Accelerated Slope Tone Control Equalizers*

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A tone-control shelving equalizer providing low shelf (bass) boost and cut, as well as high shelf (treble) boost and cut is described. The active filter stages provide sharpened (accelerated) amplitude versus frequency response characteristics at the band transitions, thus leaving-the center frequencies uncorrupted by out-of-band effect of the tone controls.

0 INTRODUCTION

The need for bass and treble tone-control circuits with steeper slopes has been obvious to the author since his 1976 writings [l] on the subject of designing tone-control circuits. It became clear that it did not matter if the tone-control circuits were passive or active, tube, transistor, or integrated circuits; they all suffered from the same malady of too much interaction with the mid-band frequencies.

The opportunity to pursue this subject did not appear again until 1987. While designing a 16-channel matrix mixer, the author investigated, using computer circuit analysis, the possibility of creating steeper slopes for conventional bass and treble tone-control circuits. The project was canceled before the circuit could be finalized. In 1989 the author resurrected the circuit for a new microphone input module. The circuit was finally completed in 1990 and steeper slope tone controls were a reality. The new circuit, dubbed "Accelerated Slope Tone Controls™," was awarded a patent in 1991 [2].[1]

1 BACKGROUND

Tone-control equalizers, as the term is used here, refer to relatively uncomplex bass and treble tone controls found on most high-fidelity systems and on certain professional audio recording consoles and mixers. Most of these circuits use some variation of Baxandall's negative-feedback circuit done in 1952 [3]. The Baxandall tone-control circuit is commonly referred to as a "shelving" control because of the shape created by the amplitude versus frequency response when boosting or cutting the low and high end frequencies. The shape of the response curves when using such a shelving circuit is that of a shelf, contrasted with peak or dip-type (bandpass) response shapes, and further contrasted with total boosting or cutting of the response. Shelving tone controls cause amplification (boost) or attenuation (cut) at a substantially constant slope or rate, then level off to a flat response. The magnitude of this constant slope is the issue.

Almost universally, these shelving tone controls use one-pole filter circuits. The steepest response slope that can ever by achieved by a one-pole filter is, of course, 6 dB/octave (or 20 dB/decade, equivalent terms). This would be for an ideal filter circuit. In practice, the overall shelving tone-control transfer function results in a response slope that rarely exceeds about 3 dB/octave. (Due to the close proximity of the pole and zero of the transfer function, there is near cancellation; a 2.7-dB/octave slope is typical for ±12 dB designs.) This gentle slope causes the control to influence the midband frequencies because of overlapping effects from the adjacent high and low frequencies. Such corruption causes disturbing effects on the critical midband frequencies. This is an unwanted situation. If you want to add bass or treble, you want to do so without disturbing the midband frequencies. What is needed are tone-control circuits with steeper (or "accelerated") slopes.

Ideally the boost and cut tone controls should change the slope of the transition frequencies into the high and low end but should not alter the response charac-

* Presented at the 92nd Convention of the Audio Engineering Society, Vienna, Austria, 1992 March 24-27.

[1] Royalty-free licenses are available from the author and Rane Corporation.

teristics of the center or midband frequencies. Practical, existing filter designs so far have not effectively isolated the high and low band tone controls from the center or midband frequencies.

Although it is conceivable that filters having additional poles with sharper response characteristics could be incorporated into the tone-control circuitry, such multiple-pole filters create a different problem. That problem is the creation of excessive phase shift, approaching 180°, which produces cancellations and dropouts due to frequencies that are out of phase with the input signal. Stability problems also appear because of the tendency of oscillations at or near the 180° phase shift region. Rather than accent such problems of dropouts, or cancellations and other instabilities, most tone-control circuits use the single-pole filter. Such single-pole filters have a maximum phase shift of 90° and, therefore, are inherently stable and preclude cancellations since the frequency shift never approaches the 180° region.

2 ACCELERATED SLOPE TONE CONTROLS

This engineering report offers a solution to the foregoing problem of unwanted corruption of the midband frequencies due to variations in the tone controls, by incorporating in the equalizer, filters that have two, three, or more poles to achieve the desired steepness of the frequency response and then compensating for the otherwise excessive phase shift that would result by incorporating one or more zeros offset from the poles so as to lie outside the high or low band frequencies of interest. One such offset zero is being provided for each additional pole that is added to the filter. This offset zero is to be distinguished from a zero occurring in the overall transfer function of the shelving-type tone control that is caused by the interaction of the filter's pole with the broad-band signal, and which causes the response curve to flatten out as a shelf. The zero due to pole interaction appears away from the midband and is directly within the high (or low) band of interest.

