The Selection of Tone-Control Parameters

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Proper design of tone controls requires a study of the conditions which must be corrected. The author delineates these conditions, and explains the requirements for each.

VARIOUS TONE-CONTROL circuits with given transition frequencies[1] and rates of boost or cut have been extensively discussed in technical literature. Little has been written, however, about considerations involved in the selection of the response-curve parameters, which sometimes seem to be chosen more or less arbitrarily. While "flat" power amplifier stages are carefully designed for an audio-frequency response which is kept to a maximum random deviation of a fraction of a decibel, improper tone compensation (either manual or automatic) in the same amplifier may introduce, or leave uncorrected, very large inaccuracies of frequency distribution relative to the perceived original. These inaccuracies have on occasion completely overshadowed the benefits of the above-mentioned careful design, and have become a primary factor in determining over-all quality.

Fixed tone equalization is used when the frequency characteristics for which compensation is being made are constant. Modern home reproducing systems contain several fixed or automatically variable audio equalization circuits associated with FM pre-emphasis, recording characteristics, pickup frequency distortion, or changes of volume level. The inclusion of such circuits does not make variable tone control superfluous, since there are many unpredictable conditions for which it may be desirable to adjust the frequency response of the reproducing equipment.

The designer of fixed equalizers does not ordinarily have to worry about what parameters to use; with certain exceptions his transition frequencies, and the required rate of boost or cut, have been exactly determined by his problem. In contrast a tone-control designer must furnish the means for correction, by the same circuit, of all sorts of signal aberrations. He can either provide a complex control system which allows for equalization of almost any frequency conditions, or he can reduce the flexibility of control, choosing compromise response curve parameters which are capable of producing approximate compensation for those conditions most likely to be encountered. The degree of tone-control complexity accepted in non-professional equipment has increased quite a bit since the day of the single treble-cut switch, and the most common arrangement in current audio amplifiers is a two-control, continuously variable system. This allows progressive cut or boost of either bass or treble, but no independent control of the reference frequencies at which the response curves begin their slopes.

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[1] The transition frequency is the intersection of the theoretical linear slope of the response curve (a slope which the actual curve only approaches) with the frequency axis—see *Fig.* 5.

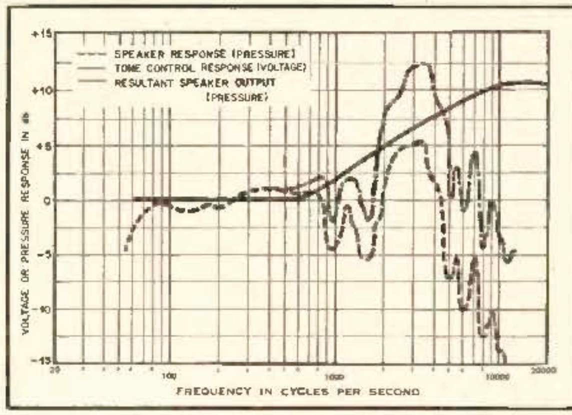
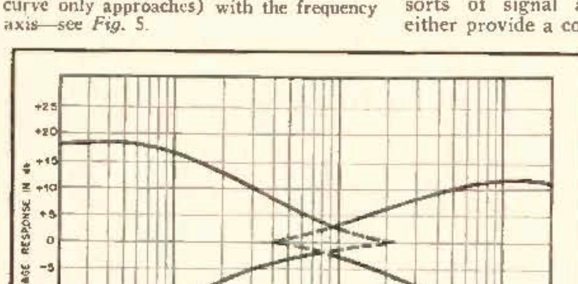


Fig. 3. Resultant frequency response of an audio system using a commercial speaker in the $50 class and the treble boost of (A), Fig. 1.



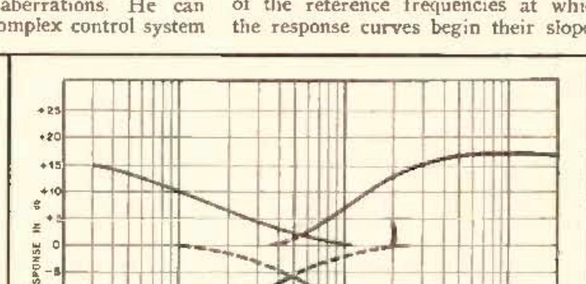


Fig. 1. (A), Voltage response curves of a typical commercial tone control circuit of the R-C type, maximum positions. (B), Voltage response curve of a commercial tone control circuit of the L-R-C type, maximum positions.

