The Dilemma

The vast majority of stereo recordings are engineered for reproduction with a pair of left and right channel loudspeaker systems. Thus that engineering takes into account that sound emanating from each speaker system is heard at both of the listener's ears.

With the pair of speaker systems conventionally positioned on opposite sides of the listener each at an equal angle in the range of 30º to 45º, there are two frequency-dependent factors affecting intensity of the sound emanating from each speaker as heard at one ear relative to that at the opposite ear. Firstly, there is intensity gain effected by anatomical parts of the human outer ear that is at a maximum when the speaker system is to one side (relative to directly in front) of the listener at a 45º angle. This gain can occur only at the ear that is on the same side of the head as the to the left or to the right -position of the speaker system, this ear being designated the near ear. The human head is an obstacle to the sound reaching the far ear on the opposite side of the head, defeating the possibility of any gain by that ear. Secondly, as a result of diffraction by the human head, the intensity of a sound emanating for example from the left speaker system is reduced at the right or far ear, relative to the intensity heard at the near ear. The extent of that reduction increases as the frequency of the sound increases from hundreds to thousands of Hertz.

When listening to a stereo recording with headphones, reproduction by the left and right headphones occurs exclusively for respectively the left and right ears. This situation is not what the recording engineer in most cases had intended! The placing of speaker transducers directly against the ears eliminates a large part of outer ear gain, and acoustic cross-feed from the left transducer to the right ear and vice versa does not occur.

The solution to this problem is to electronically restore what is eliminated acoustically as a result of listening with headphones or ear inserts. This is what my cross-feed network does, that is, to a large extent it mimics intensity at the far ear relative to that at the near ear as a function of frequency corresponding to listening with a pair of stereo loudspeaker systems.

Network Overview

This network is a passive circuit connected in cascade between power amplifier and headphones. With the network so connected, the load seen by the output stage of the amplifier at a minimum is equal to the rated impedance of the headphones. The network consists of only ten parts. The values of the components of the network correspond to rated impedance of the headphones.

The cross-feeding of the network causes localization of the instruments of a recording to be heard as originating in front of the listener without degrading channel separation, and does not produce audible distortion. As the network is connected between power amplifier and headphones, it can be used with audio source players. No power supply is required, and the network is simple to construct. A power amplifier that is suitable for directly driving your headphones is also suitable to drive the network in cascade with your headphones.

For signals of a frequency greater than 8 kHz and increasing, the level of the cross-feed signal relative to that of the direct signal of my network increasingly lacks correspondence to the theoretical difference of sound intensity at the far ear with respect to that at the near ear (of listening to reproduction by one of a pair of stereo speakers). This defect is to some extent mitigated by the fact that very little of musical sound production occurs above 10 kHz. Inserting the cross-feeding network between power amplifier and headphones does result in a lowering of volume, however not to a substantial degree. The network can only be properly used with headphones of rated impedance that the network has been designed to. If the actual impedance of the headphones substantially deviates from rated impedance at some frequency, this may result in improper cross-feed by the network. If source impedance of the power amplifier that the network is connected to is comparable to rated impedance of the headphones, this may also result in an incorrect cross-feed characteristic.

Acoustics

Where a sound source is located a few meters away and at a 45º angle relative to directly in front of a listener, there is frequency-dependent outer ear gain of the near ear only. Sound can only reach the opposite or far ear by diffraction which defeats sound approaching the far ear at a 45º angle. The three structural features of the outer ear that effect gain are the concha, flange and meatus. Wearing headphones, the phone radiates directly or straight into the ear canal with the result that the concha and flange do not provide any gain. It is assumed that the meatus, which provides gain by resonance, is not defeated by the wearing of headphones and is equally operative at both ears. Column 1 of Table 1 lists the combined frequency-dependent intensity gain of the concha and flange only, that is, omitting that of the meatus.

Diffraction of sound emanating from a source to one side of the listener, commonly referred to as the sound shadow, causes the difference of intensity at the far ear with respect to that at the near ear to steadily increase with increasing frequency of the sound. Column 2 of Table 1 lists the frequency-dependent difference of intensity at the far ear relative to that at the near ear for a side-angle or azimuth equal to 45º.

