Loudness Control for Reproducing Systems

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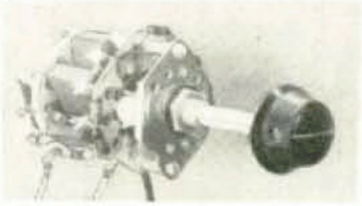
By using the device described, it is possible to maintain a close tonal balance over a wide variation in output level.



Complete loudness control unit.

A NUMBER of different methods have been utilized to control the output of reproducing systems in such a manner that the tonal balance is maintained reasonably constant at all intensity levels. These controls are essentially variable equalizers which modify the gain-frequency characteristic of the system as the intensity is changed; the desired equalization being specified by the intensity vs. loudness characteristics of the human ear. An ordinary resistive potentiometer is actually a simple intensity control, while a properly equalized intensity control might be termed a loudness control. To maintain constant tonal balance as the intensity is changed, the intensity at low frequencies must be changed less than that at high frequencies. The consequence of changing the intensity equally at all frequencies has been experienced by anyone who has noted the apparent lack of bass in the average radio at low volume settings.

A common type of loudness control employs a tapped potentiometer, with a capacitor and resistor in series between the tapped point and ground. This rather elementary structure is a large step in the right direction, and is attractive because of its simplicity. This very simplicity, however, renders it capable of yielding only a moderate approximation to the ideal. The loudness control to be described is an elaboration of the tapped potentiometer, and was designed for those applications in which a considerably closer approximation to the ideal is desired, even though some extra cost is involved.

Fletcher-Munson Curves

The basis for design of a loudness control is the set of curves shown in *Fig. 1*. These are the well-known data of Fletcher and Munson, and are the averaged results of measurements taken with a large number of individuals. Each curve represents a particular loudness, measured in decibels from a reference level; the ordinates of the curve show the intensity in decibels corresponding to that loudness. The departure of these curves from horizontal lines spaced 10 db apart on the intensity scale represents the need for a loudness control. It was concluded that the departure at frequencies above 1000 cps was relatively unimportant, and that only the low-frequency end would be considered. This leads to an appreciable simplification of the problem. Nevertheless, a single network to produce a large loudness change would require a rather complex array of elements because of the rapid change of intensity with frequency. A large loudness change can more readily be built up by the addition of a number of smaller changes, each having an appropriate intensity vs. frequency characteristic. This procedure is facilitated by the fact that the intensity differences between adjacent loudness curves are quite similar. An excellent approximation to the ideal may be realized by a control which inserts successive units of loss, each similar to the other, and having a loss-frequency characteristic proportional to the average intensity differences between loudness curves. These averages are presented in *Fig. 2* as gain-frequency characteristics for 10 db, 6 db, and 3 db loudness intervals. The 3 db interval was chosen for design; it has been found that this increment is sufficiently small for almost all applications where only the listener's reaction need be considered.

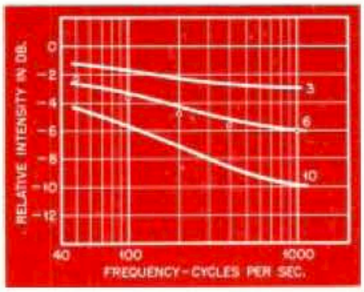


Fig. 2. Curves showing the frequency characteristic of each network section at various intensity levels.

It is evident, now, that the loudness control may take the form of a switching device which inserts, successively, a suitable number of identical network sections somewhere in the reproducing system. These sections are designed, on an image impedance basis, to match the characteristic of the 3 db loudness change of *Fig. 2*, and are inserted between proper terminating impedances. As many of these sections may be placed in tandem as are required to produce the desired loudness change. While this

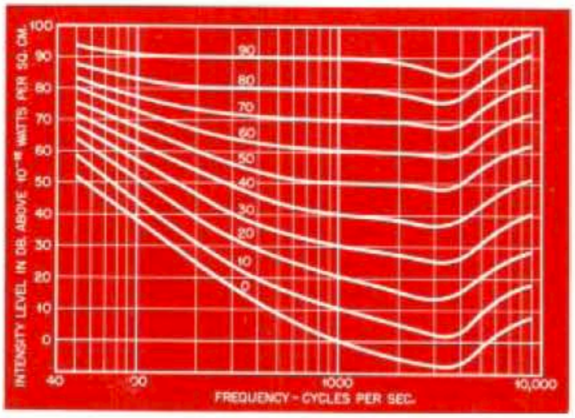


Fig. 1. Fletcher-Munson curves.

