100% foil shield, 95% braided copper shield, 24k gold contacts for better conductivity, and, among other features, specially wound wire networks (see numbers 11 and 12 in Figure 2-2) which separately carry low, middle and high frequencies. See Figure 2-2 for a diagram of the M1000i's construction.[4] All of Monster Cable's other interconnects included some of these features, although only the Interlink 800, M850i and M1000i included both the copper and the foil shielding.

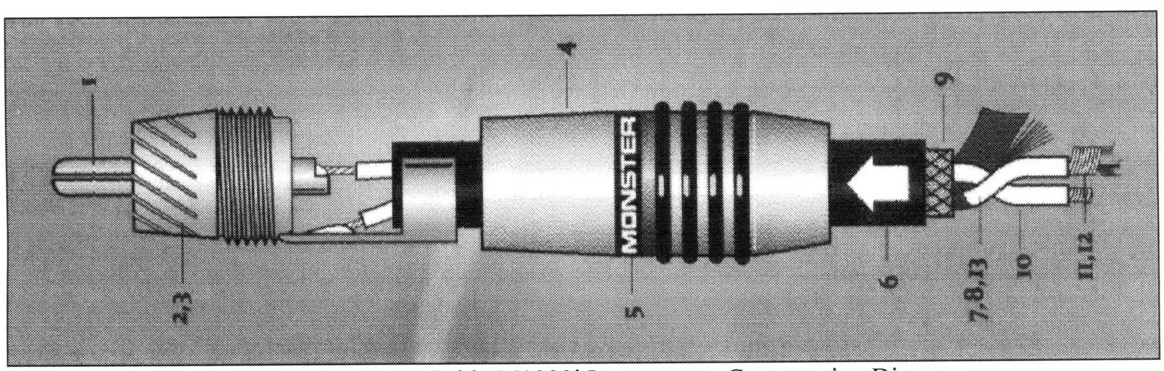

Figure 2-2: Monster Cable M1000i Interconnect Construction Diagram

[4] Monster Cable M1000i information taken, and diagram reproduced, from its retail packaging.

The following items list the cables tested and their physical characteristics.[5] All cables tested were two meters (6.6 feet) in length, unless otherwise noted. Prices are shown strictly for comparison purposes.[6]

- *Tandy Corporation "Reference" Cable (1.82 meter length) – model number and price unknown:* Coaxial design with multistranded center conductor, braided shield/return, and nickel or zinc RCA connectors.

- *Radio Shack Cat. #42-2605 (1.82 meter length) – $10.95*: Coaxial design with multistranded center conductor, braided copper shield/return, and gold plated RCA connectors

- *Monster Cable Interlink 100 – $12.95:* Approximately the same construction as the Radio Shack product.

- *Monster Cable Interlink 250 – $23.95:* 24k gold plated split-tip center pin, heavy duty RCA connector, 100% foil shield that is grounded at the source, and two balanced twisted-pair conductors.

- *Monster Cable Interlink 400 Mk II – $41.95:* In addition to the I250's characteristics, two different types of special dielectric insulation material, dual solid core center conductors, and separately wound low and high frequency wire networks. These networks supposedly bundle two separate wire windings into one larger wire (for example, see numbers 11 and 12 in Figure 2-2). Monster Cable claims that these separate networks better carry different frequency bands for "precise imaging and natural tonal reproduction."

- *Monster Cable Interlink 800 – $83.95:* In addition to the I400 Mk II's characteristics, silver content solder joints, 100% foil and 95% braided copper shield.

- *Monster Cable Interlink CD – $30.95:* Same as I400 Mk II's characteristics, but an older design.

- *Monster Cable M350i – $49.95:* Same as the I400 Mk II's characteristics, in a newer design, with seemingly heavier gauge conductors, minus one of the special dielectric insulating materials.

---

[5] Characteristics taken from the respective interconnects' retail packaging. The technologies used in Monster's interconnects were not explained in technical detail on the packaging, and are thus not discussed in this paper.

[6] The prices shown for most of the Monster Cable products were obtained from retail store chain Tweeter, Etc.'s Monster Cable displays. Prices for the I250, I400 Mk II, I800, and ICD were approximated from the price listings on Monster Cable's website, www.monstercable.com.

- *Monster Cable M550i – $69.95:* Same as the I800's characteristics, minus the braided copper shield. Possible heavier gauge conductors.

- *Monster Cable M850i – $99.95:* Same as the M550i's characteristics, plus braided copper shield.

- *Monster Cable M1000i – $129.95:* Same as the M850i's characteristics, but with three multiple-gauge separately wound networks (instead of two), for low, middle, and high frequencies, and an improved RCA connector.

Chapter 3

Interconnect Measurements

3.1 Lumped-parameter Model

The lumped-parameter model for the cables' resistance, capacitance, and inductance characteristics was used to calculate the theoretical magnitude and phase response of the interconnects, with specific load and source impedances. It should be noted, however, that this lumped-parameter model, which is shown in Figure 3-1, is only approximate and therefore has been verified via other tests. See sections 3.2, 3.3, and 3.4 for these other tests, which include impedance, magnitude, and phase response (respectively).

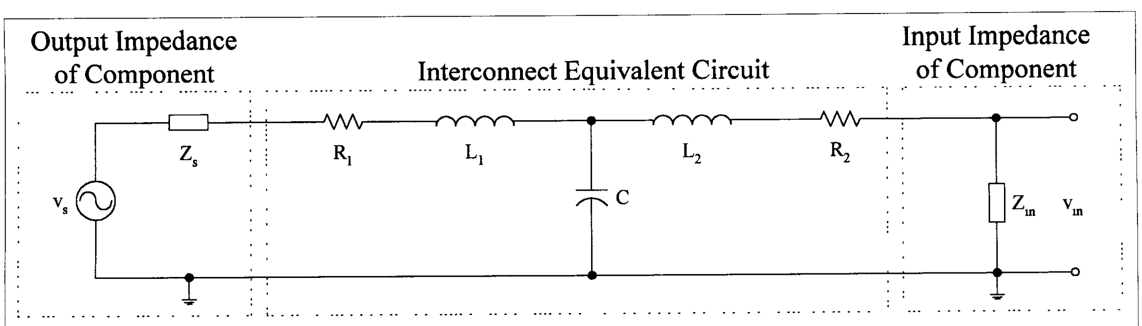

Figure 3-1: Lumped-parameter Model of the Interconnect Characteristics, Shown with Source and Load Impedances

An explanation of the component variables follows. Z_s is the output impedance of the audio component from which the signal is being sent. R_l and L_l are the resistance and inductance of the center conductor of the interconnect, while R_2 and L_2 are the resistance and inductance of the ground (return) wire. Technically, R2 and L2 exist in the ground connection between the load impedance, Z_{in}, and the capacitor. However, after running simulations on both circuits, it was found that over the frequency range 10 Hz – 50 kHz, the choice of placement for R_2 and L_2 made no difference in magnitude or phase response. However, with higher frequencies, R_2 and L_2 placed in the ground led to responses that were monotonically decreasing, rather than exhibiting spikes near 10 MHz (see Chapter 3, section 3.1.1 and 3.1.2), since the inductance L_2 has no effect on the circuit and thus no L_2-C resonance occurs. C is the lumped-capacitance of the interconnect, and is thus the most inaccurate value of measurements, since the capacitance is distributed along the length of the cable, while the measurement is taken across the center conductor and shield at one end of the cable. Finally, Z_{in} is the input impedance of the audio equipment to which the interconnect is delivering the signal.

The Hewlett Packard 4192A Low Frequency Impedance Analyzer was used to obtain the values for R_1, R_2, L_1, L_2, and C. In order to measure C, the interconnect was connected to the analyzer, with the center conductor connected to the "high" side and signal return to the "low" side, and the other end of the interconnect left open-circuited so as to quantify the center conductor-to-signal return capacitance. For the inductance and resistance measurements, the end of the interconnect not connected to the analyzer was shorted – the center conductor was connected directly to the return so that the center conductor and return wire resistance and inductance would be determined in one measurement. The resulting inductance and resistance readings given by the analyzer were, therefore, the values for the entire length of the cable twice – down the center conductor and back through the return. Therefore, the measurement returned by the analyzer was divided by two and set equal to R_1 and R_2 (or L_1 and L_2). For example, if the analyzer read 0.30 Ω, then $R_1 = R_2 = 0.15$ Ω – a valid approximation, since for most of the cables, the center conductor and return were identical wires in a twisted pair configuration. The shields of the cable with twisted pair conductors were only grounded at one end (the side that should be connected to the source), and therefore, did not add impedance to the cable. The resulting values were then recorded for use in calculating the magnitude and phase plots, which are discussed in the following text.

The transfer function for the lumped-parameter circuit shown in Figure 3-1 is

$$\frac{V_{in}}{V_s} = \frac{Z_{in} Z_C}{(Z_{in} + R_2 + Z_{L2})(Z_C + R_X + Z_{L1}) + Z_C(R_X + Z_{L1})}, \quad \textbf{(3.1)}$$

where $R_X = Z_s + R_1$. For simplicity, it will be assumed for the remainder of the text that Z_s is purely resistive.[7] If it is assumed that Z_{in} has a resistive and a capacitive component, then $Z_{in} = R_Y \| Z_Y$, where Z_Y is the impedance of the capacitive component of Z_{in}. Substituting this into equation (3.1), it follows that

$$\frac{V_{in}}{V_s} = \frac{R_Y Z_Y Z_C}{R_Y Z_Y (Z_C + R_X + Z_{L1}) + (R_Y + Z_Y)[(R_2 + Z_{L2})(Z_C + R_X + Z_{L1}) + Z_C(R_X + Z_{L1})]}. \quad \textbf{(3.2)}$$

After much algebra, letting ***Re*** equal the real part of the denominator and ***Im*** equal the imaginary part, it follows that the numerator is equal to R_Y, and that

$$\begin{aligned} \mathrm{Re} = R_2 + R_X + R_Y - \omega^2 (L_1 R_Y C + L_2 R_Y C_Y + C C_Y R_2 R_X R_Y + L_2 R_X C \\ + L_1 R_2 C + L_1 R_Y C_Y) + \omega^4 C C_Y L_1 L_2 R_Y \end{aligned} \quad \textbf{(3.3)}$$

and

---

[7] Often, power amplifier output impedance rises with frequency as a result of decreased feedback. However, the two pieces of line-level audio equipment examined in this thesis exhibited flat output impedance from approximately 100 Hz to 25 kHz (see Figure 2-1).

$$\text{Im} = \omega(CR_X R_Y + C_Y R_2 R_Y + L_2 + CR_2 R_X + C_Y R_X R_Y + L_1) - \omega^3 (CC_Y L_2 R_X R_Y + CC_Y L_1 R_2 R_Y + L_1 L_2 C). \tag{3.4}$$

Consequently,

$$\left|\frac{V_{in}(\omega)}{V_s(\omega)}\right| = \frac{R_Y}{\sqrt{(\text{Re})^2 + (\text{Im})^2}} \tag{3.5}$$

and

$$\angle H(\omega) = -\tan^{-1}\left(\frac{\text{Im}}{\text{Re}}\right). \tag{3.6}$$

A simple check for the transfer function is to set ω equal to zero and verify the result with what would be expected at DC (inductors short circuited and the capacitors open circuited). Setting $\omega = 0$, it follows that

$$\left|\frac{V_{in}(0)}{V_s(0)}\right| = \frac{R_Y}{\sqrt{(R_X + R_2 + R_Y)^2 + (0)^2}} = \frac{R_Y}{R_X + R_2 + R_Y} \tag{3.7}$$

because ***Im*** is purely a function of ω, and equals zero. The answer is the expected result – a simple voltage divider relationship.