Column 3 of Table 1 lists the frequency-dependent intensity difference resulting from both outer ear gain at the near ear only and the sound shadow. That is, the entries of Col. 3 are the intensity levels in dB of Col. 1 subtracted from those of Col. 2. With the exception of a deviation in the low frequency range that is to be explained below, the cross-feeding network mimics intensity difference of Col. 3 and the maximum intensity gain of Col. 1 that occurs at 5 kHz.

Description

The network is shown at Fig. 1 connected between an input phone jack J1 and an output phone jack J2. The network components in the direct signal path from the left channel amplifier output (tip contact of J1) to the left headphone are resistor R2a in parallel circuit with the in-series connection of capacitor C1a, inductor L1a and resistor R3a. In the same manner resistor R2b in parallel circuit with the in-series connection of capacitor C1b, inductor L1b and resistor R3b connects the ring contact (right channel input) of J1 to the right headphone. To effect left to right channel cross-feed, resistor R1a is connected from the tip contact of input jack J1 to the ring contact of output Jack J2. Resistor R1b connected from the ring contact of input Jack J1 to the tip contact of output Jack J2 effects cross-feed of the right channel amplifier output to the left headphone.

Resistor Ratios

Superposition applied to the network of Fig.1, as shown at Fig.2, is used to find the required resistor ratios. Fig. 2 is equivalent to Fig.1 including shorting the ring contact of input jack J1 to ground or the shell. Fig. 2 differs from Fig. 1 in that resistors RLa and RLb of Fig. 2 have been substituted for respectively the left and right headphones of Fig. 1. These resistors have resistance equal to rated impedance of the headphones. For the moment disregard the component values shown at Fig. 2.

At Fig. 2, CH (channel)-A voltage source produces a sine wave and the CH-B source is shorted. This results in the voltage drops across resistors RLa and RLb equal to respectively the direct and cross-feed outputs. This figure will be used to derive the resistor ratios resulting in (1) as a function of frequency above the low frequency range, electrical power dissipated by RLb with respect to that of RLa corresponding as closely as possible to decibels of Col. 3 of Table 1, and (2) for frequency initially very much less than the series resonant frequency Fs (5 kHz), and increasing to equal to Fs, then corresponding attenuation of the voltage drop across RLa decreases by 9 dB.

Where frequency is substantially less than the resonant frequency Fs, and decreasing, E standing for voltage drop, then the ratio E_{RLb} / E_{RLa} should flatten to equal to 0.71. This is done to compensate for the fact that at frequencies less than 1 kHz, localization of sound sources at a distance depends more on relative phase at the ears than intensity (according to the duality hypothesis of sound localization). With this simple network, I made no attempt at mimicking the correct phase relationship at low frequencies. The cross-feed signal at -3 dB relative to the direct signal in the low frequency range substitutes.

To solve for the required ratio of resistor values to produce this low-frequency shelf, a simplifying assumption is that the impedance of resistor R2 in parallel circuit with the in-series connection of capacitor C1, inductor L1, and resistor R3 equals the resistance of R2. Solving for E_{RLb} / E_{RLa} as a result of voltage division given this assumption, it is found that that ratio equals R2/ R1. Thus R1 must equal 1.41 times R2 to produce the -3 dB shelf.

With respect to frequency equal to 5 kHz, or series resonant frequency Fs of C1 in-series with L1 of Fig. 2, the level of the cross-feed signal with respect to that of the direct signal should be equal to the -18 dB of Col. 3 of Table 1. That is, E_{RLb} / E_{RLa} should equal 0.13. At frequency equal to Fs, the assumption is made that impedance of resistor R2 in parallel circuit with the in-series connection of capacitor C1, inductor L1 and resistor R3 equals the resistance of R3. Making this assumption, by voltage division, E_{RLb} / E_{RLa} is equal to R3 / R1. Thus setting R3 equal to 0.13 times R1 results in the desired attenuation of the cross-feed signal relative to that of the direct signal.

In Col. 1 of Table 1, for frequency increasing from hundreds to thousands of Hertz, acoustic gain of the outer ear is initially zero and reaches a maximum at 5 kHz equal to 9 dB. To mimic this with the network, attenuation of the voltage drop across RLa, with respect to the applied voltage of source CH-A, should decrease by 9 dB for that increase of frequency.