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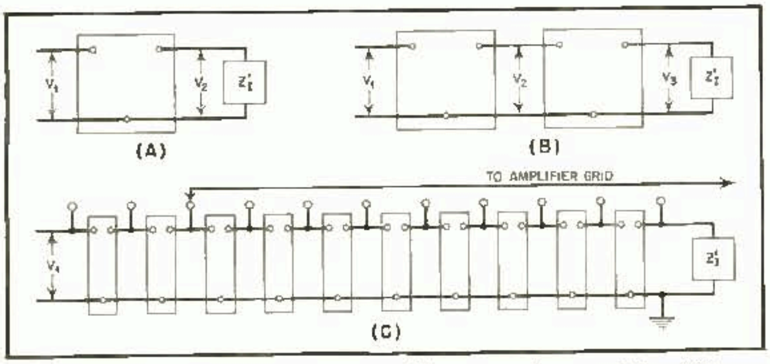

Fig. 3. In (A), representation of network. In (B), two networks in parallel, and (C), ten section in tandem.

control would be satisfactory in its performance, the switching mechanism would be rather unwieldy. A somewhat simpler method of attaining the same end is available.

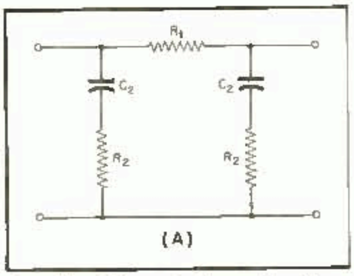

Fig. 4A. Schematic of network section.

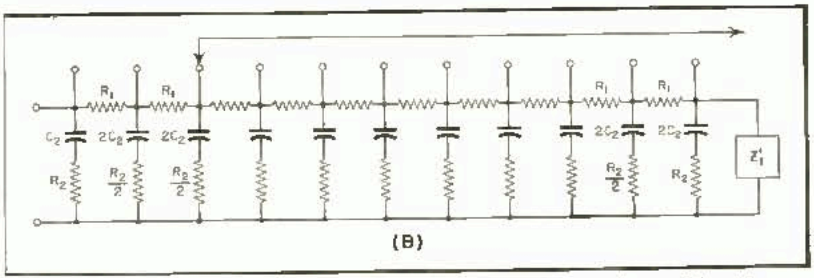

Fig. 4B. Schematic of complete loudness control using the network design of Fig. 4A.

Transfer Constant

The transfer constant of a network designed on an image impedance basis defines the complex ratio between the voltages across the input and output terminals of the network, when the output is terminated in the proper image impedance. Thus, in *Fig. 3-A*, the voltage V_1 on the input terminals is related to the voltage V_2 on the output terminals by the equation

$$\frac{V_1}{V_2} = \epsilon^{\theta}$$

In this equation θ is the complex transfer constant whose real part is the loss of the network in nepers. If two identical networks are connected in tandem, as in *Fig. 3-B*, then three voltages exist, related as follows:

$$\frac{V_1}{V_2} = \epsilon^{\theta}, \quad \frac{V_2}{V_3} = \epsilon^{\theta}, \quad \frac{V_1}{V_3} = \epsilon^{2\theta}$$

Thus the ratio of voltages between input and output of this two-section network is defined by 2 θ, and the loss in nepers (or in decibels) at any frequency is just twice that of one section. Consider, now, ten sections in tandem with an appropriate terminating image impedance Z'_I, as in *Fig. 3-C*. Let the input to the network be the voltage output, V_1, of a vacuum tube amplifier. Let an eleven-position switch connect the grid of a second vacuum tube amplifier to any of the eleven connection points of the chain. If each network section has a transfer constant such that its transmission is represented by the 3 db curve of *Fig. 2*, and the terminating impedance is the proper image impedance for that network section, this structure will be a loudness control with 30 db total loudness change, in 3 db steps.

Network Section

A satisfactory network section is shown in *Fig. 4-A*. The transmission of this section can be made to match the desired characteristic quite closely. It would, however, require ten series resistors, R_1, eleven shunt arm resistors, R_2, and eleven shunt arm capacitors, C_2, to construct the loudness control of *Fig. 4-B*. The number of shunt arms with their expensive capacitors may be halved by using, instead of ten 3 db sections, five 6 db sections each divided into two parts. Unfortunately, the voltage in the middle of a section is not related to that at the ends by half the transfer constant; still, the section can be divided in such a manner that exactly half the high frequency loss exists across each portion with only a minor distortion of the low-frequency loss. The exact manner in which the section is divided depends on the image impedance of the section, which in turn requires that the element values be specified. *Figure 5-A* presents the design of a section which has