3.1.1 Matlab Simulation

The transfer function and phase response given in equations 3.5 and 3.6, respectively, are good candidates for use in Matlab simulations. Using these equations and some of the measured values (shaded) of interconnect resistance, capacitance, and inductance given in the following table, Table 3-1, Matlab was utilized to find the ideal response of the system given in Figure 3-1.

Cable	Resistance $R_1 + R_2$ (Ω)	Inductance $L_1 + L_2$ (μH)	Capacitance C (nF)
Reference	0.210	0.68	0.1966
Radio Shack	0.234	0.85	0.1371
Int 100	0.256	1.23	0.1598
Int 250	0.378	1.98	0.1822
Int 400	0.137	1.34	0.3328
Int 800	0.122	1.18	0.2853
Int CD	0.418	1.19	0.3328
M350i	0.266	1.68	0.2413
M550i	0.116	1.37	0.3411
M850i	0.112	1.35	0.3386
M1000i	0.073	1.36	0.3655

Table 3-1: Interconnects' Lumped Parameter Values at 10 kHz

This table gives all of the lumped parameter measurements taken on all of the interconnects that were used in the tests. The listings and description of each interconnect is given in Chapter 2. The Hewlett Packard 4192A was used to take each of the above measurements for R, L, and C at 1 kHz, 10 kHz, 25 kHz, and 50 kHz. Values at 10 kHz were used. See Chapter 2 for a description of the HP4192A.

The values for R_1, R_2, L_1, and L_2 were worst case values from actual interconnect measurements (see shaded boxes in Table 3-1 above) – $R_1 = R_2 = 0.209\ \Omega$ and $L_1 = L_2 = 0.99\ \mu H$. The value chosen for the capacitance, C = 0.3386 nF, was nearly the highest value of all the cable measured, and it was the worst-case measurement at the time that these simulations were run. The actual worst-case capacitance measured was 0.3655 nF, which would presumably add 7.4% error over using C = 0.3386 nF (i.e. a 7.4% lower break point frequency).

The following magnitude and phase plots in Figure 3-2 are the result of the Matlab simulations with Z_{in} equal to a purely resistive 100 kΩ load and Z_s set to an ideal value of zero ohms. Zoomed plots that cover only the audible frequency range have been provided since it is the range of interest in dealing with audio system performance. As a note: Matlab wraps the phase; therefore, any discontinuities in the phase response are places where the phase falls too low to fit into the –180° to 180° y-axis values.

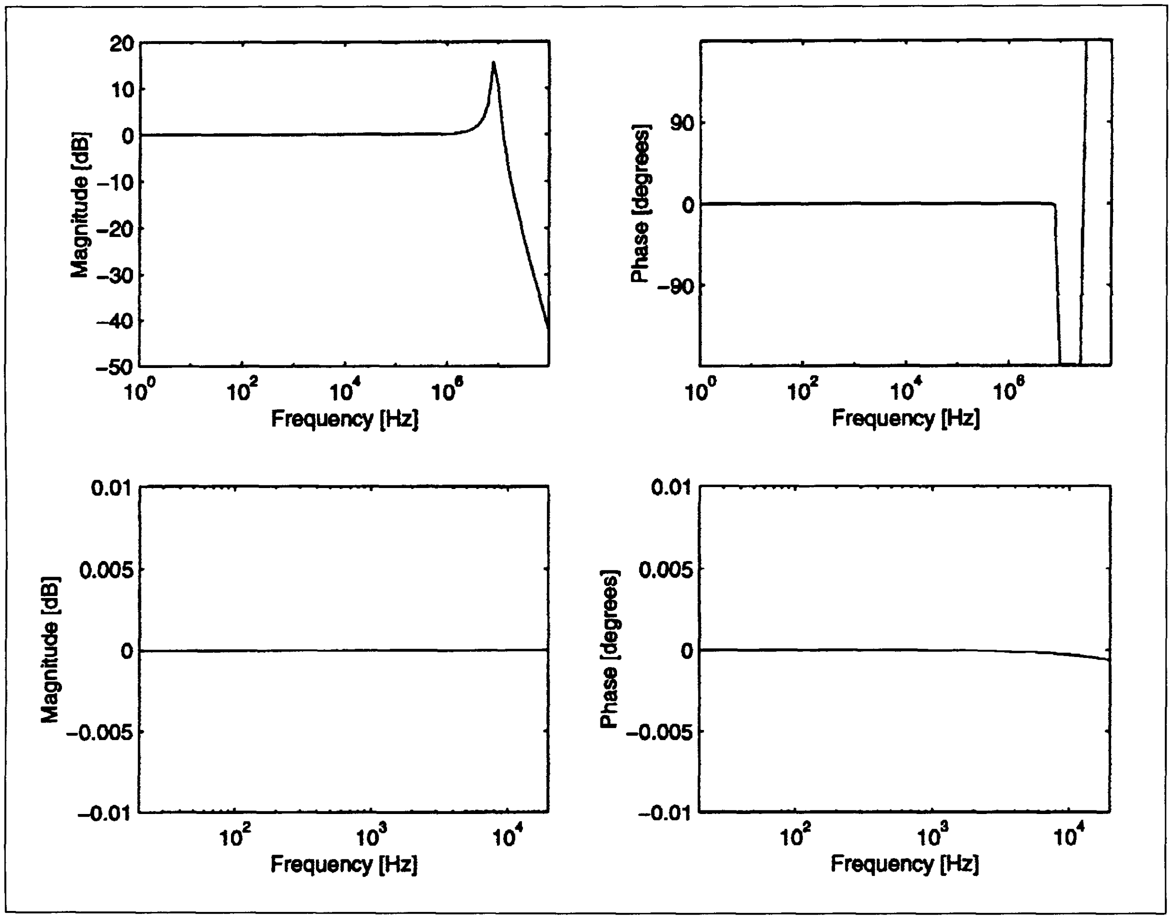

Figure 3-2: Matlab Magnitude and Phase Plots for System Under Ideal Conditions, Plus 20 Hz – 20 kHz Zoomed Plots

Figure 3-2 shows that the system response is flat over the audible frequency range. Furthermore, neither the magnitude nor phase deviates from flat until frequencies above 1 MHz. However, these simulations were performed using the ideal conditions of zero source impedance and very high input impedance of 100 kΩ. A more relevant simulation would be one that embraces a more worst-case scenario. One such simulation that better approximates real-world situations is to use a source impedance that is closer to that found in a piece of audio equipment. A source impedance, Z_S, equal to 1 kΩ is a more realistic value since, during output impedance measurements, the Teac EQ-220A Graphic Equalizer exhibited approximately this value over most of the audible range[8]. Therefore, this value for Z_s was added to the circuit model. In addition, the input impedance Z_{in} was changed to mirror a worst-case load.

The Electronics Industries Association (E.I.A.) has published guidelines on standard loads to be used in audio component tests[9]. One guideline is that audio components should be loaded with a 1 kΩ resistor in parallel with 1000 pF capacitor during testing, called the IHF (for the Institute of High Fidelity, which created the testing guideline) standard load. Therefore, one more simulation was conducted with Z_{in} set equal to this standard load of 1 kΩ in parallel with 1000 pF. This can be considered a worst-case simulation for the system, since the E.I.A.'s recommendation for input impedances is 100 kΩ minimum, and none of the audio equipment input impedances tested for this thesis even approached 1 kΩ over most of the audible range. Figure 3-3 shows the 0 – 100 MHz and 20 Hz – 20 kHz results of this IHF standard load simulation with Z_s set equal to 1 kΩ, as discussed in the previous paragraph.

---

[8] The actual impedance was approximately 930 Ω over most of the range, going as high as 1178.8 Ω at 20 Hz. See Figure 2-1 for a plot of output impedance versus frequency.

[9] *E.I.A. Standard RS-490: Standard Test Methods of Measurement for Audio Amplifiers*, Electronic Industries Association, November, 1981. See Appendix A for a listing of pertinent standards.