A circuit which introduces a progressive response slope rather than uniform elevation or depression of a whole band of frequencies, besides being of far simpler design, provides the desired form of compensation in most applications. It is common although not universal practice for dual tone controls to use approximately the same transition frequency region, usually at or below 1,000 cps, for both bass and treble variation. *Figure* 1 shows the response curves of two such tone control circuits employed commercially.

The justification for selecting this reference frequency region is that it is considered psychologically "neutral" in pitch. It has been pointed out that 800 cps is the geometric mean between 40 and 16,000 cps, frequencies which may be taken as nominal limits of hearing under average conditions. Since the perception of frequency, like that of amplitude, closely follows the Weber-Fechner law (in that the degree of sensation varies logarithmically with the stimulus) the geometric and not the arithmetic mean of the audible frequency spectrum is its psychological mid-point. Thus there are about four and one-half octaves of useful audio frequencies on each side of 800 cps.

If we assume, however, that the operator's adjustment of tone controls is in the nature of a search for maximum fidelity to the perceived original, the psychological mid-point ceases to have much significance. Tone control becomes tone compensation, and the problem of response-curve parameters revolves about the question of what the controller must be equipped to compensate for. In the following discussion it will be assumed that the amplifier is being designed as an independent unit, and that the brands of components with which it is to be used are not known.

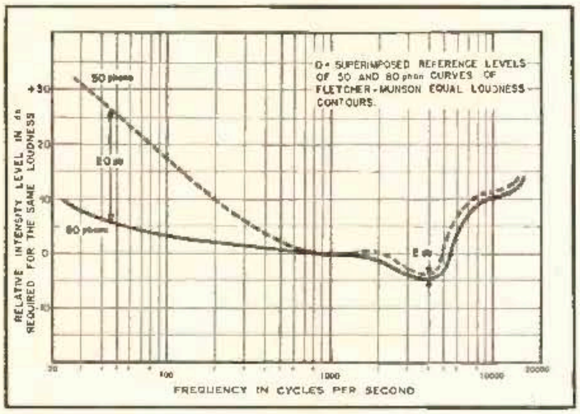


Fig. 4. The 50- and 80-phon equal loudness contours (from Fletcher and Munson) superimposed.

Treble Boost

The most common purposes for which treble boost will be needed are:

1. Compensation for treble deficiencies in associated reproducing equipment.
2. Compensation for treble deficiencies in program material.
3. Compensation for discriminatory acoustic absorption with a frequency characteristic different from that of the hall or studio in which the sound originated.

An additional purpose for which treble boost has on occasion been considered necessary, but is not, is compensation for the variation in hearing frequency characteristics associated with changes of sound intensity level. This factor, referred to as the Fletcher-Munson effect, will be discussed in the paragraphs devoted to bass boost.

Equipment treble deficiencies are usually most severe in electro-acoustic devices such as loudspeakers, pickups, and recording heads, but also occur in coupling circuits in audio or intermediate-frequency amplifiers.

The worst offender in a given system is ordinarily the loudspeaker. In *Fig.* 2 manufacturers' published on-axis response curves for six speakers in different price ranges are plotted. Although the performance represented by these curves will vary greatly under different acoustical conditions the graphs may be taken as indicators of a general trend. There is one feature which all may be seen to have in common, and which is characteristic of the great majority of cone loudspeakers with high-frequency droop; the frequency region of the first two octaves above 1,000 cps, far from being attenuated, is accentuated (because of the new resonances introduced by cone break-up), and treble droop does not begin before 4,000 cps or higher. This fact has a significance beyond the obvious implication concerning compensation for speaker deficiencies. Any losses in the first two treble octaves which are likely to be met with from other causes will probably be compensated or even over-compensated by speaker characteristics.