Thus a two-pole shelving filter is used, with one, additional offset zero being located away from the two poles and toward the midband. The two poles provide the desired steep rise or fall into the low (or high) end frequencies, and yet as the frequency moves back into the midband, the otherwise excessive phase shift that would occur with such a two-pole circuit is neatly canceled out by the offset zero, restricting the phase shift back to a maximum of approximately 90° or less. The offset zero is preferably located toward the midband, and the influence the zero has on the amplitude of the signal in the low and high adjacent bands is inconsequential because of the effects of the remaining uncanceled pole.

Alternatively, three poles are used in the shelving filters and two offset zeros are provided to cancel the phase change contributions due to the second and third pole essentially in the same manner as described for a two-pole, one-offset zero filter.

Thus, in general, the accelerated slope circuit provides a tone-control equalizer having a low and/or high end controllable gain filter stage with n poles and $n - 1$ offset zeros, where n is any integer value of 2 or more. While the principles of the circuit may be adopted in a variety of controllable equalizer circuits, the preferred application is in a relatively simple bass and treble tone-control equalizer configured in a shelving-type filter using active filter components. These and other advantages and features of Accelerated Slope Tone Controls will be better understood after reading the detailed description of the figures in the next section.

3 DESCRIPTION OF FIGURES

Fig. 1 is a schematic diagram of an Accelerated Slope Tone Control using the phase-compensating offset zero in a two-pole, one-zero equalizer filter circuit adapting the author's equalizer topology [4] for tone-control use.

Fig. 2 is a plot of relative amplitude versus frequency showing, for comparison, the two- and three-pole. one- and two-zero phase-compensated tone-control circuits superimposed on a corresponding plot of the response characteristics of a conventional one-pole tone-control filter. Note the comparisons between the steepness of the slopes, and that it takes a three-pole phase-compensated circuit to approach the theoretical 6 dB/octave expected from the conventional one-pole design. It is very interesting to note that the actual slope of the full theoretical +12 dB boosted response, using the three-pole circuit, is only about 5.2 dB/octave. So three poles want to be 18 dB/octave, but only yield about 5 dB/octave. Very roughly each pole improves the slope by about 1 dB/octave. However, the sonic benefit is immense since the total area under the curve now unaffected is quite large.

Fig 3 shows the amplitude versus frequency and related phase shift versus frequency plots of the two-pole phase-compensated filter of Fig. 1 (large solid squares) and, for comparison, the corresponding plots of a conventional one-pole filter (small solid squares), a two-pole filter without phase compensation (small open squares), and the three-pole filter phase-compensated circuitry of Fig. 5 (large open squares).

It is observed from Fig. 3(a) that the two-pole phase compensation provides a relative attenuation slope that is significantly steeper than the one-pole response characteristics, but is slightly less sharp relative to the two-pole uncompensated attenuation slope. The three-pole phase compensation is even sharper than the two-pole phase compensation and may be a desirable alternative in some applications.

In Fig. 3(b) the constraint on the phase shift is well illustrated by comparing the two-pole uncompensated phase shift characteristics of the bass filter where the signal will shift in phase through 90° at 100 Hz and continues on toward the 180° phase shift region as the signal approaches midband. By comparison, the two-pole phase-compensated curve (with the offset zero added) shows that the phase shift increases toward the 90° shift level but never reaches 90°, leveling out to a shift of somewhat less than 90° as the frequency approaches the center of midband, The three-pole phase-compensated curve shows. a matching phase shift to that of the two-pole uncompensated circuit just beyond the 90° point and then the zeros kick in and bring

