SYNERGETIC AUDIO CONCEPTS
SYN AUD CON

TECH TOPICS

P.O. BOX 669, SAN JUAN CAPISTRANO, CA 92693

VOLUME 10, NUMBER 1
FALL 1982

TERMINATION, IMPEDANCE MATCHING AND THE MAXIMUM POWER TRANSFER THEOREM IN AUDIO SYSTEMS

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Impedance matching and termination are two of the most widely misunderstood concepts in audio. Many of us in the field got here by way of radio, television, or related technologies where one rule dominates - TERMINATE EVERYTHING. Transmission line and network theory and the maximum power transfer theorem make this generally excellent practice for rf and video systems but often not good practice for audio.

The maximum power transfer theorem, shown here in a derivation supplied by Mike Pratts of NBC, 1981 Chicago class, (see Appendix I) is a basic theorem of linear circuit theory. It states that for a linear circuit, the maximum power will be removed from a generator of constant voltage or constant current and having a fixed source impedance when the load impedance (the variable) is made equal to the source impedance and their reactive components of opposite sign.

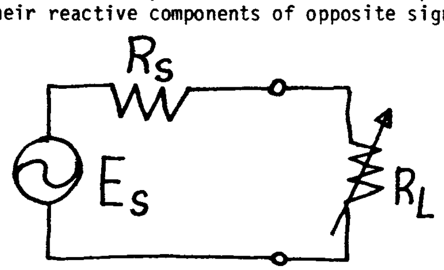


FIGURE NO. 1

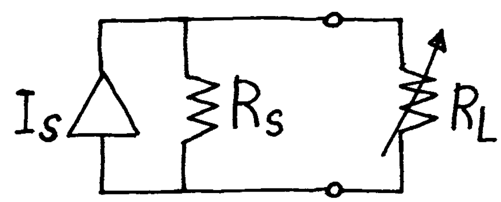


FIGURE NO. 2

In Figure #1 (a constant voltage source) and Figure #2 (a constant current source), R_L is the load impedance (the variable), R_S is the output (source) impedance of the output stage E_S or I_S. Thus, a 600 ohm source would provide maximum power output to a 600 ohm load. Of course, if the source impedance were made the variable, more power could be supplied by reducing the output impedance of the voltage source or raising the output impedance of a current source.

Unfortunately, modern solid state (and even vacuum-tube) amplifiers do not fit into the conditions described by the maximum power transfer theorem. Solid state output stages generally have an output impedance much lower than the loads they are meant to drive (generally 20 to 100 times lower). When these amplifiers are loaded by impedances lower than intended (thus attempting to absorb more power and more current than the amplifier is designed to supply), the amplifier becomes non-linear and its gain drops. In other words, the mathematical model (the amplifier's equivalent circuit with a generator and an internal impedance) is no longer valid. Because it is no longer valid, the maximum power transfer theorem no longer applies. The equivalent circuit (on which the maximum power transfer theorem is based) falls apart. In fact, the actual electrical circuit falls apart as an amplifier, producing clipping, increased distortion, reduced headroom, and reduced output. Naturally, it may also be more likely to fail.

What Is Impedance Matching In Audio?

What then is the practical meaning of the actual output and input impedance of amplifiers? What is impedance matching in audio? Well, from the above discussion it should be obvious that there are optimum loads for most amplifiers (or systems) and these are specified by the designer (manufacturer or systems engineer). We all know that power amplifiers are designed for certain minimum load impedances, but did you know that the thing that drives power amplifier manufacturers crazy is the reactive component of the load impedance? Although rarely specified on data sheets, many popular speakers and matching transformers can look almost like a short circuit (capacitive or inductive) at crossover, resonance frequencies, or at very high or very low frequencies.

Line level devices are generally specified for 600 ohm loads. This does not mean that they must see a 600 ohm load but merely that they have enough power output capability to supply full rated output voltage into a 600 ohm load. They will generally have slightly more headroom and somewhat less distortion into a higher impedance load since that load does not absorb as much power.

Output Impedance of an Amplifier

Why then do we care about output impedance of an amplifier (or other gear)? To understand the answer to this question, consider a signal path in an electrically noisy environment. (See Figure #3) An amplifier having an output (source) impedance of 20 ohms is driving a console at another location which has a 10K ohm input impedance (R_L). R_L is then said to be "bridging" the line since it is more than 10 times higher than the 600 ohm rated output load impedance of the amplifier. Now, let's represent our noise source by a generator E_X = 100 mv through a source impedance R_X = 1 Meg ohm (the noise is induced by electromagnetic coupling in the wiring between the two amplifiers). Figure #3 can be redrawn to Figure #4.