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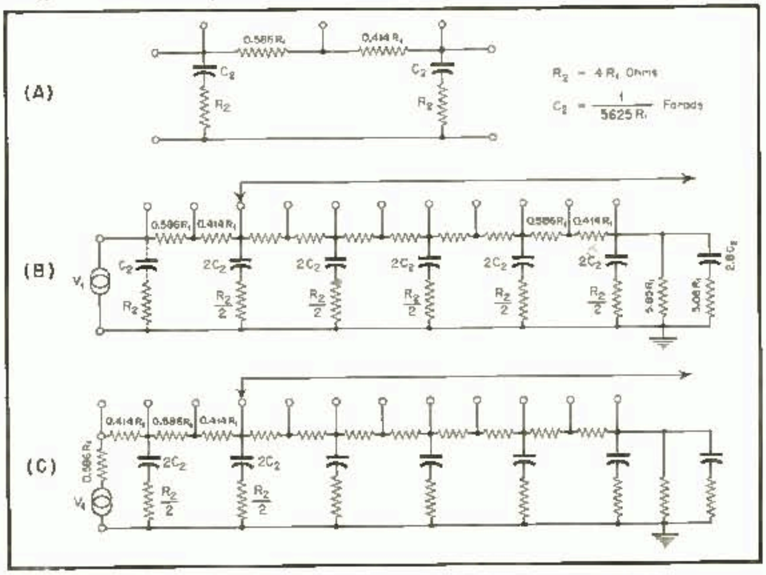

Fig. 5A. Design of section calculated to provide the characteristic shown by circles in Fig. 2.

Fig. 5B. Complete loudness control, including terminating network.

Fig. 5C. Arrangement when the amplifier resistance is 0.586R1.

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the calculated full-section transmission shown by the circles on *Fig. 2*. *Figure 3-B* shows the complete loudness control including the terminating network. The exact image impedance can only be obtained by an infinite number of additional sections, but the elements shown are entirely adequate. The impedance level of the control is determined when R_1 is chosen. This choice will be influenced by the effects of parasitic capacitance in the switching, the desirability of using RMA values for the elements, and the amplifier to be used as a drive for the control.

Amplifier Problems

The problem of the amplifier can be analyzed as follows: consider first that the amplifier has zero internal resistance. The removal of the first shunt arm (shown connected by dotted lines in *Fig. 3-B*) will not affect the voltage at the input to the network, nor the transmission through it. The load presented to the amplifier is now made up of the first two series resistors, which total R_1, plus the balance of the network. This remainder has an impedance which varies from a very high value at low frequencies to R_1 at frequencies above 1000 cps.

When the amplifier has a non-zero internal resistance, two alternatives are available. If R_1 may reasonably be made ten times the magnitude of the amplifier resistance, the amplifier can be considered to have effectively zero resistance, and the network may be reduced by leaving off the first shunt arm. An attempt at this procedure may lead to a value of R_1 which is too large for the parasitic capacitances that will be present in the switching. In this event, R_1 may be adjusted so that the amplifier resistance is any convenient fraction of R_1. The network is now augmented: the first shunt arm is made the same as the others, and the difference between R_1 and the amplifier resistance is inserted between the amplifier and network input. In the special case of an amplifier resistance equal to 0.586 R_1, the added resistance is 0.414 R_1, and an extra loudness interval is available at the amplifier terminals. This arrangement is illustrated in *Fig. 3-C*; it will be seen that one 3 db loudness interval is inside the amplifier, and so cannot be switched out. If R_1 were adjusted to equal the amplifier resistance, the added resistance is zero; in this case, there is a 6 db loudness interval inside the amplifier.

The network elements may be mounted on a two-deck wafer type switch with shorting contacts. One deck is used for switching, and has the resistors of the series arms mounted between terminals. The capacitors of the shunt arm are mounted between corresponding terminals of the two decks. Shunt arm resistors and terminating elements are then arranged on the circular area of the second deck with a ground termination in the center. The moving arm of this deck should be removed. Constructed in this fashion, the loudness control does not require an excessive mounting space.

A representative network is one which has the basic element values:

R_1	50,000 ohms
R_2	200,000 ohms
C_1	0.00355 μf

Values which approximate the individual network components are:

.586 R_1	30,000 ohms
.414 R_1	20,000 ohms
.500 R_2	100,000 ohms
2 C_1	.0068 μf
5.85 R_1	300,000 ohms
3.08 R_1	150,000 ohms
2.8 C_1	.010 μf

A loudness control built with these elements, and driven from a low impedance source, has the measured characteristics shown in *Fig. 5*. The several approximations made in the design, as well as the element deviations, have but small effect on the over-all performance.

It will be recognized that this control is accurate only in producing appropriate changes in intensity. To be correct on an absolute basis, each program to be reproduced should be adjusted by a resistive control elsewhere in the system so that with the loudness control at the top position, the acoustic intensity is equal to that of the original sound. This adjustment is rather impractical. Nevertheless, when the loudness control is simply used as a replacement for the ordinary resistive volume control, quite gratifying results are obtained. The most conclusive evidence of the superiority of this loudness control over flat intensity control is that a low level of intensity in the reproduction of music is as enjoyable as the higher level usually required for good tonal balance.

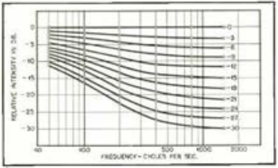

Fig. 5. Measured characteristics of loudness control constructed from data supplied in this article. It closely approximates hearing curves.