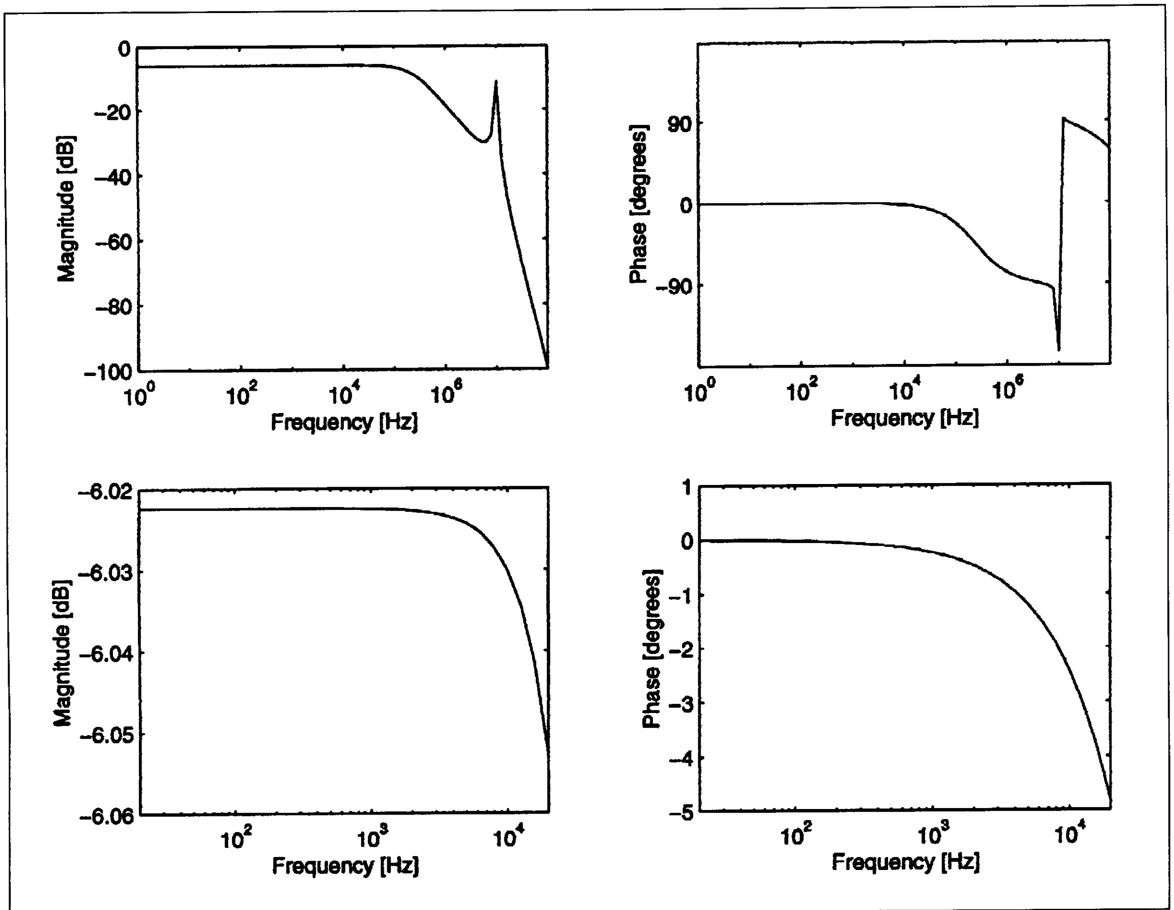

Figure 3-3: Matlab Magnitude and Phase Plots for System Using IHF Standard Load Values, Plus 20 Hz – 20 kHz Zoomed Plots

In this worst-case scenario, there are a few points of interest. According to these simulations, the magnitude of the system is approximately 6 dB down, compared to the previous simulation shown in Figure 3-2, right from the beginning. However, this -6 dB level is due to the output impedance, Z_S, of 1 kΩ forming a voltage divider with the 1 kΩ input resistance of the IHF standard load values. This divider relationship caused the 6 dB of loss. Therefore, the other ~0.022 dB (see zoomed magnitude plot) is due to the 0.418 Ω of cable resistance. This very small loss is constant over most of the audible range, so it would unnoticeable to the human ear since there are no magnitude variations. Near 10 – 20 kHz, though, the response falls another ~0.03 dB. This change is due to capacitance of the IHF simulated input (load) impedance starting to make a measurable difference in the resistor/capacitor parallel combination. The same reasoning can be applied to the phase response. Therefore, over the audible frequency range, the cable can be taken to have a flat response; the capacitive component of the input impedance (which is higher than would ever exist in audio components) is the culprit disturbing the response in the 20 Hz – 20 kHz range.

3.1.2 ICAP/4 Spice Simulation

Using Intusoft's ICAP/4Windows (Student Version) Circuit Design Software, the circuit in Figure 3-1 was simulated, using R, L, and C values obtained as explained above, in order to find the theoretical response of the system under various situations, and as a check for the Matlab simulations. The circuit in Figure 3-1 was entered into the software identically as shown, except that Z_s was assumed to be resistive (as noted earlier) and was lumped together with R_l, and Z_{in} was assumed to be a resistance in parallel with a capacitance. Figure 3-4 shows the system's response with Z_s assumed to be zero (an ideal case), and Z_{in} to be 100 kΩ in parallel with no capacitance – the recommended standard input impedance for audio equipment[10].

[10] *Preferred Voltage and Impedance Values for the Interconnection of Audio Products* – Consumer Products Engineering Bulletin No. 6-A, Electronic Industries Association, July, 1974.

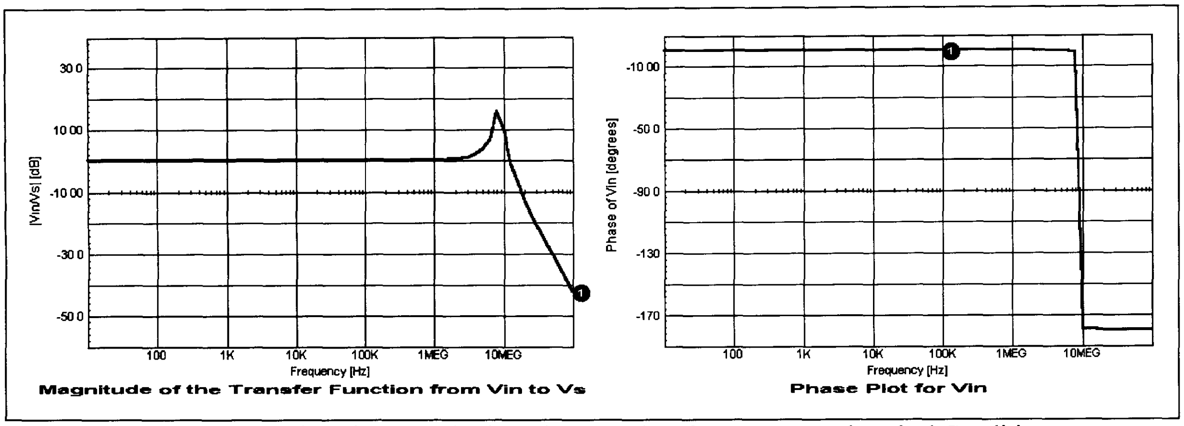

Figure 3-4: ICAP/4 Spice Magnitude and Phase Plots for System Under Ideal Conditions

As can be seen, the magnitude and phase are flat until nearly 1 MHz – well beyond the audible range. Referring back to Figure 3-2, the magnitude closely agrees with the Matlab simulation. Obviously, the real world is not ideal, especially concerning the approximation that output (source) impedance is zero. As mentioned earlier, the Teac EQ-220A had a measured output impedance of approximately 1 kΩ. Therefore, a more realistic simulation would be with a source impedance of 1 kΩ (to model the EQ-220A's output impedance), and the same 100 kΩ input impedance which models the E.I.A.'s recommendation for input impedance for audio components. Figure 3-5 shows the results of the simulation using these values and the previously discussed cable lumped-parameter values.

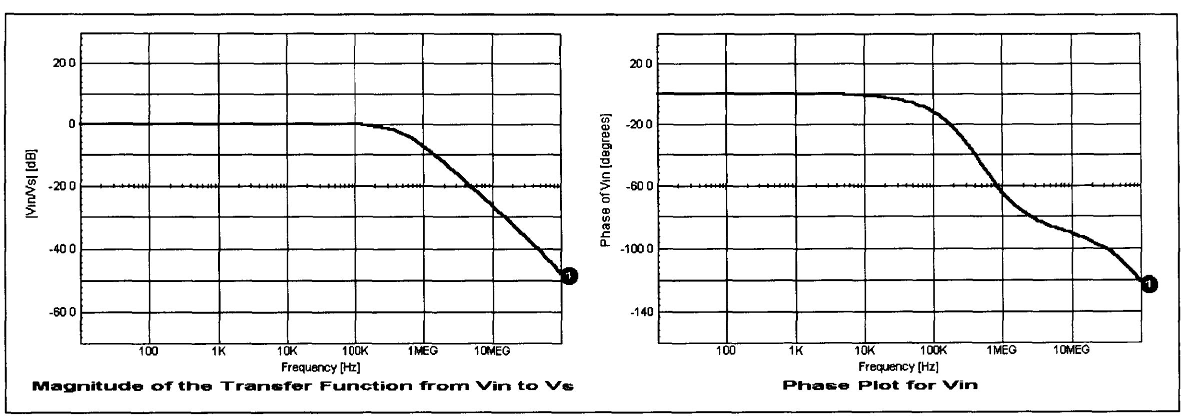

Figure 3-5: ICAP/4 Magnitude and Phase Plots for System Using $Z_s = 1$ kΩ

In this case, the source impedance actually damped out the natural self-resonant frequency of the cable (the peak at approximately 8 MHz in Figure 3-2). However, the system begins to lose its flatness at around 50 kHz, and is down 3 dB at nearly 500 kHz. The phase is down ~4° at 20 kHz. However, this is insignificant when one considers all of the phase added in other parts of audio systems – namely, the speakers. Therefore, the simulations thus far give no indication that the interconnects' performance affects the audible quality of audio systems.

Figures 3-6 and 3-7 are the resulting plots of simulations run with Z_s = 1 kΩ and Z_{in} equal to the IHF standard load. These plots mirror the Matlab simulations that resulted in Figure 3-3, except that Figure 3-7 was taken over the range from 10 Hz to 50 kHz, rather than 20 Hz to 20 kHz as in the Matlab simulations. The simulations were run for comparison purposes with the Matlab results.