Crystal phonograph pickups have a typical velocity response above a few hundred cps which decreases with frequency quite regularly up to a rather sharp cut-off somewhere between 4,000 and 10,000 cps. When this regular droop does not conform to the desired recording characteristic further compensation is properly provided by a fixed R-C network rather than by the tone control. The comparatively smooth and accurately predictable slope lends itself to fixed equalization, and the recommended circuits or necessary data for their design are usually readily available from the manufacturer. But whether or not such a fixed network is provided, the treble boost control cannot be designed

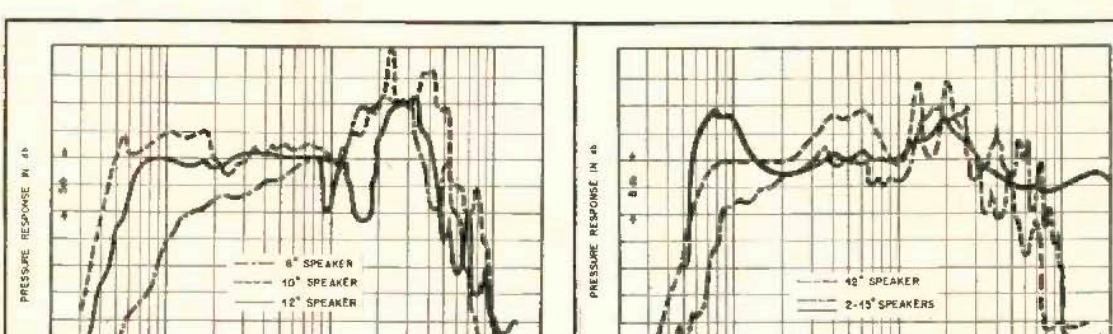


Fig. 2, (A) and (B). Pressure response curves of three commercial speakers in a price range of $20 to $150.

for correct crystal pickup equalization except for the second droop, because the required transition frequency would be well into the bass region.

The contribution of high-frequency losses by other components cannot, of course, be predicted, except as to one factor; it may be expected that losses will be confined to frequencies above the second treble octave. A survey of circuit components, recording heads, etc., will indicate that it is rare for treble droop to set in before 4,000 cps or so. Even AM broadcast band i.f. transformers provide, at worst, relatively even coupling to 3,000 cps.

Treble deficiencies in program material may result from low-grade studio equipment, from transmission circuits, and from old records. Such losses are almost always associated exclusively with the third and/or fourth treble octaves.

The writer has not found a quantitative study which compares the frequency transmission of typical living rooms with that of halls or studios, although methods for room transmission measurements have been outlined.[2] Therefore no comment will be made on the subject other than to mention the fact that room acoustics—notably the reverberation time *versus* frequency relationship—may be a factor requiring tone compensation. Reference is made to this factor under the heading of treble boost merely on the basis of subjective experience, but undoubtedly other compensations are also involved.

When treble boost is needed, then, a high transition frequency is usually desirable. The use of a lower transition frequency for the sake of increasing the amount of boost available at the upper end might prove satisfactory if it were not for the marked tendency of loudspeakers to emphasize the frequency region of the first few thousand cps. A transition frequency of 1,000 cps or lower may cause treble boost to accentuate a shrillness towards which the speaker performance is already inclined, and needed boost at frequencies above 4,000 cps may carry such a penalty that the compensation will not be used. This unhappy effect is illustrated by *Fig.* 3, in which the tone-control and speaker-response curves of two high-grade commercial units are combined.

Determination of an optimum transition frequency that will best suit the various requirements of treble boost cannot be made with precision, but it would seem that present commercial practice makes use of a frequency which is at least two octaves too low. The operator of the set may be impressed with the dramatic power of his treble boost but may still be loath to use it. (Some British manufacturers lean towards higher transition frequencies for treble emphasis—one manufacturer uses 3,500 cps.)

A single R-C network can approach 6 db per octave in rate of boost. The simplicity of the single network is one good reason for accepting this slope as the maximum, and it will prove ample for most purposes, particularly in view of the fact that treble emphasis brings to the fore harmonic distortion in the higher ranges. If the transition frequency is chosen as 3,200 cps—two octaves above 800 cps—an insertion loss of 20 db will produce something less than 12 db of maximum boost at 13,000 cps, including about 3 db of boost at the reference frequency itself. These characteristics seem to represent a reasonable compromise between the requirements of all factors. The use of an even higher transition frequency might be desirable, but would place a greater limitation on the maximum boost of useful frequencies that could be achieved with a single R-C network.