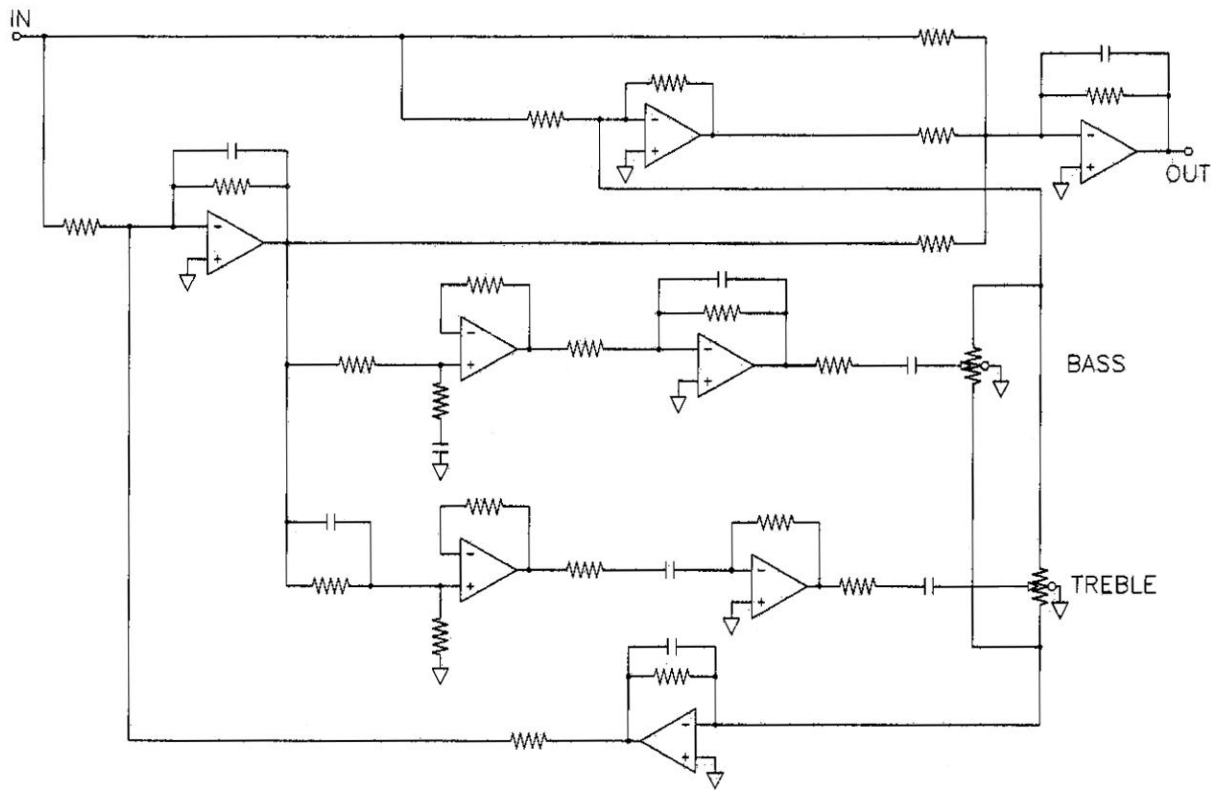


Fig. 1. Accelerated Slope Tone Control equalizer using two-pole, one-zero phase-compensated networks.