In the low frequency range at Fig. 2, impedance in-series with RLa equals the resistance of R2a. At 5 kHz or Fs, impedance in-series with RLa equals the resistance of R3a. Given these two simplifying assumptions, an equation is derived for the increase of voltage drop across RLa that occurs corresponding to the increase of frequency. That equation is set equal to 2.8, as 20 times $\log_{10}$ of 2.8 equals 9 dB. We know that R1 equals 1.41 times R2 and R3 equals 0.13 times R1; thus R3 equals 0.18 times R2. Substituting 1.41R2 and 0.18R2 for respectively R1 and R3 in the equation solve for R2 as a factor times RL. The solution is R2 equals 2.91 times RL.

The proper values of capacitor C1 and inductor L1 were determined with a computer simulation program comparing the voltage drop E_{RLb} to voltage drop E_{RLa} in the network of Fig. 2 as a function of frequency. Where the values of resistance of the resistors of the network are according to the above equations, it was found by trial and error that reactance of L1 and C1 should equal RL or rated headphone impedance at the resonant frequency Fs (5 kHz). When the network is configured in this way, with the exception of the low frequency range, relative attenuation compared to (acoustic) intensity difference of Col. 3 of Table 1 as a function of frequency on average closely corresponds.

Decibels of Col. 4 of Table 1 are the result of a computer simulation of the network of Fig. 2 where component values of the network are those shown at Fig. 2.

Construct the Network

Where rated impedance and sensitivity of the headphones to be connected to the network equal about 50 Ω or less and 100 dB/ 1 mW, wattage of the resistors of the network could most likely be 1/4 Watt. To be on the safe side, recommended wattage in all cases is 1/2 Watt. If DCR of inductor L1 is significant, then that DCR should be subtracted from the calculated value of resistor R3. The pair of inductors should be mounted at a right angle and at least 8 cm apart.

Here are the equations in order for solving values of the components of the network of Fig. 1. In the equations RL stands for rated headphone impedance.

$$R2 = 2.91RL$$
$$R1 = 1.41R2$$
$$R3 = 0.13R1$$
$$L1 = \frac{RL}{31.4} mH$$
$$C1 = \frac{1000}{31.4RL} \mu F$$

Minimum load to amplifier

Minimum load of the network connected in cascade between amplifier and headphones occurs at the series resonant frequency of C1 in-series with L1. Fig. 2 is used to analyze minimum load presented to each channel amplifier. Adopting the simplifying assumption that resistance of R3 in parallel circuit with R2 equals the resistance of R3, and noting that R1 and R3 equal respectively 4.1RL and 0.53RL, it is calculated that load seen by the amplifier equals 1.02RL. The combined impedance of the network and headphones is greater than RL at frequencies other than resonant frequency Fs. In other words, the properly constructed network inserted between your amplifier and headphones won't draw more current than your amplifier can supply.

Freq. kHz	Col. 1 acoustic gain at near ear dB	Col. 2 acoustic intensity difference dB	Col. 3 dB of Col. 3 minus Col. 1	Col. 4 20 times $\log_{10}(E_{RLb} / E_{RLa})$ dB
0.1	0.0	0.0	0.0	-3.0
0.2	0.0	-0.5	-0.5	-3.1
0.3	0.0	-1.4	-1.4	-3.1
0.4	0.0	-2.0	-2.0	-3.3
0.5	0.0	-2.5	-2.5	-3.4
0.6	0.0	-2.9	-2.9	-3.6
0.7	0.0	-3.2	-3.2	-3.8
0.8	0.0	-3.5	-3.5	-4.0
0.9	0.0	-3.7	-3.7	-4.3
1.0	0.2	-4.0	-4.2	-4.6
2.0	1.5	-6.1	-7.6	-8.1
3.0	3.2	-7.4	-10.6	-12.3
4.0	6.5	-8.3	-14.8	-16.8
5.0	9.0	-9.0	-18.0	-19.3
6.0	6.5	-10.6	-17.1	-17.4
7.0	3.0	-11.9	-14.9	-14.9
8.0	0.5	-13.0	-13.5	-12.8
9.0	0.0	-14.1	-14.1	-11.3
10.0	0.0	-15.0	-15.0	-10.2

TABLE 1: Comparing cross-feed relative level of the network of Fig. 2 in Col. 4 to relative acoustic level of Col. 3. Columns 1 & 2 are taken from respectively Fig. 4.2 on p.76, and Fig. 13.5 on p. 324 (azimuth = 45º), of Hearing by Gulick, Gescheider and Frisina, Oxford University Press, 1989.