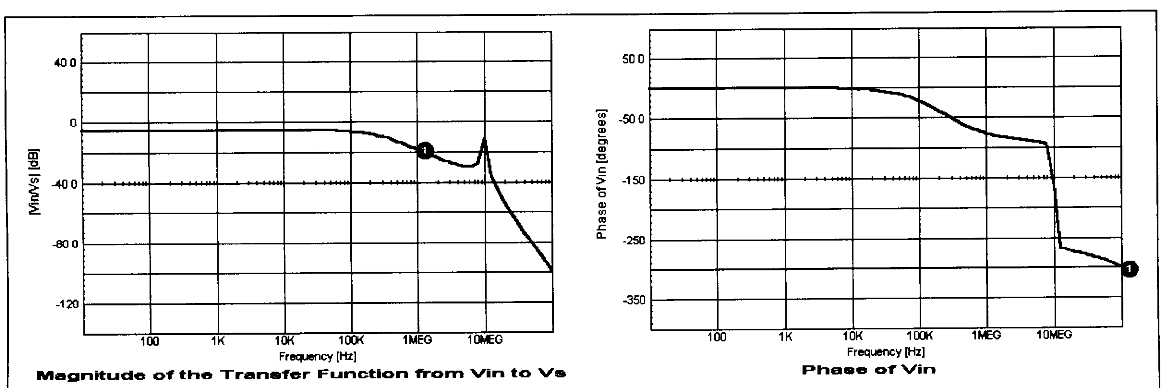

Figure 3-6: ICAP/4 Magnitude and Phase Plots for System Using IHF Standard Load

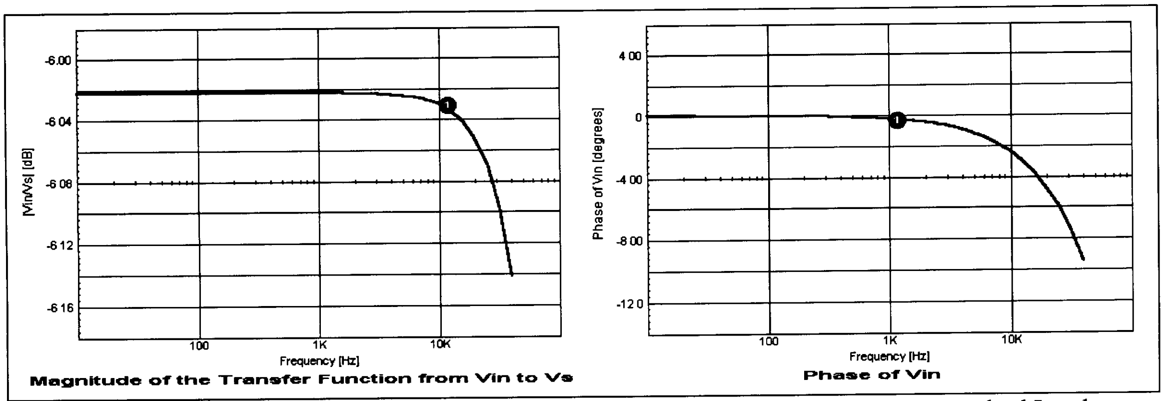

Figure 3-7: ICAP/4 Zoomed Magnitude and Phase Plots for System Using IHF Standard Load

These figures closely agree with Matlab. For example, the magnitude is down about 0.02 dB at 20 kHz, and the phase is down approximately four degrees. Again, the roll-offs in the responses are due to the 1000 pF capacitive component of Z_{in}, and are not attributable to the response of the cable itself.

3.2 Interconnect Impedance Measurements

Impedance measurements using the Audio Precision Portable One were taken so as to obtain plots of interconnect impedance verses frequency. These measurements were very useful since they were a reality check for the calculations and simulations presented in the previous two sections. Figure 3-8 shows the plots for all of the various interconnects that were available for testing.

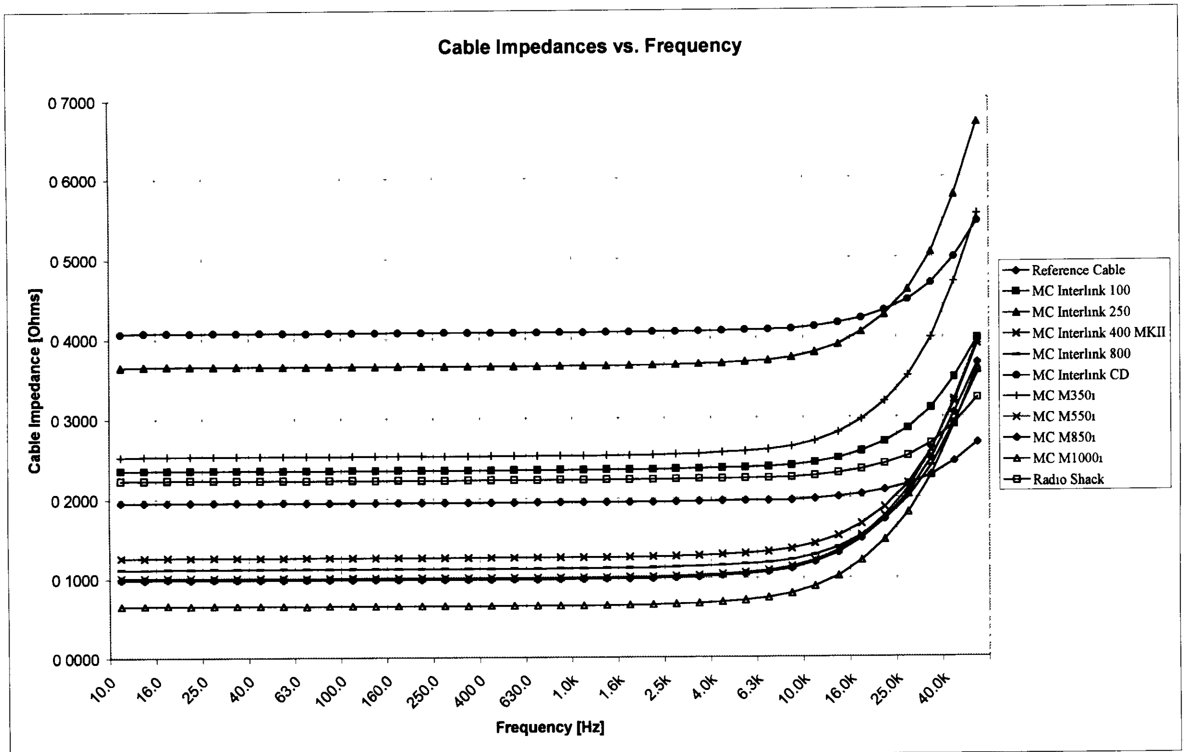

Figure 3-8: Interconnect Impedances versus the Logarithm of Frequency

As can be seen, half of the interconnects' impedances generally fall below the "reference", and half above. It is interesting to note that the half that are below the reference actually climb above the reference at approximately 25 kHz. This is due to the reference cable having the lowest inductance of all the cables tested; inductive impedance becomes significant at higher frequencies since $Z_L = j2\pi fL$. Regardless, all of the impedances remain below seven-tenths of an Ohm over the frequency range 10 Hz – 50 kHz. Since the output impedance of audio equipment is to be no greater than 10 kΩ and the input impedance no greater than 100 kΩ, according to the E.I.A.[11], then the resultant loss due to the interconnect's added impedance to the system is negligible. Even if the input impedance of the audio equipment falls below 100 kΩ, the interconnect impedance

[11] Consumer Products Engineering Bulletin No. 6-A, Electronic Industries Association, July, 1974.

still does not matter, since for 0.43 Ω (the Interlink CD's approximate impedance at 20 kHz) to have a noteworthy impact on the system, the input impedance would have to be below 100 Ω. For example, if the a CD player had 0.0 Ω of source impedance and was connected through two meters of Monster Cable Interlink CD to an amplifier with 50 Ω of input impedance, then the interconnect would cause a loss of 8.53 mV for every volt of input voltage. In other words, the interconnect would cause a loss of 0.074 dB over an ideal interconnect that results in 0 dB of loss. This small change in amplitude would not be perceivable by the ear. In fact, 3 dB is commonly assumed to be the smallest difference an untrained listener (1 dB for a trained listener) can detect.

3.3 Amplitude

The amplitude measurement is closely related to impedance, since the interconnect only affects the voltage received at the scope or analyzer input as a result of a voltage divider with the input impedance. Consequently, assuming a fairly accurate lumped-parameter model, the amplitude measurements should not deviate significantly from the Matlab and Spice predictions. In fact, it turned out that none of the interconnects tested in the amplitude measurements exhibited any unexpected response or roll-off.

The amplitude measurement, and all of the rest of the measurements discussed in the sections that follow, was conducted in the following way: the Audio Precision instrument was set for 40 Ω unbalanced output impedance and 1/3 octave measurement intervals. Then, a reference test was conducted in which the response of the two XLR-to-phono jacks (connected by an RCA-RCA adapter plug) were tested – the generator output was connected to an XLR-to-phono that was linked to the other phono-to-XLR via the

RCA-RCA, which was then connected to the analyzer input. The purpose of this reference test was to obtain the response of the XLR-to-phone connectors, so that they could be "normalized away" once the response of the two XLR-to-phono cables and interconnect under test (IUT) was obtained. For example, at 10 Hz, the reference (baseline) measurement was –0.02 dBV and the Monster Cable Interlink 100's measurement was –0.03 dBV. Therefore, the I100 actually had a response that was down 0.01 dB at 10 Hz. Not all of the interconnects were tested. Rather, going up the product line, approximately every other interconnect was used for testing. The reason for this is that from one product to the next, there was not a big change in construction, and using each yielded test results that showed insignificant changes in performance between two subsequent model numbers. As such, the following interconnects were used for the amplitude, phase, noise, total harmonic distortion plus noise (THD+N), and intermodulation distortion (IMD) tests: reference, MC I100, MC I400 Mk II, MC I800, MC ICD, MC M550i, MC1000i, and the Radio Shack product.

After running the Matlab and Spice simulations, the amplitude measurement was uninformative – the measurement results of the IUTs never deviated from the reference measurement by more than ±0.01 dB. As a result, no plots have been provided since all of the responses would overlap each other and no interesting visual information would result. To give this tolerance some meaning, it is interesting to note that loudspeakers are often specified to have some frequency response (say 25 Hz – 21 kHz, for example), with a magnitude tolerance of ±3 dB (some of the highest quality speakers are specified at ±1 dB). In other words, the speaker will have a magnitude response that is 0 dB centered, which may deviate from that center by as much as ±3 dB. Therefore, a change in the system of 0.01 dB due to the interconnects is negligible compared to this wide variation in loudspeaker response. Furthermore, a comparison between the actual responses of the interconnects themselves (neglecting the reference measurement) shows that they all exhibit nearly identical responses, and therefore switching from cable to cable would yield nearly identical frequency response.

3.4 Phase

The phase response tests produced as little useful information as the amplitude tests. A phase plot is provided in Figure 3-9 to show how close the phase measurements were to baseline reference. The response for only two cables has been provided because any more cable phase plots would clutter the graph and would yield no additional helpful information since all of the cable phase responses were nearly identical.