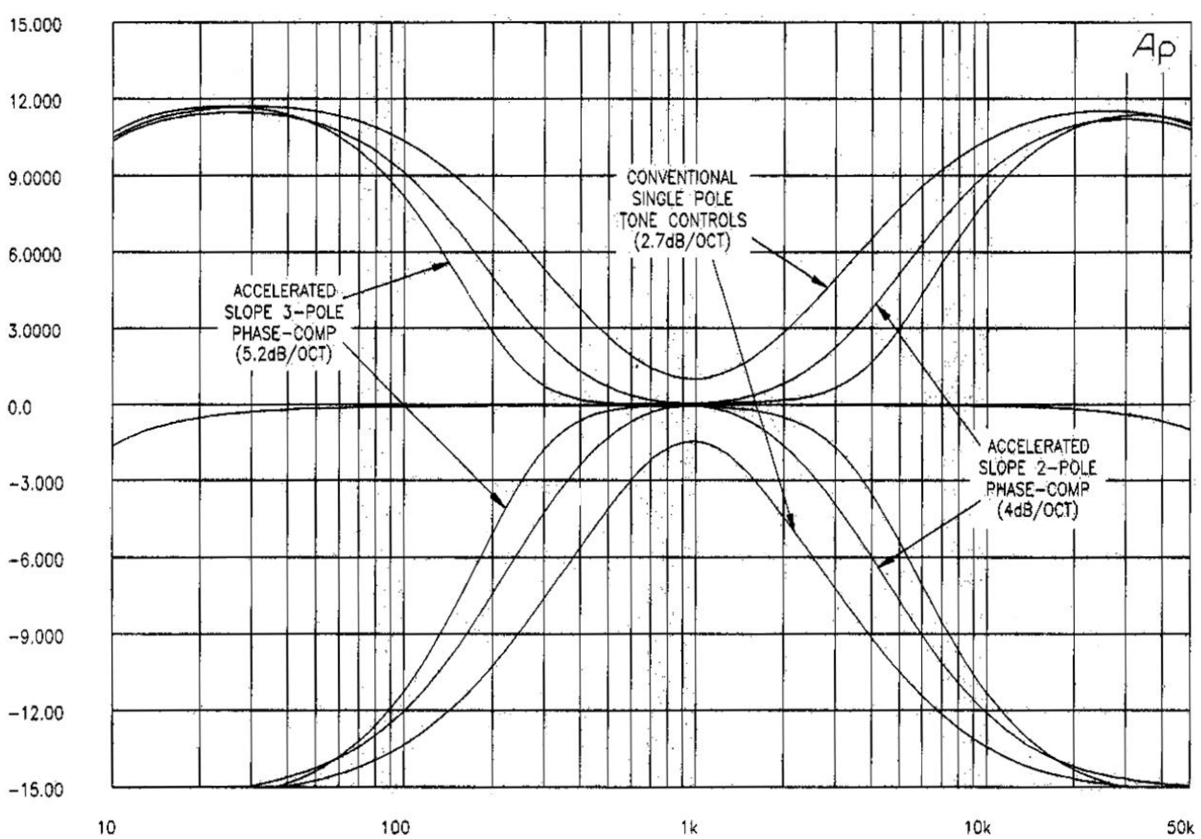


Fig. 2. Comparison between conventional and accelerated slope designs.

the phase shift back to 90° by the time midband frequencies are reached. Thus the phase shiftplots for one-pole, two-pole phase-compensated, and three-pole phase-compensated filters all provide stable filter circuits, and yet the two- and three-pole phase-compensated filter circuits offer the significantly enhanced steepness of the accelerated response curve at the edges of the high and low bands.

Fig. 4(a) and (b) shows schematic diagrams of the bass and treble active inverting filter stages removed from the shelving circuitry of the equalizer of Fig. 1. Fig. 4(c) gives the formulas relating the *RC* component values to the recommended pole and zero locations. As indicated, the zero of the bass network is placed optimally at 1.8 times the corner frequency of the pole; and the zero for the treble network is placed at a frequency obtained by dividing the pole corner frequency by the 2.2 factor.

Fig. 5 is a schematic diagram of an alternative application having three-pole, two-zero filters in which the added offset zero phase compensates the added third pole just as the one zero compensates for the one additional pole in the two-pole, one-zero equalizer circuit of Fig. 1.

The set of related diagrams in Fig. 6 shows, respectively a noninverting phase-compensated filter stage for bass (low end) frequencies and associated frequency/component value computations for the pole and zero locations, a simplified amplitude versus frequency plot showing the location of the corner frequencies of the poles and zero related to the circuit components of the filter stage of Fig. 6(a), and a treble (high end) filter stage of the noninverting type that is the complement of the bass filter and also showing the frequency/com-