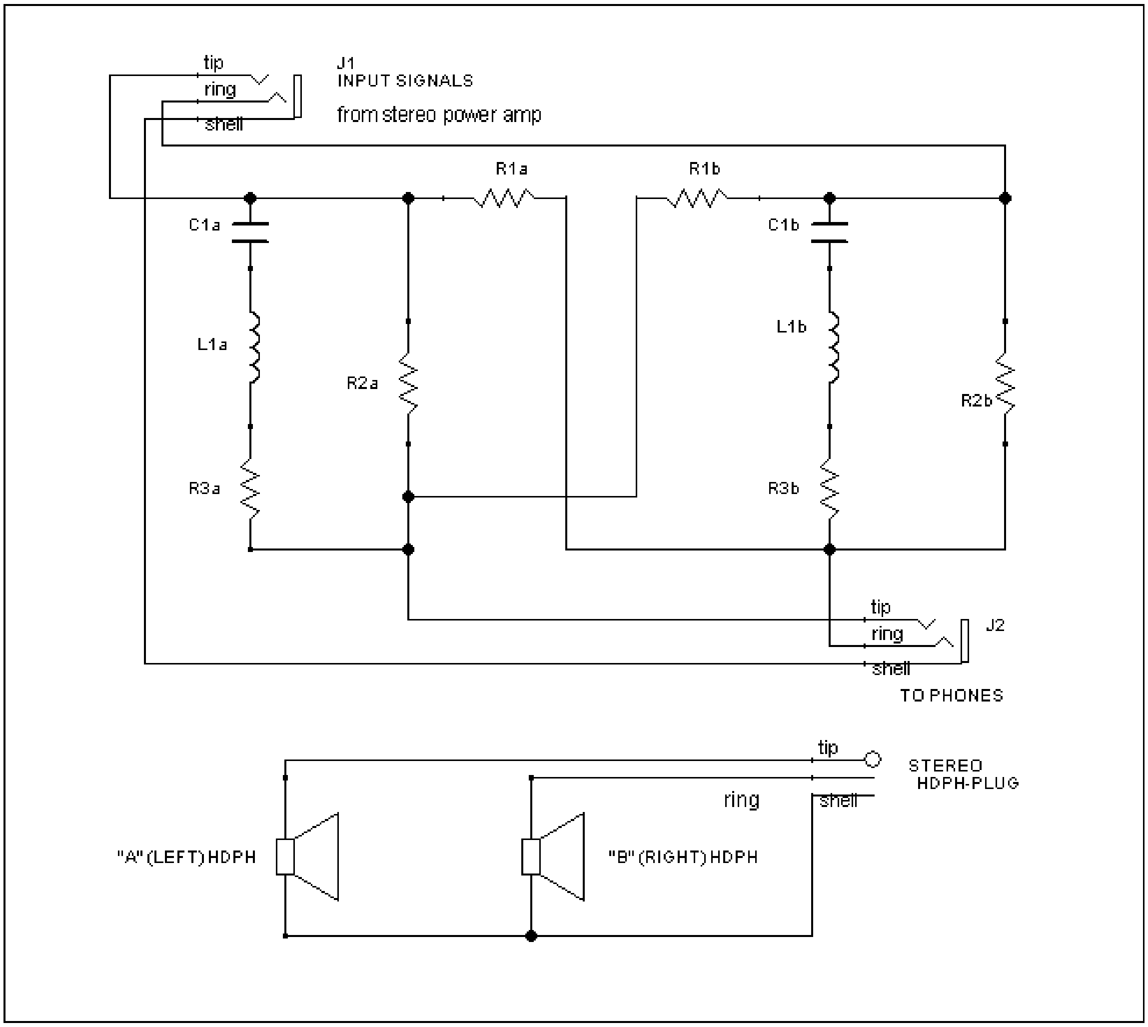

FIGURE 1: Cross-feed Network for Headphones

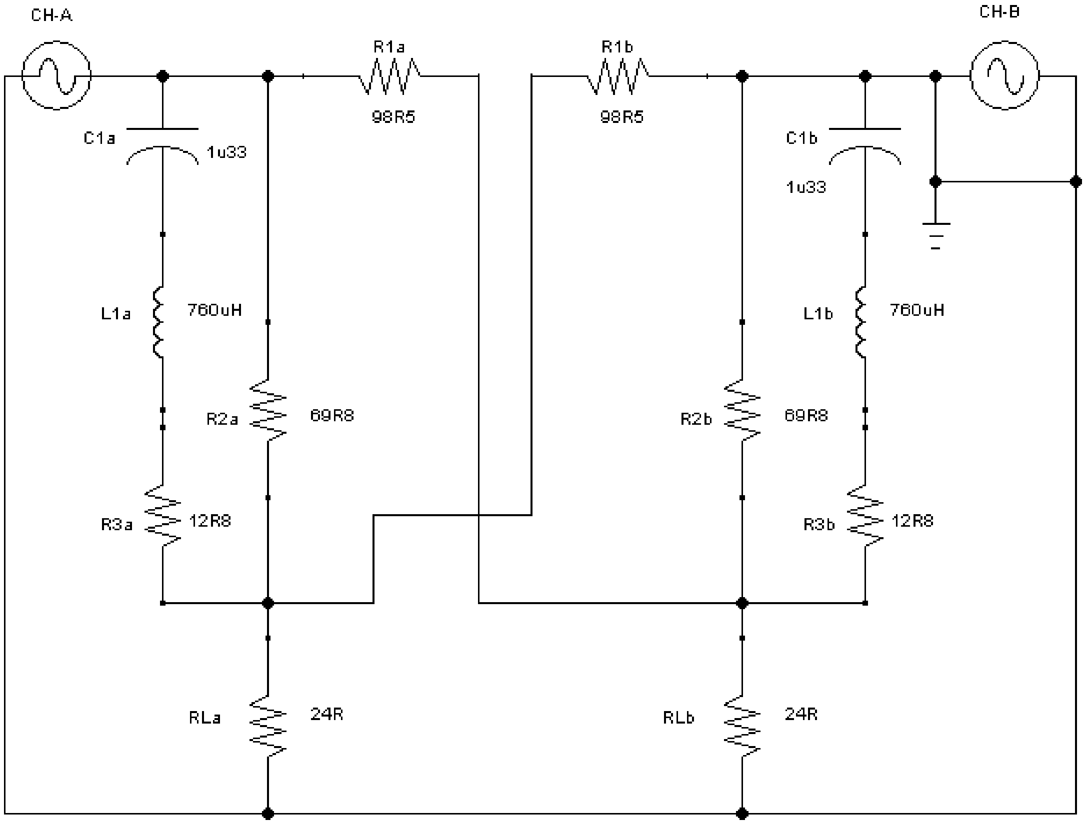

FIGURE 2: Application of superposition to the network of Fig. 1.

APPENDIX- FOR REFERENCE ONLY, NOT FOR PUBLICATION

A. Derivation of R1 = 1.41R2

Referring to Figure 2, given that frequency << the resonant frequency Fs equal to 5 kHz, then

$$\sqrt{R_3^2+\left\{X_{L1}^{\,2}+X_{C1}^{\,2}\right\}}\ //\ R2 \cong R2$$

where // stands for "in parallel circuit with".

The voltages E_i and E_{RLa} stand for respectively the CHA input voltage and the voltage drop across the "a" load resistor (standing for load of headphone "a"). Direct attenuation is the ratio of E_{RLa} with respect to E_i according to the equation,

$$\frac{E_{RLa}}{E_i}=\frac{R_{La}\ //\ R_{1b}}{\left(R_{La}\ //\ R_{1b}\right)+R_{2a}}$$

Cross-feed attenuation is the ratio of E_{RLb} with respect to E_i according to the equation,

$$\frac{E_{RLb}}{E_i}=\frac{R_{Lb}\ //\ R_{2b}}{\left(R_{Lb}\ //\ R_{2b}\right)+R_{1a}}$$

Solving for cross-feed with respect to direct attenuation,

$$\frac{E_{RLb}}{E_{RLa}}=\frac{R_{Lb}\ //\ R_{2b}}{\left(R_{Lb}\ //\ R_{2b}\right)+R_{1a}}\times\frac{\left(R_{La}\ //\ R_{1b}\right)+R_{2a}}{R_{La}\ //\ R_{1b}}$$

$$\frac{E_{RLb}}{E_{Rla}}=\frac{R_L\ //\ R_2}{R_L\ //\ R_1}\times\frac{\left(R_L\ //\ R_1\right)+R_2}{\left(R_L\ //\ R_2\right)+R_1}$$