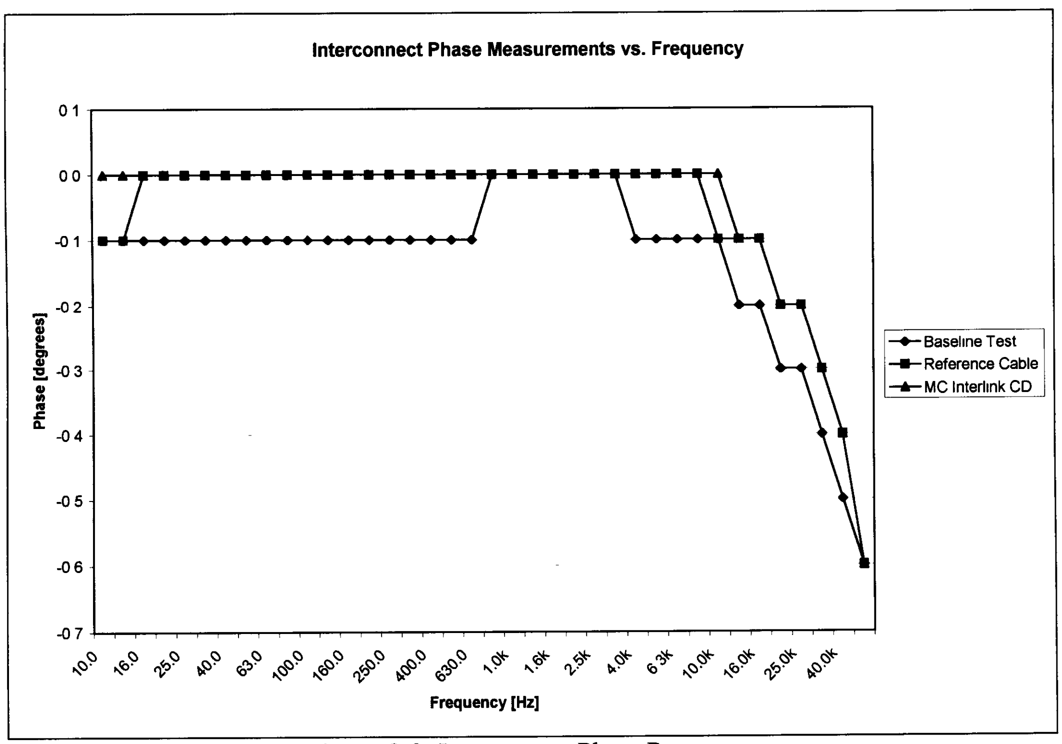

Figure 3-9: Interconnect Phase Responses

The phase tests were run on the Audio Precision Portable One from 10 Hz to 50 kHz, using 1/3 octave measurement intervals. It turns out, as seen in Figure 3-9, that the phase response tests yielded interconnect performance of –0.0°/+0.1° from baseline over the entire frequency range.

3.5 Total Harmonic Distortion and Noise (THD+N)

The total harmonic distortion plus noise (THD+N) tests yielded somewhat more interesting results. In this case, THD+N was measured against frequency (10 Hz – 50 kHz), with the reference (baseline) test being performed with the XLR-to-phono connectors and RCA-RCA plug as in the previous two tests discussed in sections 3.3 and 3.4. Then, the RCA-RCA plug was removed and the interconnect under test was put in its place.

The plot in Figure 3-10 on the following page shows the results of all the THD+N tests. The Audio Precision instrument was set for medium integration speed, rather than fast, in order to yield more accurate results. The bottom (lowest level) plot is the reference measurement, labeled baseline test. All of the interconnect measurements fall at, or above, this reference level, with the one exception of the M1000i at 3125 Hz. This discrepancy is likely due to the selected integration speed of the Portable One and the randomness of white noise in the environment. For instance, at the period of time when the Audio Precision instrument was measuring the THD+N performance of the M1000i at 3125 Hz, some of the noise samples may have been slightly lower in magnitude than when the reference measurement was taken.[12] If the measurement falls on the same point

[12] For a discussion of white noise, refer to a textbook dealing with signals and systems or discrete time signal processing.

as the reference (e.g. the Radio Shack product, MC I100, and MC M1000i at some frequencies), then the cable is adding negligible THD+N to the system at that particular frequency because the cable and reference measurements have the same value.

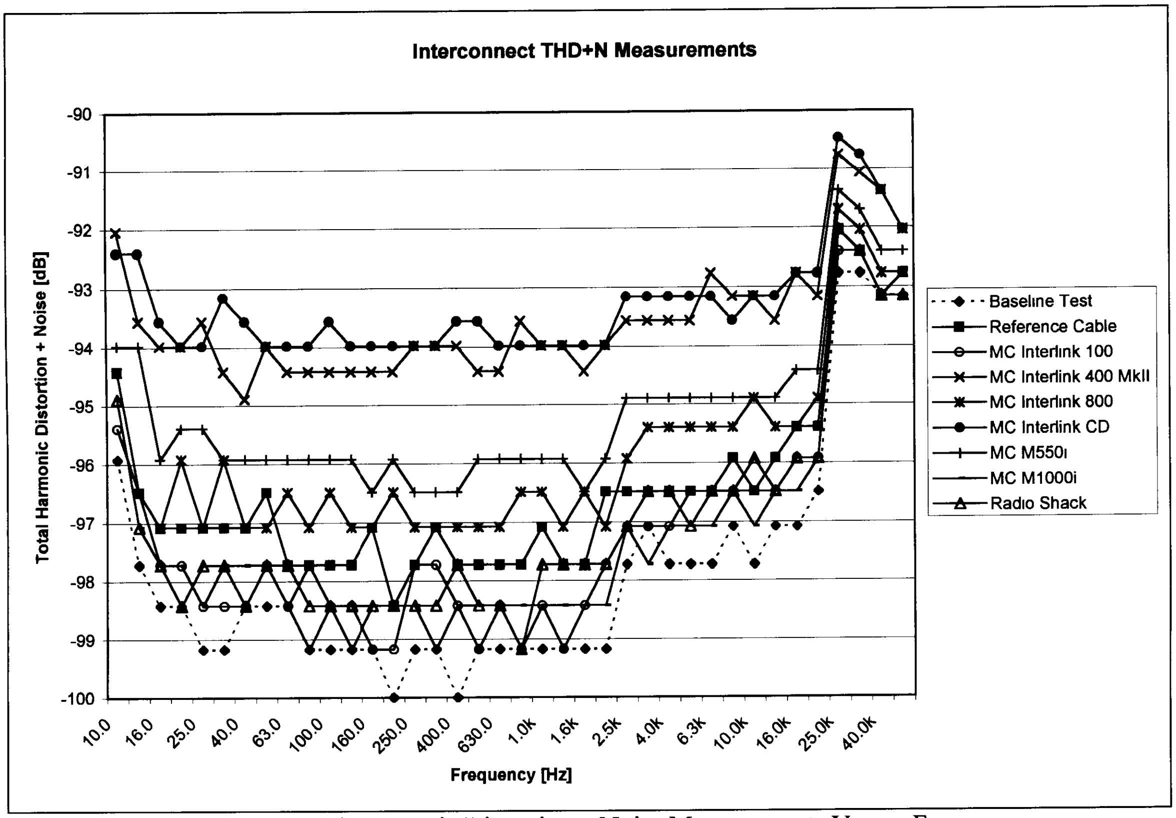

Figure 3-10: Total Harmonic Distortion + Noise Measurements Versus Frequency

As Figure 3-10 shows, most of the cables fall in a general grouping between –100 dB and –95.92 dB over most of the audible range. However, two interconnects fall outside that range – the MC Interlink CD and MC Interlink 400 Mk II. This result – that both interconnects exhibit approximately similar THD+N performance – is not too surprising since the ICD appears to be an earlier model of, or of the same construction as, the 400 Mk II. The performance of the I100 and Radio Shack interconnects were noteworthy, since neither made use of a 100% foil shield.

Consequently, the THD+N test gives one possibility as to why some cables are believed to sound better that others. However, in this case, it is not possible to find a price/performance correlation since the two cheapest and the most expensive interconnect tested all exhibited the same average THD+N performance over the audible frequency band (-97.72 dB average) and over the entire test bandwidth (-97.08 dB average). Furthermore, the issue of whether the ear can actually hear the difference between a reference system and the same system with 6 dB of noise added to it arises when determining the cable's effect on sound quality. In fact, a closer examination into what these results mean lead to the realization that is unlikely a listener would ever hear this distortion or noise. The threshold of pain is approximately 120 dB_{SPL}. Therefore, if one was listening to music at 120 dB_{SPL} peak, the noise/distortion floor would be down below 30 dB_{SPL}, since Figure 3-10 shows that the distortion and noise is down 90 dB below the signal level of 1 VAC. Because background noise levels are well above 30 dB_{SPL} (background noise in an anechoic chamber may approach this low level) the noise/distortion would not be perceivable.

3.6 Noise

The noise measurements were made in the exact same manner as the THD+N measurements. Again, the Audio Precision instrument was set on medium speed integration. Figure 3-11, below, shows the results of the noise measurements.