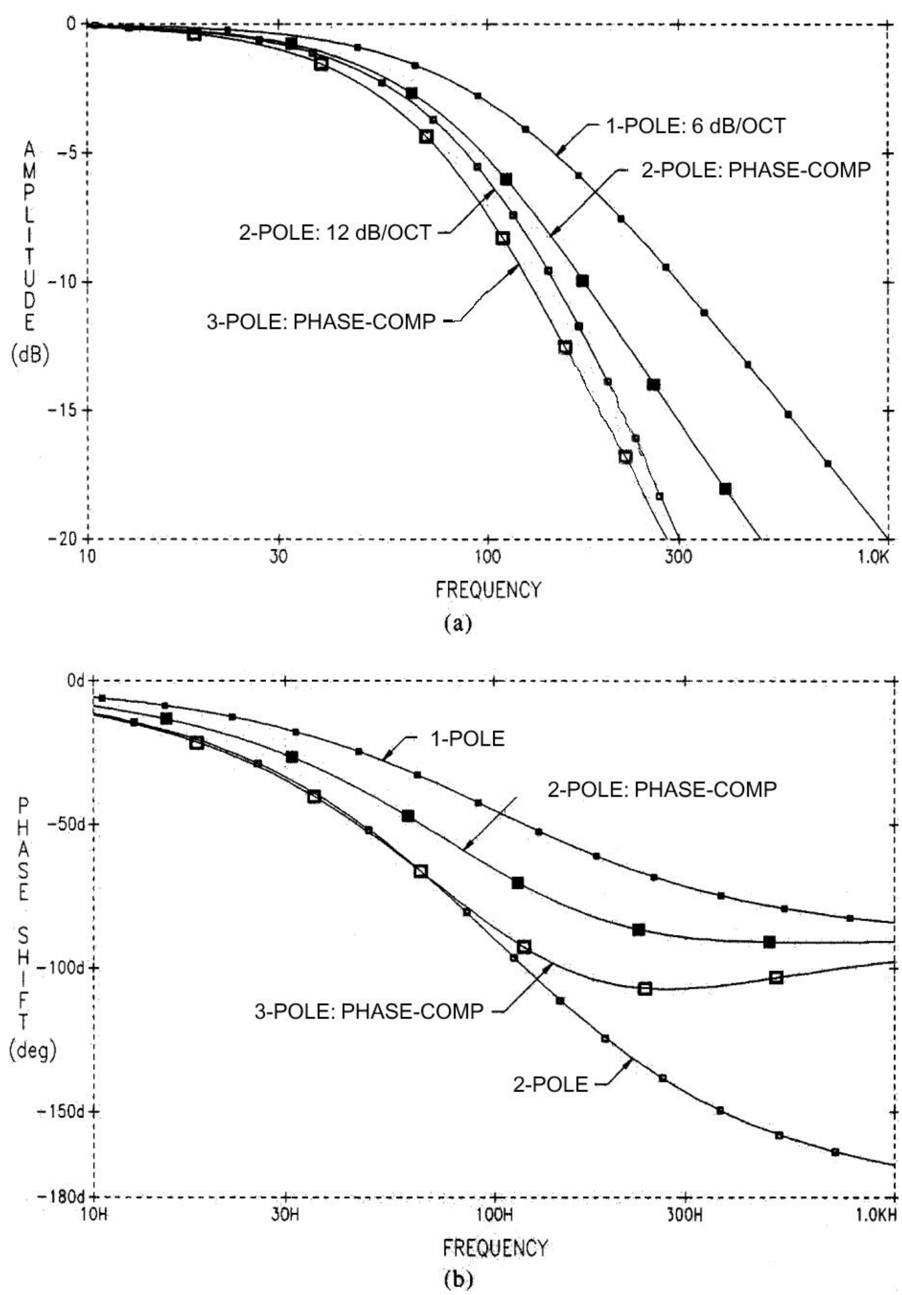


Fig. 3. (a) Amplitude comparison between designs, (b) Phase shift comparison between designs.

ponent value computations. Fig. 6(b) includes a step-by-step design procedure. (Noninverting phase-compensated filter stages find application in any equalizer topology requiring filters that do not invert phase, the most common example being the popular two operational amplifier boost/cut series summing circuit of Gundry [5] and others.

4 OBSERVATIONS, DETAILS, AND THEORY

Thus by careful selection of the pole and zero locations of filter sections in this type of shelving filter equalizer, sharper amplitude versus frequency curves are achieved in the transition regions between the midband, as indicated in Fig. 2 and the adjacent treble and bass end bands. The manner of selecting the pole and zero locations is discussed in the following. When properly placed in accordance with the principles described, the filter response characteristics of the high-pass and low-pass circuits leave the center frequencies (in the Fig. 1 example centered at 1 kHz) substantially uncorrupted by the out-of-band effects of the frequency-dependent characteristics of conventional one-pole filters (see Fig. 2). In effect, by using multiple-pole filters with one or more offset compensating zeros, one compensating zero for each excess pole, the slope of the amplitude versus frequency response at the adjacent high and low bands is accentuated or, in other words, "accelerated" over what is normally achieved by the single-pole active filters. Yet by placing the zeros to cancel out the excess poles as the frequencies enter the midband region, the center frequencies are left uncorrupted, as shown by the solid-line response characteristics of Fig. 2. With regard to the placement of the additional pole and zero in a two-pole, one-zero accelerated slope circuit, some discussion is needed of the operation of the equalizer circuit. This type of equalizer circuit (typical, in principle, of many topologies) has the effect of adding back a frequency-dependent signal to an input signal having a flat (frequency-independent) signal in the case of boost, and adding back the reciprocal of the frequency-dependent component in the case of cut. As mentioned, a conventional one-pole filter within a shelving equalizer causes a pole-induced zero (due to the characteristic signal-combining effects of this type of equalizer) to