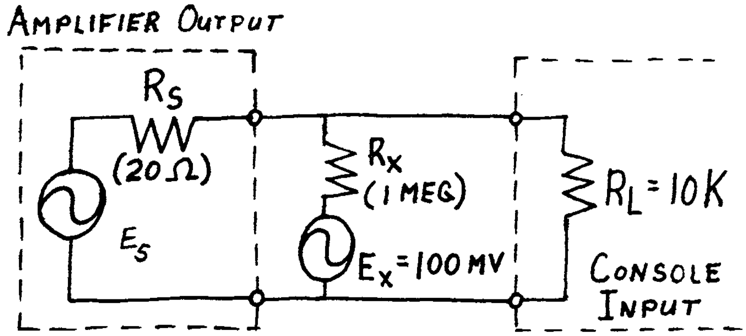


FIGURE NO. 3

Since R_S = 20 ohms, the noise source is attenuated by the voltage divider ratio $R_S/(R_X + R_S)$ before showing up at R_L. The desired signal E_S sees no such loss and appears at full strength in R_L. Thus, in this example $E_n = 100 \text{ mv} \cdot \frac{20 \text{ ohms}}{10^6 \text{ ohms}} = 2$ uv. We could say that the 20 ohms source impedance has attenuated the induced voltage by $20 \log \frac{R_S}{R_X} = -94$ dB and the signal to noise ratio is $20 \log \frac{E_S}{E_n} = 114$ dB.

If, in another example, the output amplifier were replaced by a less professional device having an actual output impedance of 1000 ohms and designed to work into a 10K load, the modified circuit of Figure #5 applies.

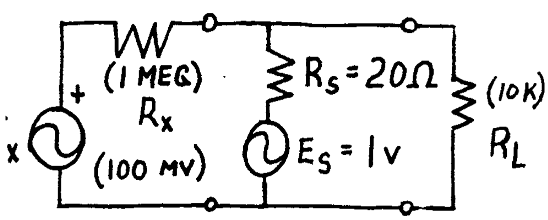


FIGURE NO. 4

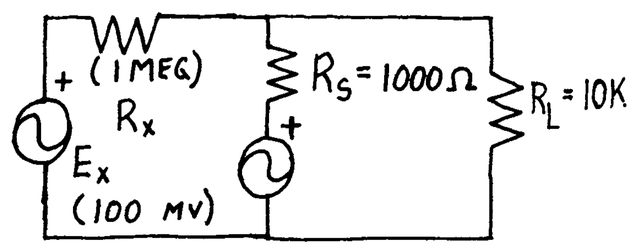


FIGURE NO. 5

For this new circuit, $E_n = 100 \text{ mv} \cdot \frac{1 \text{ K}}{1 \text{ Meg}} = 100$ uv, for a signal to noise ratio of $20 \log \frac{E_S}{E_n} = 80$ dB. Note that this second "high impedance" circuit is 34 dB poorer with respect to noise immunity than the first "low impedance" circuit simply by virtue of its output impedance.

The same characteristic can often eliminate the need for distribution amplifiers in many applications. If all loads are bridging (10 times higher than the rated load impedance), then by basic circuit theory (Kirchoff's law) ten such loads can be connected on the circuit without overloading and moderate noise levels swamped by the low output impedance.

Passive Networks

Next we come to what is really impedance matching in audio. The first example is the passive network such as a resistive pad, passive equalizer, or passive crossover. These passive networks are combinations of resistors, inductors, and capacitors designed to be driven from a specified source impedance and loaded by a specified load impedance (often called the termination). The correct network performance, whether frequency response, crossover slopes, or pad loss, depends on the proper driving source and load impedances. If these impedances are not correct (within about 10% for most purposes), the equalizers and crossovers can exhibit ringing, incorrect slopes, and otherwise poor response. Similarly, the pads would not provide the correct loss or isolation.

In the typical example shown in Figure #6, a passive network designed for 600 ohm input and output impedances needs to be driven by a compressor having an output impedance of 25 ohms and will feed a power amplifier having an input impedance of 25 K ohms. It is then necessary to add a resistor R_b (often called a "build-out" resistor) in series with the input of the equalizer making the source impedance as close as possible to 600 ohms. 560 ohms, a standard value, is usually chosen and is certainly close enough for audio work. In addition, a load resistance (R_L') of 620 ohms (also a standard value) would be required on the output.