$$\frac{R_L\ //\ R_2}{R_L\ //\ R_1}=\frac{R_2\left(R_L+R_1\right)}{R_1\left(R_L+R_2\right)}$$

$$\left(R_L\ //\ R_1\right)+R_2=\frac{R_LR_1+R_2\left(R_L+R_1\right)}{R_L+R_1}$$

$$\left(R_L\ //\ R_2\right)+R_1=\frac{R_LR_2+R_1\left(R_L+R_2\right)}{R_L+R_2}$$

$$\frac{(R_L // R_1) + R_2}{(R_L // R_2) + R_1} = \frac{(R_L + R_2)[R_L R_1 + R_2(R_L + R_1)]}{(R_L + R_1)[R_L R_2 + R_1(R_L + R_2)]}$$

Solving for E_{RLb} / E_{RLa} by substituting for the two multiplied terms to the right of the equal sign,

$$\frac{E_{RLb}}{E_{RLa}} = \frac{R_2(R_L + R_1)}{R_1(R_L + R_2)} \times \frac{(R_L + R_2)[R_L R_1 + R_2(R_L + R_1)]}{(R_L + R_1)[R_L R_2 + R_1(R_L + R_2)]}$$

$$\frac{E_{RLb}}{E_{RLa}} = \frac{R_2[R_L R_1 + R_2(R_L + R_1)]}{R_1[R_L R_2 + R_1(R_L + R_2)]}$$

$$\frac{E_{RLb}}{E_{RLa}} = \frac{R_2(R_L R_1 + R_L R_2 + R_1 R_2)}{R_1(R_L R_2 + R_L R_1 + R_1 R_2)}$$

$$\frac{E_{RLb}}{E_{RLa}} = \frac{R_2}{R_1}$$

According to the planned relative attenuation characteristic of the network,

$$20\log_{10}\frac{E_{RLb}}{E_{RLa}} = -3dB \Rightarrow \frac{R_2}{R_1} = 0.71$$

Finally,

$$R_1 = 1.41 R_2$$

B. Derivation of R3 = 0.13R1

Attenuation of E_{RLb} with respect to that of E_{RLa} is at a maximum at the series resonant frequency F_S of C1 in-series with L1. With respect to frequency equal to F_S, solve for attenuation of the direct and cross-feed voltage drops across the loads at Figure 2, then solve for E_{RLb} / E_{RLa}.

$$\frac{E_{RLa}}{E_i} = \frac{R_{La} // R_{1b}}{(R_{La} // R_{1b}) + (R_{3a} // R_{2a})}$$

$$R_{La} // R_{1b} = \frac{R_L R_1}{R_L + R_1}$$

Assume that R3 << R2. Then,

$$R_{3a} // R_{2a} \cong R_{3a}$$

$$\frac{E_{RLa}}{E_i} = \frac{R_L R_1}{R_L + R_1} \times \frac{R_L + R_1}{R_L R_1 + R_3 (R_L + R_1)}$$

$$\frac{E_{RLa}}{E_i} = \frac{R_L R_1}{R_L R_1 + R_3 (R_L + R_1)}$$

Solving for cross-feed attenuation again as occurs at resonant frequency F_S and referring to Fig. 2,

$$\frac{E_{RLb}}{E_i} = \frac{R_{Lb} \,//\, R_{3b} \,//\, R_{2b}}{(R_{Lb} \,//\, R_{3b} \,//\, R_{2b}) + R_{1a}}$$

Given the earlier assumption that R3 << R2,

$$R_{Lb} \,//\, R_{3b} \,//\, R_{2b} \cong \frac{R_L R_3}{R_L + R_3}$$

$$\frac{E_{RLb}}{E_i} = \frac{R_L R_3}{R_L + R_3} \times \frac{R_L + R_3}{R_L R_3 + R_1 (R_L + R_3)}$$

$$\frac{E_{RLb}}{E_i} = \frac{R_L R_3}{R_L R_3 + R_1 (R_L + R_3)}$$

Finally solving for cross-feed attenuation with respect to direct attenuation,

$$\frac{E_{RLb}}{E_{RLa}} = \frac{R_L R_3}{R_L R_3 + R_1 (R_L + R_3)} \times \frac{R_L R_1 + R_3 (R_L + R_1)}{R_L R_1}$$

$$\frac{E_{RLb}}{E_{RLa}} = \frac{R_3}{R_1}$$

$$20 Log_{10} \frac{E_{RLb}}{E_{RLa}} = -18 dB \Rightarrow \frac{R_3}{R_1} = 0.13$$

C. Derivation of R2 = 2.91RL

For frequency initially << the resonant freq. Fs, and increasing to Fs, to mimic gain of the outer ear, attenuation of the direct signal voltage should decrease by about 9 dB. Note that 20 times $\log_{10}$ of 2.8 equals 9 dB.