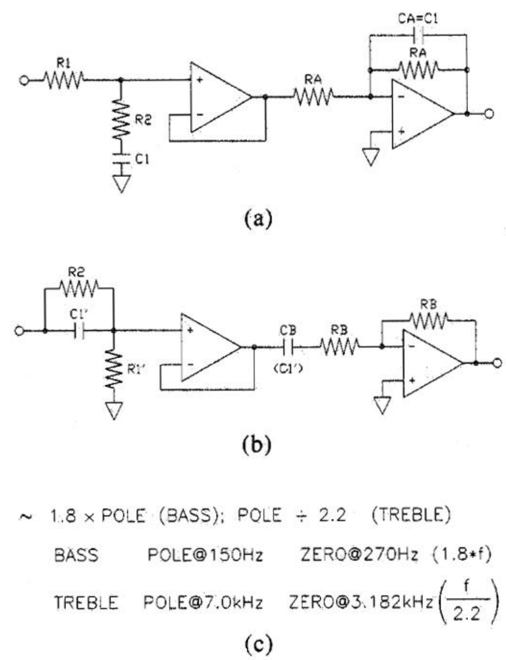


Fig. 4. (a) Inverting bass network. (b) Inverting treble network. (c) Compensating zero locations.

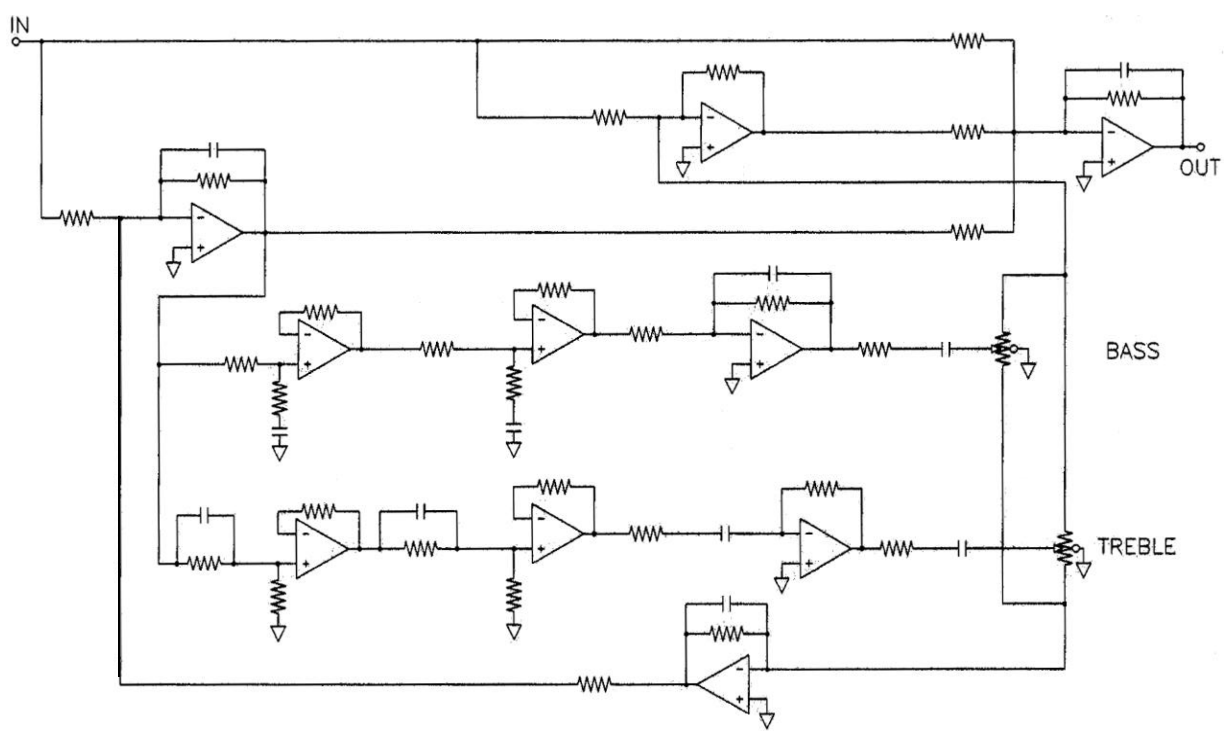


Fig. 5. Accelerated Slope Tone Control equalizer using three-pole, two-zero phase-compensated networks.

occur at a frequency away from midband and located at the corner of the shelf. Such a pole-induced zero is to be compared with and distinguished from the filter's offset compensating zero of this engineering report, which is incorporated in the filter stage itself and has a frequency located toward the midband from the filter's pole and away from the high (or low) band of interest.