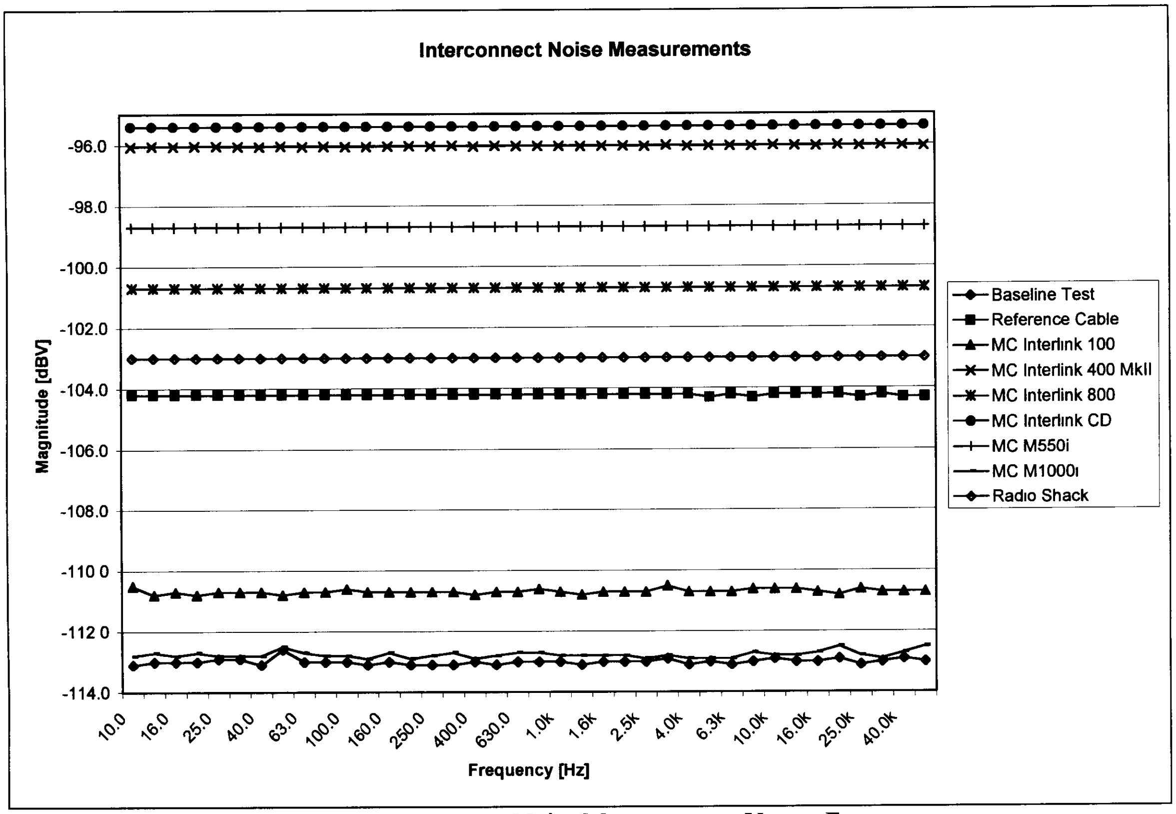

Figure 3-11: Interconnect Noise Measurements Versus Frequency

The noise ends up being (nearly) flat with frequency because it can be considered white noise, which has equal energy per Hertz. It turns out that the Monster Cable M1000i exhibited the best noise performance – adding less than half of a decibel of noise (over baseline levels) to the system. Following closely behind the M1000i is the Interlink 100, which added less than 3 dB of noise to the system. Here again, as in the THD+N test, the Interlink CD and 400 Mk II were the worst performers as a result of being approximately 16 dB above the noise floor, leading to the theory that it was these cables' noise performance that lead to the poorer THD+N performance.

It would make sense that the M1000i has very good noise performance, since it is shielded by 100% foil and 95% copper shielding. On the other hand, the Interlink 100, which has nothing other than the signal return as a "shield", performed nearly as well.

Therefore, no construction/performance correlation is readily seen, as well as a price/performance correlation being nonexistent, since the M550i is near the top in price and yet only average in noise performance.

3.7 Intermodulation Distortion (IMD)

Intermodulation distortion is a measure of the non-linearity of a device under test. Two sinusoids of frequencies f_1 and f_2 are the stimuli in the IMD test. It turns out that a non-linear device under test will output the original two sinusoids, plus an infinite number of IMD products given by $\alpha \cdot f_1 \pm \beta \cdot f_2$, where α and β are all possible integers.

Absolutely no differences between the interconnects' effect on intermodulation distortion was seen, as could be expected since nothing about the cable should be non-linear. The only case where non-linearities could occur are in the contact boundaries between the RCA connector on the cable and RCA jack on the audio equipment. An example would be a gold plated RCA connector connected to a nickel plated (and possibly dirty or oxidized) RCA jack. There exists the possibility that this poor connection could yield very poor diode-like results. However, this is particularly unlikely since the cables tested had snug fitting RCA connectors that removed oxidation when being twisted onto the RCA jack.

Tests were conducted at 50 Hz/8 kHz, 70 Hz/8 kHz, and 250 Hz/8 kHz. All cables, as well as the baseline reference test, yielded 0.0013% IMD for the 50 Hz/8 kHz and 70 Hz/8 kHz tests, and 0.0012 % IMD for the 250 Hz/8 kHz.

3.8 Crosstalk

Crosstalk is unwanted signal coupling from one channel of a multi-channeled system to another channel.[13] Since audio signals travel in pairs – via right and left channels – two cables usually exist in space very close the each other. Often, the right and left interconnects are physically connected by their flexible rubber jackets. As a result, the possibility exists for coupling between the two lengths of cable. Figure 3-12 shows the results of the crosstalk measurements.

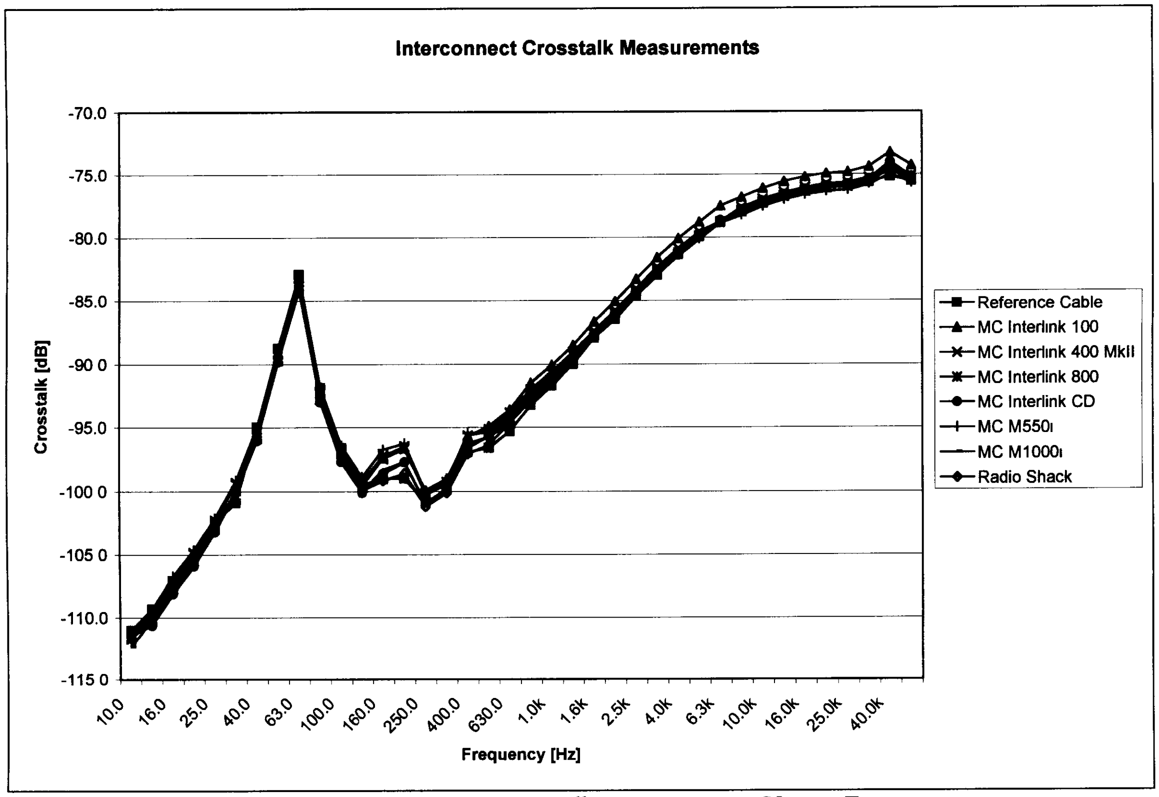

Figure 3-12: Interconnect Crosstalk Measurements Versus Frequency

The crosstalk response of the cables is nearly identical. Since most of the cables tested were not linked together by their jackets – instead, they were two completely

[13] Definitions for IMD and crosstalk taken from the *Audio Measurement Handbook,* authored by Bob Metzler, and published by Audio Precision, Inc. of Beaverton, Oregon.

separate cables – it would be expected that they would exhibit better crosstalk performance. However, this measurement was taken using only the input impedance of the Audio Precision instrument (100 kΩ). Therefore, since the input voltage to the cables was 1 V_{rms}, only 10 μA of current flowed. However, when the IHF standard load was placed in parallel with the Audio Precision input impedance, the current increased by a factor of ~100, and the crosstalk performance degraded by between 5 – 20 dB over the frequency range 10 Hz – 50 kHz (using the reference cable). Still, worst-case crosstalk in the audible frequency range using the IHF standard load and the reference cable was –69.94 dB at 20 kHz. According to Bob Metzler[14],

> "Good values for crosstalk and stereo separation in electronic devices range from 50 dB upwards, with crosstalk in excess of 100 dB achievable by sufficient isolation. When the application is stereo, such values are far higher than really necessary for a full stereo effect. Psychoacoustic experiments have shown that stereo separation of 25 dB to 30 dB at midband audio frequencies (500 Hz – 2 kHz) is sufficient for good stereo effect, with even less stereo separation acceptable at frequency extremes)."

Consequently, all of the cables' crosstalk responses are well beyond this 30 dB recommendation for full stereo effect.

[14] Metzler, page 92.

Chapter 4

Summary and Conclusions

The measurements conducted on the cables, aside from the noise and THD+N tests, failed to conclude anything as to why some cables allegedly sound better than others. The THD+N and noise tests gave one remotely possible explanation as to why some cables might sound better, but it failed to give any correlation between price and performance or construction and performance. Therefore, it is the basic conclusion of this research that cable quality is of very little consequence in audio systems.

During my search for interconnects to test, I talked to a salesman at two different stores, and both gave me about the same advice/information regarding cables. In effect, what they said was that different cables sound better in different systems – that some cables may make one system sound bright and "airy" while making another sound flat and dull. They recommended trying different cables to see which sounded better in my system. This was about the same information that was written in Butterworth and Griffin's article in *Home Theatre*.

Upon hearing this advice, it lead me to wonder what about a cable could make one system sound good and another sound not as good. A big issue in all of this is pyschoacoustics and the perception of sound. What sounds good to one person may not sound good to another. Furthermore, if someone knows that they purchased the supposedly best cable on the market, it may lead them to believe it is making his audio system sound better – the "paying more must lead to better performance" thought. In reality, a listener who was unaware of the change may never notice the difference.

No clear formula exists for choosing which manufacturers' cable to buy, what model to buy, and how much to spend. It is surprising how well the Radio Shack product and the MC Interlink 100 performed (and how low their lumped-parameter values were in comparison to the more expensive cables), despite their low cost and simple construction. My recommendation is to buy the $10.95 Radio Shack cables, the $12.95 Monster Cable Interlink 100s (cables with low parasitic inductance and capacitance), or use the ones that come packaged with the audio components, especially if you need very short lengths of a meter or less. In any case, rather than spending $50 - $100 (or more) on interconnects, save that money and apply it towards a better set of speakers. This action has the potential to improve the system's sound much more than the expensive interconnects could.