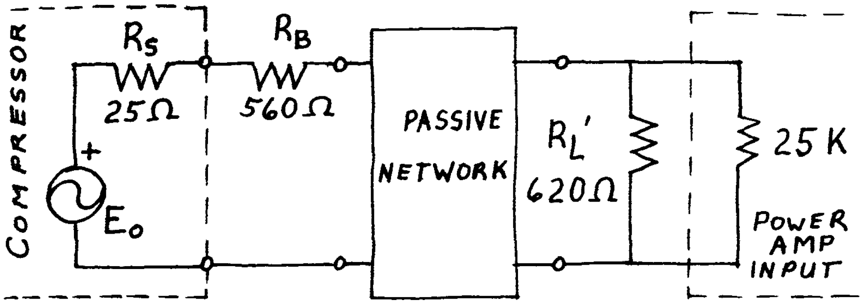


FIGURE NO. 6

Telephone Lines

Next, consider the telephone line. Telephone lines are transmission lines and follow classic transmission line theory. Although they nominally have a characteristic impedance of 600 ohms, in practice they rarely get very close to that value. This happens because the characteristic impedance of transmission lines depends on its physical construction and is governed by such parameters as wire diameter, spacing, insulation, inductance, and capacity. If a transmission line is terminated by its correct characteristic impedance, you may look into the opposite end and see that value of impedance. If it is not, however, the value of impedance will vary with distance along the line and can vary as widely either side of the characteristic impedance as the degree of mismatch of the load (and the degree to which the characteristic impedance is not 600 ohms due to different wire/line dimensions!). It is no wonder then that, as Harrison Klein found in his measurements on a number of telephone lines at a Chicago broadcast facility, the impedance of telephone lines can vary widely. In his measurements he found variations from 200 to 2000 ohms to be quite common.

How then do we deal with telephone lines in audio systems? Well, if we have ordered an equalized line from a telephone company, it has, by standard practice, been equalized flat for a driving source impedance of 600 ohms and a load impedance of 600 ohms. In other words, the telephone company supplying the line has provided passive equalization for the circuit which assumes 600 ohms on each end. It is, therefore, necessary to treat it just like the passive networks described above, terminating and driving with 600 ohms.

If the line is *not* equalized, it may work better *without* the build-out resistor. A "short" line (a mile or so) could act like a large capacitor in parallel with the output. The build-out resistor working into the line becomes an R-C filter or "integrator" degrading square-wave or high frequency response! (Thanks - Tom Knauss, WLUP, Chicago)

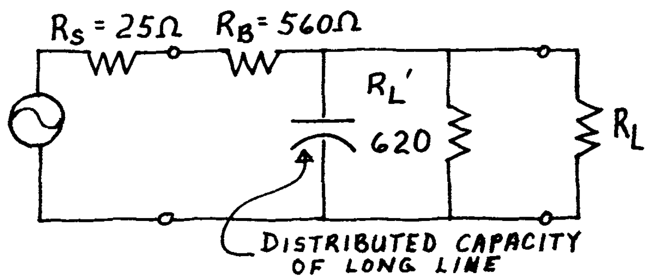


FIGURE NO. 7

Transformers

Another set of misconceptions surrounds the use of transformers in audio, and the common ways we label and specify them by impedance ratios reinforce these errors. For all practical purposes, a good audio transformer will have no impedance of its own but will simply multiply the impedance connected to its opposite winding by the square of the turns ratio. If nothing is connected to the secondary winding of the transformer, the impedance Z_1 (looking into the primary) will be infinite (assuming a perfect transformer). Consider Figure #8 below the ideal transformer.

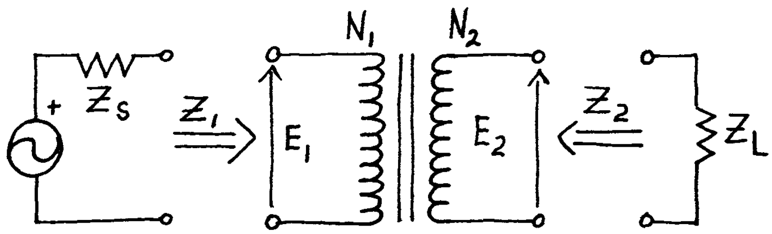


FIGURE NO. 8

That is, $\frac{Z_1}{Z_2} = \left(\frac{N_1}{N_2}\right)^2$

or $Z_1 = \left(\frac{N_1}{N_2}\right)^2 Z_L$

and $Z_2 = \left(\frac{N_2}{N_1}\right)^2 Z_S$

The voltage is transformed by the turns ratio itself: $\frac{E_1}{E_2} = \frac{N_1}{N_2} = \sqrt{\frac{Z_1}{Z_2}}$

In other words, we say that the voltage is proportional to the square root of the impedance ratio. Hence, a 600:15K ohm transformer has an impedance transformation ratio of 1:25 and a turns ratio of 1:5. It is designed to be loaded (on its secondary) by 15K but if it is loaded by 30K instead, the impedance Z_1 (looking into the primary terminals) will be 1200 ohms. Notice also that if the primary is driven by a typical 30 ohm input stage, the impedance Z_2 (looking back into the secondary terminals from the load) will be 750 ohms.

All of the above relationships are simplified for ideal transformers. To modify them for real life, consider the following imperfections and losses of real transformers. Wire resistance, iron, and insulation losses show up as resistance in series with the windings. Imperfections in the magnetic and coil structure show up primarily as resistance and capacitance as shown in Figure #9.