Treble Attenuation

Treble attenuation is required for:

1. Compensation for varying treble pre-emphasis in recording.
2. Reduction of record suface noise and high-frequency distortion.
3. Compensation for rising treble response of associated reproducing or studio equipment.
4. Tonal balance against a thin bass.

Treble pre-emphasis in recording varies considerably, and there is no standard, either of transition frequency or rate of boost, to which recording companies subscribe. Table 1 lists some of the different ways in which the treble spectrum is or has been treated by record manufacturers.

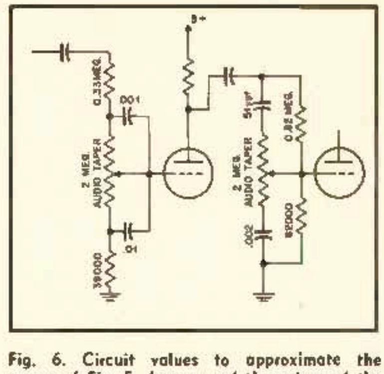


Fig. 6. Circuit values to approximate the curves of Fig. 5. As many of the values of the original Æ circuit as possible have been retained.

Although treble recording characteristics are ideally equalized at the pickup, variable pickup equalizers are still the exception rather than the rule, and the tone-control designer must assume that at least some of the burden will fall on the treble-cut control. If the setting for minimum treble furnishes close to 6 db of attenuation per octave from a transition frequency of 2,000 cps, approximate compensation for any of the recording pre-emphasis curves can be achieved.

TABLE 1

Typical Transition Frequencies

Records	Transition Frequency (cps)	Rate of Boost (db/octave)
AES Standard Curve	2500	6
Columbia 78 & 33 1/3[3]	1590	6
RCA 78[3]	1000	2.5
London ffrr 78[3]	3000	3
London 33 1/3[3]	3000	6
EMI 78[4]	—	none
Older records	—	none

Settings of the treble control which yield less than maximum attenuation will also, in most circuits, automatically shift the transition frequency higher, correcting equalization for some of the records with more gradual pre-emphasis slopes. The desirability of equalization for treble recording characteristics prior to the tone control is emphasized by the differences between the transition frequencies of some of these recording curves and the frequencies at which the equipment deficiencies previously discussed introduce treble losses. For example, an improperly equalized disc which has been recorded with a given treble characteristic can present an unsatisfying choice between shrill and muffled reproduction, because the tone

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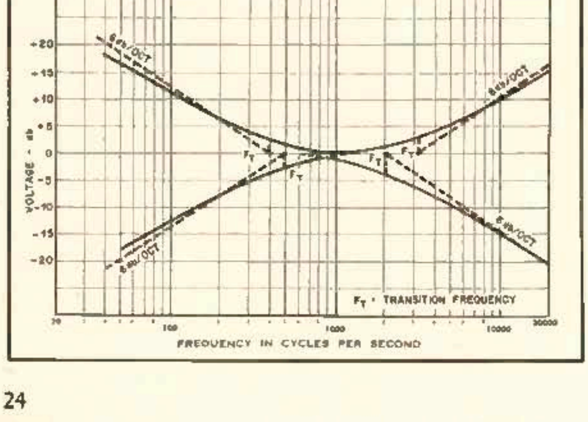

Fig. 5. Suggested tone control frequency characteristics, controls at maximum positions.

[2] E. C. Wente, "The characteristics of sound transmission in rooms," *J. Acous. Soc. Am.*, 7, p. 134, Oct., 1935.

[3] Paul W. St. George and Benjamin B. Drisko, "Versatile phonograph preamplifier," AUDIO ENGINEERING, 33, p. 14, March, 1949.

[4] D. T. N. Williamson, "High-quality amplifier modifications," *Wireless World*, 58, p. 173, May, 1952.

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control may not be able to compensate for the characteristics of both the record and the reproducing equipment.