Appendix A

Reproduced from the E.I.A. Standard RS-490, November 1981:
Standard Test Methods of Measurement for Audio Amplifiers

Operating Temperature

2.2.1 A power amplifier, integrated amplifier, or receiver shall be preconditioned by driving all channels simultaneously with a 1 kHz sinusoidal signal to a nominal power output into the rated load equal to 33% of the rated power output until one hour of operating time has been accumulated.

2.2.2 A preamplifier shall be preconditioned by operating it undriven for one hour.

Output Reference Level

2.4.1 For output terminals whose primary function is to deliver signal voltage to a subsequent device, the output reference level shall be 0.5 V_{rms}.

Load Impedance

2.5.2 Each output terminal whose primary function is to deliver signal voltage to a subsequent device shall be terminated with a load consisting of a 1000 ohm ±5% resistor in parallel with a 1000 pF ±5% capacitor.

Input Termination

2.6.1 The input termination for each line input shall consist of a 1000 ohm ±10% resistor.

2.6.2 The input termination for each MM-phono input shall consist of a 1000 ohm ±10% resistor.

2.6.3 The input termination for each MC-phono input shall consist of a 10 ohm ±10% resistor.

Control Settings

2.8.1 Gain control, whose primary function is the simultaneous adjustment of gain of all inputs, shall be preset so that a reference-input level produces a reference-output level except that the gain control of a power amplifier (if available) shall be preset to the position of maximum gain.

2.8.2 Tone, loudness-contour, and other controls, whose primary function is the adjustment of frequency response, shall be switched out (if possible) or shall be preset for flattest electrical frequency response as indicated by markings.

2.9 Test Equipment

The net input impedance of all test equipment connected to the output terminals shall be considered as a portion of the load impedance.

The net source impedance of all test equipment connected to the input terminals shall be considered as a portion of the input termination impedance.

Input signal levels shall be the level of the Thevenin-equivalent generator of the input circuitry.

All measuring instruments used shall be at least five times more accurate than the test results to be recorded, so that no more than 20% uncertainty will be introduced. If this is not possible, then the accuracy of the measurement shall be stated as part of the test data.

2.9.1 The test frequency shall be within 1% of specified value

2.9.2 The voltmeter shall have full-wave average rectifying characteristics and be calibrated to read the RMS voltage of a sine wave to an accuracy of at least 2% of full scale at any frequency to be measured. A voltmeter having true RMS characteristics shall be an acceptable substitute.

2.9.3 The harmonic distortion measurement device shall be capable of measuring distortion components within a 50 kHz bandwidth to an accuracy of at least ±3% of full scale.

Appendix B

The following are specification sheets for the Portable One, reproduced from the Audio Precision Portable One *Plus* User's Manual, pages 9-1 and 9-2.

9. SPECIFICATIONS

GENERATOR CHARACTERISTICS

Signals	Sine, square, IMD signal (optional)
Frequency Range	10 Hz-120 kHz, sinewave 20 Hz-30 kHz, squarewave
Frequency Resolution	0 02%
Frequency Accuracy	±0.5%
Amplitude Range[1]	0.25 mV-26.25 V [-70 to +30.6 dBu] for 20 Hz-30 kHz sinewaves. 0 25 mV-12 28 V [-70 to +24 dBu] for all other signals
Amplitude Resolution	0 01 dB
Amplitude Accuracy	±0 2 dB, sinewave; ±0.3 dB, squarewave and IMD
Output Impedances	600 BAL, 150[2] BAL, 40 BAL, 40 UNBAL; all ±2 Ohms. Transformer coupled
Maximum Output Current	75 mA peak BAL, 150 mA peak UNBAL
Sinewave Flatness	±0 05 dB, 10 Hz-20 kHz; ±0.3 dB, 20 kHz-120 kHz
Sinewave THD+N[3]	0.0025% + 3 µV (80 kHz BW), 25 Hz-20 kHz; 0 010% + 10 µV (>300 kHz BW), 10 Hz-50 kHz
Residual Output Xtalk	10 µV or -110 dB to 20 kHz
Squarewave Risetime	2 5-3 0 µsec

ANALYZER CHARACTERISTICS

Input Impedance	100 kOhms (±1%) // 150-200 pF, each side to ground
Maximum Rated Input	350 Vpeak; 140 Vrms, dc-20 kHz (250 Vrms, 48-63 Hz)
Common-Mode Rejection	70 dB, 50 Hz-20 kHz, V_{in} ®2 V, 50 dB, 50 Hz-1 kHz, V_{in} >2 V

AMPLITUDE/NOISE FUNCTIONS

Measurements can be unweighted (UN-WTD), weighted (WTD), or SELECTIVE

Measurement Range	<1µV-140 V [-118 to +45 dBu]
Accuracy	±0.2 dB UN-WTD, ±0 5 dB WTD or SELECTIVE
Flatness (UN-WTD)	±0 05 dB, 20 Hz-20 kHz ±0 2 dB, 10 Hz-50 kHz ±0 5 dB, 50 kHz-120 kHz -3 dB at >300 kHz
UNWTD Mode Filters	400 Hz ±5% (3 pole) or <10 Hz (no highpass) plus 22 kHz ± 5% (5 pole)[4], 30 kHz ± 5% (3 pole), 80 kHz ± 5% (3 pole), or >300 kHz (no lowpass)
WTD Mode Filters	400 Hz ±5% (3 pole) or <10 Hz (no highpass) plus "IEC-A" per IEC 179 (rms det); "CCIR-QPK" per CCIR Rec 468; "CCIR-ARM" per Dolby Bulletin 19/4, "CCIR-RMS" (0 dB at 1 kHz, rms det) AUX1 or AUX2 (option filters)
Selective Tuning Range	20 Hz-120 kHz ±3% (2-pole, Q=5)
Residual Noise	1.5 µV [-114 dBu], UNWTD 22-22 kHz, 1 0 µV [-118 dBu], WTD IEC-A 5 0 µV [-104 dBu], WTD CCIR-QPK.

THD+N/SINAD FUNCTIONS

The THD+N function features three different tuning modes "AUTO-TUNE" (determined by input frequency counter), "GEN-TRACK" (ganged to generator setting), or "FIX-TUNE" (set using the front panel frequency controls, ±3% lock range) Measurements can be unweighted (UN-WTD) or weighted (WTD) using the same filters as the Amplitude/Noise function Display also includes input level and frequency (notch frequency in FIX-TUNE mode)

Fundamental Range	10 Hz-100 kHz, THD+N mode, 400 Hz or 1 kHz (±3%), SINAD mode
Measurement Range	<0 001%-100%
Accuracy	±1 dB, harmonics to 120 kHz
Residual THD+N[3]	0 0025% + 3 µV (80 kHz BW), 25 Hz-20 kHz; 0 010% + 10 µV (>300 kHz BW), 10 Hz-50 kHz
Minimum Input	20 mV[5] [-30 dBu] in AUTO-TUNE mode, 800[6] µV [-60 dBu] in other modes
Nulling Time	Typically 2-3 seconds above 25 Hz Increases in a "1/V" fashion for inputs below 20 mV [-30 dBu]

WOW & FLUTTER FUNCTION

Measurements are processed to display only the highest ("PEAK") or second-highest ("2σ") of the previous 20 raw readings Display also includes input level and frequency The frequency readout can be selected to display the absolute frequency or speed error relative to 3.00 kHz or 3 15 kHz

Test Signal Frequency	2.80 kHz to 3 35 kHz
Detection Modes	IEC (quasi-peak), NAB (average), or JIS
Response	UNWTD (0 5-200 Hz BW) or WTD per IEC 386
Measurement Range	<0 005%-3% (single range)
Accuracy	±[5% of reading + 0 002%]
Residual W+F	®0 005% WTD, 0 01% UNWTD
Minimum Input	20 mV[5] [-30 dBu]

LEVEL FUNCTION

Displays both input levels simultaneously, plus phase difference or frequency of the selected input

Range	<10 mV-140 V [-38 to +45 dBu].
Accuracy	±[0.1 dB +100 µV] (rms detection)
Response Flatness (V_{in} ≥ 10 mV)	±0.05 dB, 20 Hz-20 kHz, ±0.2 dB, 10 Hz-50 kHz, ±0.5 dB, 50 kHz-120 kHz, -3 dB at ≥300 kHz

RATIO FUNCTION

Measurement Range	<-80 dB to +100 dB, 0.01 dB resolution
Accuracy	±0.1 dB, 20-20 kHz
Minimum Input	10 mV [-38 dBu], numerator signal; 10 µV [-98 dBu], denominator signal

PHASE FUNCTION

Measurement Ranges	-270/+90°, -180/+180°, or -90/+270°, 0.1° resolution
Accuracy	±2°, 20 Hz-20 kHz, ±5°, 10 Hz-50 kHz
Minimum Input	20 mV[5] [-30 dBu], both channels

CROSSTALK FUNCTION

Similar to RATIO function except numerator signal is processed by a tracking bandpass filter (2 pole, Q = 5).

Measurement Range	-140 dB to 0 dB
Accuracy	±0.5 dB
Frequency Range	10 Hz-120 kHz
Residual Input Xtalk	-120 dB at 20 kHz, R_s ≤600 Ohms
Minimum Input	20 mV[5] [-30 dBu] in reference channel

AC MAINS CHECK FUNCTION

Displays voltage, THD+N (20 kHz BW limited), and frequency of the ac mains

Measurement range	0.85-1.10 of nominal setting
Voltage Accuracy	±1%

GEN LOAD FUNCTION

Displays the equivalent ac resistive loading on selected generator output. Intended for checking input terminations, loudspeaker impedance, or locating shorts

Measurement Range	<1 Ohm to 20 kOhm
Accuracy	±[5% +0.5 Ohm] for readings ≤ 1 kOhm. Degrades rapidly above 1 kOhm, or with reactive loads
Frequency Range	20 Hz-20 kHz
Test Voltage	200 mV default. Usable from 10 mV to generator maximum

FREQUENCY MEASUREMENT (all functions)

Measurement Range	<10 Hz->200 kHz
Accuracy	±0.01% [100 PPM]
Resolution	5 digits
Minimum Input	20 mV[5] [-30 dBu]

AUXILIARY OUTPUT SIGNALS

Analyzer Signal	Buffered analyzer output signal. Typically 3 Vpp max, R_{out} = 600 Ohm ±10%
Input Signal	Buffered version of selected input. 0.8Vp-p-3 Vpp nominal range, R_{out} = 600 Ohm ±10%.
Generator Sync	3 Vpp sinewave at same frequency as generator (LF tone only with IMD). R_{out} = 680 Ohm ±10%.