In a well designed transformer and within the specified impedance ranges for the transformer, the loss and stray components will be small enough to ignore.

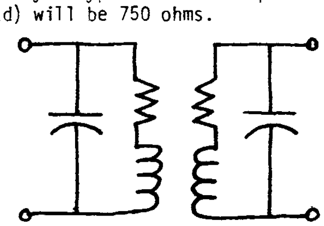


FIGURE NO. 9

In a good line or mic level transformer, $P_{in} = P_{out}$ within one or two dB so that the voltage ratios will be approximately as described above. As the impedance gets very far away from the design impedances of the transformer, though, the reactive components can easily take over and cause bumps in the frequency response curves or ringing in the square wave response.

Transformers designed to be used as the output transformers in line level devices are normally designed to be driven by the low (10 - 50 ohm) impedance stages of modern audio gear and are designed to be loaded by impedances from 600 ohms to 50K or higher. They may have turns ratios of 1:1 or even as high as 1:2 to improve output headroom from relatively low voltage power supplies. In other words, the transformer designer understands the design limitations of the audio circuit designer and comes up with a transformer design to fit those parameters. He understands that the amplifier will probably work best without termination but must also work well with it, and he designs a transformer that will perform well under both circumstances.

Just as line level audio circuits are not normally terminated, mic input circuits are almost never terminated. A mic input labeled 150 ohms is meant to be driven by a 150 ohm mic but it is nearly always bridging to that mic. I do not know of any modern mic input stages having an input impedance of less than 800 ohms and most are much higher. Mic input transformers have the additional design limitation of needing to optimize signal to noise ratio so that shielding and turns ratio will be determined by these factors.

Summary

We can summarize our discussion of impedance matching in audio circuits with these observations. In the case of active devices (amplifiers, output stages, etc.), load impedance is specified only as a means of pinning down a minimum level of performance for the equipment in a standardized set of operating conditions which are generally accepted to be worst case. In most cases, the equipment will perform better (less distortion, more headroom, etc.) without the termination. Hence, the first rule:

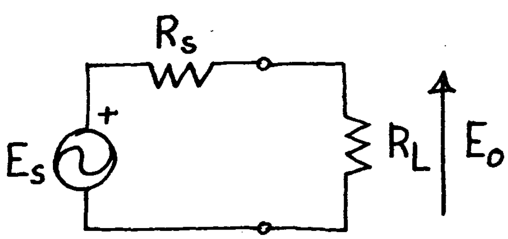
1. Avoid terminating active devices (amplifiers, compressors, d.a.'s, etc.).

2. Terminate and build out all passive networks, passive equalizers, and telephone lines.

3. Termination will sometimes aid in the solution of interference (noise, RF interference) problems, ringing in transformers.

APPENDIX I:

Maximum Power Transfer Theorem by Mike Pratts with Notes Added by Jim Brown



In the circuit, R_L is the output load and it is desired to pick a value for R_L such that the power taken by it from the generator E_s having output resistance R_s is maximum.

Writing the equation for the voltage across R_L:

$$E_o = E_s \frac{R_L}{R_s + R_L}$$

And the power in the load (P_o):

$$P_o = \frac{E_o^2}{R_L} = \left(E_s \frac{R_L}{R_s + R_L}\right)^2 \frac{1}{R_L} = \frac{E_s^2 R_L^2}{R_L (R_s + R_L)^2} \qquad P_o = E_s^2 \frac{R_L}{(R_s + R_L)^2}$$

To find the maximum power, we take the first derivative of P_o with respect to R_L and set it equal to zero. (E_s and R_s are constants.)

$$\frac{dP_o}{dR_L} = E_s^2 \frac{(R_s + R_L)^2 - R_L \cdot 2(R_s + P_L)}{(R_s + R_L)^4} = 0 \qquad = E_s^2 \frac{(R_s + R_L) - 2 R_L}{(R_s + R_L)^3} = \frac{R_s - R_L}{(R_s + P_L)^3} = 0$$

$\therefore R_s = R_L$ for maximum power output and $P_o = E_s^2 \frac{R_L}{(2 R_L)^2} = \frac{E_s^2}{4 R_L}$

Note that an equal power is lost in R_s and that half the voltage (6 dB) of the generator is lost in R_s (its own source impedance). This is not a particularly healthy situation in amplifiers since that R_s is mostly inside the transistor or integrated circuit and the dissipation of *more* audio power there is not desirable.

Note also that the 6 dB loss from $R_s = R_L$ will happen as well with passive circuits when matched and terminated. It is not uncommon to lose 6 to 12 dB in a passive equalizer or telephone line in addition to the cutting action of the filters! This is an important reason for providing 20 dB of additional gain on amplifier inputs!