The direct signal voltage at Fig. 2 is E_{RLa}. Where // equals "in parallel circuit with", two simplifying assumptions are the following.

freq. << Fs → R2 // (C1-L1-R3) in series ≈ R2
freq. = Fs → R2 // (C1-L1-R3) in series ≈ R3

At Fig. 2, solving for E_{RLa} at freq. = Fs with respect to that same voltage at freq. << Fs,

$$\Delta E_{RLa} = \frac{\dfrac{R_{La} // R_{1b}}{R_{3a} + \left(R_{La} // R_{1b}\right)}}{\dfrac{R_{La} // R_{1b}}{R_{2a} + \left(R_{La} // R_{1b}\right)}} = 2.8$$

Thus

$$\frac{R_{2a} + \left(R_{La} // R_{1B}\right)}{R_{3a} + \left(R_{La} // R_{1b}\right)} = 2.8$$

$$R_1 = 1.41\, R_2 \wedge R_3 = 0.13\, R_1 \rightarrow R_3 = 0.18\, R_2$$

$$R_{2a} + \left(R_{La} // R_{1b}\right) = \frac{R_2\left(R_L + 1.41\, R_2\right) + 1.41\, R_L R_2}{R_L + 1.41\, R_2}$$

$$R_{3a} + \left(R_{La} // R_{1b}\right) = \frac{\left(0.18\, R_2\right)\left(R_L + 1.41\, R_2\right) + 1.41\, R_L R_2}{R_L + 1.41\, R_2}$$

$$\frac{R_2\left(R_L + 1.41\, R_2\right) + 1.41\, R_L R_2}{\left(0.18\, R_2\right)\left(R_L + 1.41\, R_2\right) + 1.41\, R_L R_2} = 2.8$$

$$R_2 R_L + 1.41\, R_2^2 + 1.41\, R_2 R_L = 0.5\, R_2 R_L + 0.71\, R_2^2 + 3.95\, R_2 R_L$$

$$1.41\, R_2^2 - 0.71\, R_2^2 = -2.41\, R_2 R_L + 4.45\, R_2 R_L$$

$$0.7\, R_2^2 = 2.04\, R_2 R_L$$

$$0.7\, R_2 = 2.04\, R_L$$

$$R_2 = 2.91\, R_L$$

D. Minimum Network Impedance

Minimum load to the amplifier occurs at resonance, so the relevant components determining the load seen by the amp are R1, R3 and RL (standing for headphone impedance). As has been previously calculated,

R1 = 1.41R2 & R2 = 2.91RL → R1 = 4.1RL

R3 = 0.13R1→ R3 = 0.53RL

Referring to Fig. 2, the direct signal leg has R3 in-series with the parallel combination of RL and R1. Call the direct signal leg R_{T1} and // equals "in parallel circuit with".

$$R_1 // R_L = \frac{4.1 R_L \times R_L}{4.1 R_L + R_L} = 0.8 R_L$$

$$R_{T1} = R_3 + R_1 // R_L$$

$$R_{T1} = 0.53 R_L + 0.8 R_L = 1.33 R_L$$

Continuing at Fig. 2, the cross-feed signal leg consists of R1 in-series with (RL // R3).

$$R_3 // R_L = \frac{0.53 R_L \times R_L}{0.53 R_L + R_L} = 0.35 R_L$$

Call the cross-feed signal leg R_{T2}.

$$R_{T2} = R_1 + 0.35 R_L$$

$$R_{T2} = 4.1 R_L + 0.35 R_L = 4.45 R_L$$

Finally, the (minimum) load as seen by the amplifier at resonance of the network is equal to R_{T1} // R_{T2}.

$$R_{T1} // R_{T2} = \frac{\left(1.33 R_L\right)\left(4.45 R_L\right)}{1.33 R_L + 4.45 R_L}$$

$$R_{T1} // R_{T2} = \frac{5.92 R_L^2}{5.78 R_L} = 1.02 R_L$$