It has been established by several investigators that record-surface noise is fairly evenly distributed over the frequency spectrum on the basis of energy content per cycle. Since each arithmetic frequency interval has a similar amount of noise energy, the noise content will increase with each successively higher octave.[5] It is therefore correct to think of perceived surface noise as increasing with frequency, and compensation for treble pre-emphasis in recording is very effective in reducing scratch, as the system intends it to be.

There is however, an advantage in being able to introduce sharp cut-offs at given points of the frequency band, since records which have little or no frequency content above the cut-off point can then have their surface noise reduced without the signal being severely penalized. Some types of distoration are also most pronounced in the range above 5,000 cps, and sharp cut-off helps reduce such effects with least change of the signal. Sharp cut-off at high frequencies, however, is incompatible with the other duties of the treble tone control, and should be accomplished by separate networks. The general tone control must be limited in its scratch reducing role to a more gradual attenuation of the treble band.

Certain microphones, if incorrectly equalized at the studio, have a rising treble response above one or two thousand cps. Attention is occasionally called to this characteristic when broadcast studio use of an incorrectly compensated microphone produces over-crisp and "hissy" speech. The compensation required for this type of emphasis is compatible with that already planned for records.

Tonal balance of bass and treble for the most satisfactory over-all result is an inherently subjective problem. Like compensation for the Fletcher-Munson effect, it involves a decrease of objective fidelity for the sake of an increase in apparent realism. The fact that the problem is one of perception rather than of reality indicates that investigation requires a statistical technique.[6]

[5] B. B. Bauer, "Crystal pickup compensation circuits," *Electronics*, 17, p. 128, Nov., 1945.

[6] It is suggested that a useful approach would be to compile judgment data in which the jury compares various conditions of tonal balance, both symmetrical and asymmetrical to 800 cps, with the full range of sound, indicating which condition seems more like the undistorted one. (Asking the jury to indicate preference between balanced and unbalanced conditions, without an ever-present standard, involves the danger of measuring factors other than apparent frequency distortion.)

Discussions of aural balance[7] have indicated that approximately equal frequency distortion, geometrically relative to the frequency mid-point, is more desirable than unequal frequency distortion, but that there is considerable latitude in design for balanced response. The parameters of treble attenuation for achieving careful balance would be determined by a study of bass deficiencies likely to be met with. The treble attenuation discussed in previous paragraphs is fairly symmetrical to most of these low-frequency deficiencies.

It will be seen that the transition frequency suggested for treble attenuation is different from that for treble boost, and conditions are likely to exist in which both are required simultaneously. Such simultaneous compensation, however is inherently barred when a single control is used for both boost and cut.

Bass Boost

The conditions requiring bass boost are:

1. Decreased hearing sensitivity to bass frequencies at low sound intensities (Fletcher-Munson effect).
2. Recording characteristics whose bass turnover frequency is higher than the one for which the repoducing equipment is designed.
3. Bass deficiencies in records.
4. Bass deficiencies in reproducing or studio equipment.

The well known family of equal loudness contours published by Fletcher and Munson makes it evident that the apparent frequency distribution of energy in given program material will vary greatly at different intensity levels. If the amplifier has a correctly designed compensating network associated with its volume control this effect will be counteracted, but the volume control setting required for a desired intensity level is not necessarily an accurate index of the intensity level of the original program, and further adjustment may be necessary. The electrical level of an input signal does not have a constant relationship, in different program material, to the sound level which it represents.

The purpose of volume compensation is not, of course, to straighten out the curve of frequency perception, (that's the way the music sounds in the concert hall) but to shape this curve at the reproduced intensity level so that the perceived frequency distribution is similar to the perceived distribution at the original intensity. We may take 80 db[8] as the average level of a 75-piece orchestra heard from a good seat, and 50

[7] Hugh S. Knowles, "Loudspeakers and room acoustics," *The Radio Engineering Handbook*, Keith Henney, editor, p. 881, 3rd edition, 1941.
[8] Ibid.

db[9] as the lowest level at which this music is likely to be reproduced, with any concern for quality, in the living room. Superimposing the two appropriate curves on the same horizontal axis (*Fig.* 4), it will be seen that in order to achieve the original perceived frequency distribution in reproduction at the 50-db level, bass boost at slightly more than 6 db per octave, with a transition frequency of 400 cps, is required. This is, of course, for the extreme case of a 30-db difference between the original and the reproduced level. At this 30-db difference the bass boost required during orchestral peaks, when both levels may be increased by 20 db, is much less; during very soft passages the boost required will be more. We must work on the basis of the average levels.