IMD OPTION CHARACTERISTICS

Generator Signal	Selectable 50-60-70-250 Hz (±1%) plus 7 kHz or 8 kHz (±1%), mixed in a 4:1 ratio (LF:HF)
Analyzer Signal Compatibility	Any combination of 40-250 Hz (LF) and 3 kHz-20 kHz (HF) tones, mixed in any ratio from 0.1-8:1 (LF:HF)
Measurement Range	<0.0025%-20%
Accuracy	±1 dB, per SMPTE RP120-1983, DIN 45403
Residual IMD[3]	0.0025% [-92 dB], Vin ≥200 mV
Minimum Input	100 mV[5]

GENERAL CHARACTERISTICS

Temperature Range	0C to +40C, operating -20C to +60C, storage
Power Requirements	100/120/220/240 V (-12%/+10%), 48-63 Hz 50 VA max
Dimensions (WxHxD)	16.5 x 6.0 x 13.6 inches [41.9 x 15.2 x 34.5 cm]
Weight	Approx. 20 lbs [9.1 kg]

NOTES TO SPECIFICATIONS

1. Open-circuit, balanced source impedance selection. Reduce maximum amplitude by a factor of 2 [-6 dB] with 40 Ohm UNBALanced output impedance selection. Accuracy and flatness are unspecified below 1 mV.
2. 200Ω with option EGZ installed
3. System specification including contributions from both generator and analyzer. Generator R_{load} must be ≥600Ω
4. Combined with 22 Hz highpass per CCIR Rec 468. "22 kHz-QPK" selection uses quasi-peak detection per CCIR Rec 468
5. For fully specified performance. Usable with inputs as low as 10 mV. Measurements are disabled for inputs below approximately 8 mV
6. Input must be ≥10 mV with "%" or "dB" unit for specified accuracy

Appendix C

Matlab Simulation Code: In all cases, variable names are identical to those shown in Figure 3-1. Z_{in} is comprised of R_Y in parallel with C_Y, and R_X is Z_s plus R_1.

For Figure 3-2: Magnitude and Phase plots for interconnect transfer function with no source impedance and Z_{in} = 100 kΩ.

```
RX = 0.2090;
R2 = 0.2090;
RY = 100e3;
L1 = 0.99e-6;
L2 = 0.99e-6;
C = 0.3386e-9;
CY = 0.0000;
F = [0:.1:8];
F = 10.^F;
W = 2*pi*F;
Re = R2+RX+RY-
(W.^2).*(L1*RY*C+L2*RY*CY+C*CY*R2*RX*RY+L2*RX*C+L1*R2*C+L1*RY*CY)
    +(W.^4).*(C*CY*L1*L2*RY);
Im = W.*(C*RX*RY+CY*R2*RY+L2+C*R2*RX+CY*RX*RY+L1)-
    (W.^3).*(C*CY*L2*RX*RY+C*CY*L1*R2*RY+L1*L2*C);

Mag = RY./(sqrt((Re.^2)+(Im.^2)));
Phase = -(360./(2.*pi)).*atan2(Im,Re);

figure(1);
subplot(2,2,1);
semilogx(F,(20.*log(Mag))./log(10));
xlabel('Frequency [Hz]');
ylabel('Magnitude [dB]');
set(get(gcf,'CurrentAxes'),'XLim',[1 10^8],'XTick',[1 10^2 10^4 10^6]);

subplot(2,2,2);
semilogx(F,Phase);
xlabel('Frequency [Hz]');
ylabel('Phase [degrees]');
set(get(gcf,'CurrentAxes'),'XLim',[1 10^8],'XTick',[1 10^2 10^4 10^6]);
set(get(gcf,'CurrentAxes'),'YLim',[-180 180],'YTick',[-90 0 90]);

F = 10.^[1.3:.1:4.3];
W = 2*pi*F;
Re = R2+RX+RY-
(W.^2).*(L1*RY*C+L2*RY*CY+C*CY*R2*RX*RY+L2*RX*C+L1*R2*C+L1*RY*CY)
    +(W.^4).*(C*CY*L1*L2*RY);
Im = W.*(C*RX*RY+CY*R2*RY+L2+C*R2*RX+CY*RX*RY+L1)-
    (W.^3).*(C*CY*L2*RX*RY+C*CY*L1*R2*RY+L1*L2*C);
Mag = RY./(sqrt((Re.^2)+(Im.^2)));
Phase = -(360./(2.*pi)).*atan2(Im,Re);

subplot(2,2,3);
semilogx(F,(20.*log(Mag))./log(10));
xlabel('Frequency [Hz]');
```

```
ylabel('Magnitude [dB]');
set(get(gcf,'CurrentAxes'),'XLim',[20 2e4],'XTick',[1e2 1e3 1e4]);
set(get(gcf,'CurrentAxes'),'YLim',[-0.01 0.01],'YTick',[-0.01 -0.005 0 0.005 0.01]);

subplot(2,2,4);
semilogx(F,Phase);
xlabel('Frequency [Hz]');
ylabel('Phase [degrees]');
set(get(gcf,'CurrentAxes'),'XLim',[20 2e4],'XTick',[1e2 1e3 1e4]);
set(get(gcf,'CurrentAxes'),'YLim',[-0.01 0.01],'YTick',[-0.01 -0.005 0 0.005 0.01]);
```

For Figure 3-3: Magnitude and Phase plots for interconnect transfer function with 1 kΩ source impedance and Z_{in} = 1 kΩ in parallel with 1000 pF. Shown are the value changes; everything else is as shown in the code above (for Figure 3-2):

```
RX = 1000.209;
RY = 1e3;
CY = 1000e-12;

subplot(2,2,1);
set(get(gcf,'CurrentAxes'),'XLim',[1 10^8]);
set(get(gcf,'CurrentAxes'),'XLim',[1 10^8],'XTick',[1 10^2 10^4 10^6]);

subplot(2,2,2);
set(get(gcf,'CurrentAxes'),'XLim',[1 10^8],'XTick',[1 10^2 10^4 10^6]);
set(get(gcf,'CurrentAxes'),'XLim',[1 10^8],'YLim',[-180 180],'YTick',[-90 0 90]);

subplot(2,2,3);
set(get(gcf,'CurrentAxes'),'XLim',[20 2e4],'XTick',[1e2 1e3 1e4]);

subplot(2,2,4);
set(get(gcf,'CurrentAxes'),'XLim',[20 2e4],'XTick',[1e2 1e3 1e4]);
set(get(gcf,'CurrentAxes'),'YLim',[-5 1],'YTick',[-5 -4 -3 -2 -1 0 1]);
```

ICAP/4 Simulation Setup Code: In all cases, **R3** is the resistive component of Z_{in}, and **C2** is the capacitive component of Z_{in} in Figure 3-1.(these are the same as R_Y and C_Y in the transfer function given in equation 3.2). All other variables are labeled as in Figure 3-1.

For Figure 3-4: Interconnect simulation with no source impedance and 100 kΩ Z_{in}:

```
C:\SPICE4S\CIRCUITS\cable.cir
*SPICE_NET
*INCLUDE STUDNT.LIB
R1 1 2 0.209
L1 2 3 0.99UH
L2 3 4 0.99UH
R2 4 5 0.209
C2 5 0 0
R3 5 0 100000
```

```
C1 3 0 0.3386NF
V1 1 0 AC 1
.AC DEC 10 10 100MEG
.VIEW AC V(5) -10 0
.PRINT AC  V(5)  VP(5) VDB(5)
.END
```

For Figure 3-5: Interconnect simulation with 1 kΩ source impedance and 100 kΩ Z_{in}:

```
C:\SPICE4S\CIRCUITS\cable.cir
*SPICE_NET
*INCLUDE STUDNT.LIB
R1 1 2 1000.209
L1 2 3 0.99UH
L2 3 4 0.99UH
R2 4 5 0.209
C2 5 0 0
R3 5 0 100000
C1 3 0 0.3386NF
V1 1 0 AC 1
.AC DEC 10 10 100MEG
.VIEW AC V(5) -10 0
.PRINT AC  V(5)  VP(5) VDB(5)
.END
```

For Figure 3-6 and 3-7: Interconnect simulation with a 1 kΩ source impedance and 1 kΩ in parallel with 1000 pF (E.I.A. standard load) Z_{in}:

```
C:\SPICE4S\CIRCUITS\cable.cir
*SPICE_NET
*INCLUDE STUDNT.LIB
R1 1 2 1000.209
L1 2 3 0.99UH
L2 3 4 0.99UH
R2 4 5 0.209
C2 5 0 1000PF
R3 5 0 1000
C1 3 0 0.3386NF
V1 1 0 AC 1
.AC DEC 10 10 100MEG
.VIEW AC V(5) -10 0
.PRINT AC  V(5)  VP(5) VDB(5)
.END
```

References

Audio Precision, Inc. *Portable One Plus User's Manual, Issue 4, Firmware Version 2.0.* July 1994

Bateman, Cyril. "Speaker Cables, Part Three." *Electronics World* February 1997: 119-124.

Bateman, Cyril. "Speaker Cables." *Electronics World* February 1997: 119-124.

Butterworth, Brent and Al Griffin. "String 'em Up!" *Home Theater* August 1997: 90-108.

Davis, Fred E. "Effects of Cable, Loudspeaker, and Amplifier Interactions." *Journal of the Audio Engineering Society* June 1991: 461-468.

Duncan, Ben. "Measuring Speaker Cable Differences." *Audio* July/August 1997: 570-571.

Ford, E. "Speaker Cables Pulse Tested." *Electronics World* December 1996: 930-934.

"Getting Wired." *Stereo Review* June 1990: 75-79.

Greiner, R. A. "Cables and the Amp." *Audio* August 1989: 46-53.

Hewlett Packard. *Test & Measurement Catalog 1997.* Pages 134-5,153-4, 350.

Metzler, Bob. *Audio Measurement Handbook.* Beaverton: Audio Precision, Inc., 1993.

Otala, Matti and Pertti Huttunen. "Peak Current Requirement of Commercial Loudspeaker Systems." *Journal of the Audio Engineering Society* June 1987: 455-462.

Peterson, Arnold P.G. *Handbook of Noise Measurement.* Concord: GenRad, Inc., 1980.

Self, Douglas. "Cable Sonics?" *Electronics World* October 1997: 831-835.

Teac Corporation. *EQA-220 Graphic Equalizer Owner's Manual.*

Williams, Geoff. "Cable Science?" *Electronics World* December 1996: 937-940.