The 50- and 80-phon curves, and the 60- and 70-phon curves in between, are practically identical in shape and slope from 500 cps up, meaning that a reduction of intensity level from 80 db to 50 db will produce no significant change in the apparent frequency distribution in the treble region. Even if it were desired to compensate for the 2-db maximum loss in treble, the ordinary R-C network could not produce the necessary shape of response curve, which may be read from *Fig.* 5 as a uniformly elevated plateau over most of the treble spectrum. Correct volume compensation should therefore involve no adjustment of treble frequencies.

If the record reproducing equipment has only a single turnover frequency a compromise value of 500 to 600 cps is usually chosen. Some records have been made with higher turnover frequencies as high as 800 cps. Thus a moderate amount of boost to add to that of the fixed equalization will on occasion be called for. Such equalization, however, is required by a relatively small number of records.

Acoustically recorded discs, and some electrically recorded ones, have a thin bass because of weaknesses in recording equipment and techniques. These ordinarily require boost below two or three hundred cps, although the drop in bass response is in general too sharp for adequate compensation.

Bass deficiencies in reproducing equipment, like treble deficiencies, alto tend to occur towards the extreme of the frequency scale. Most moderate quality loudspeakers (see *Fig.* 2), pickups, etc., do not show a significant drop in bass response until frequencies below 100 cps, and then with sharply dropping curves. Here too compensation cannot be adequate.

Adjustment for the Fletcher-Munson effect is probably the most frequent function of bass boost. The transition frequency required for this equalization lies between that for a high turnover frequency and for record and equipment deficiencies, and the compromise parameters that appear most reasonable to the writer include a transition frequency one octave down from the spectrum mid-point, or 400 cps, and the standard maximum boost rate of 6 db per octave.

Bass Attenuation

Bass attenuation may be required for the following conditions:

1. Recording characteristics with a bass turnover frequency lower than that of the reproducing equipment.
2. Accentuation and distortion of bass frequencies by reproducing equipment.
3. A weak treble which creates tonal imbalance.

The required compensation for equipment designed with a 500-cps turnover, and playing a record with a turnover frequency of 250, 300 or 400 cps (all of which values have been used) may be approximately achieved by a gentle attenuation of about 2 db per octave from 750 cps down, or by a sharper downward slope from a lower transition frequency of 500 cps. The second method is more consistent with the other requirements of bass cut.

Bass accentuation in reproducing equipment is most often associated with acoustical resonance of an open speaker enclosure at some frequency below 200 cps and with mechanical-acoustical resonance of the speaker system below 100 cps. The effects of tone-arm resonance and turntable rumble usually occur below 50 cps. As in the case of low-frequency boost, we cannot furnish accurate compensation for equipment frailties at the extreme low end, but we can alleviate the condition in some measure.

Aural balance of a weak treble appears to demand a low transition frequency. Probable treble droop occurs, as we have seen, at least two octaves above 800 cps, and geometrically symmetrical bass losses would begin at about 200 cps.

A reference frequency and slope to compromise between the various requirements for which bass attenuation will be needed are: transition frequency 500 cps, maximum slope, 6 db per octave.

Conclusion

Figure 5 is a graph of tone-control frequency characteristics chosen on the basis of the above discussion. The parameters vary from many of those in common commercial use in that the reference frequencies are shifted away from the spectrum mid-point, about one octave down for the bass, and two octaves up for treble boost. As a consequence the total amount of control is somewhat less than is often provided.

Figure 6 is a tone control circuit with values assigned to approximate these curves. Some allowance has been made for the fact that the transition frequencies are affected by the degree of boost or cut used by the operator.

[9] "*Frequency Range and Power Considerations in Music Reproduction,*" Jensen Technical Monograph No. 3, Jensen Manufacturing Company. Note that a level of 50 db is less than 10 db above the average random noise level in a city apartment.