When the phase shift of the added back or cut back signal is 45° or less in phase shift from the main signal, then a straightforward addition and reciprocal feedback circuit works fine. The problem comes when the equalizer circuit starts introducing a phase shift of 90° or more. Between 90 and 180° or more, cancellation starts to take effect because the equalized signal has become shifted in phase so that it is opposite in amplitude relative to the main signal. The cancellation area of concern is between 90 and 270° and is maximum with complete cancellation at 180°.

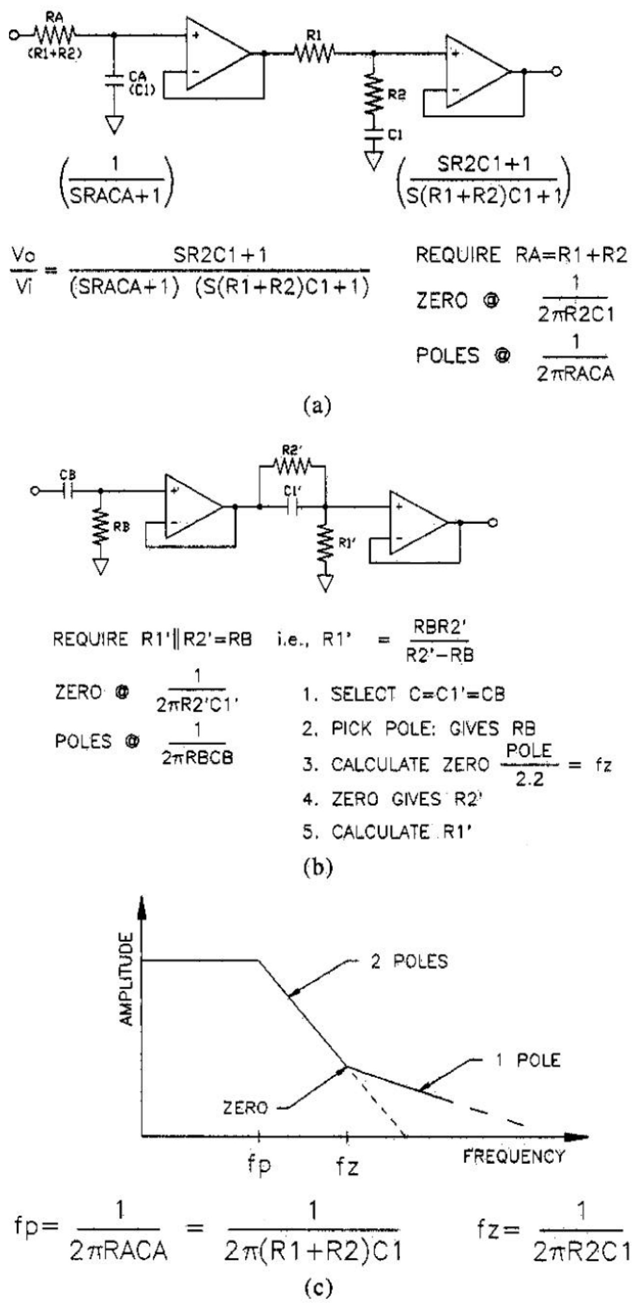


Fig. 6. (a) Noninverting bass network. (b) Noninverting treble network. (c) Pole-zero relative locations.

The configuration of a two-pole, one-zero offset equalizer network has the effect of adding an additional pole to sharpen the rise in the case of boosting, and the fall in the case of cutting. The offset placement of the zero relative to the poles is to minimize or limit the amount of phase shifting that occurs in the equalizer, particularly as the corner frequency of the filter is approached. In other words; right around the 90° phase shift point, the zero kicks in and starts to minimize the amount of overall phase shifting that occurs to a maximum of 90° rather than a maximum of 180°. as in the case of a two-pole circuit without an offset zero.

In designing the bass filter, the compensating zero on a two-pole circuit is placed at an octave above the pole corner. More particularly, it is placed at substantially 1.8 times the corner frequency, hence toward the midband for bass to achieve in this particular tone control an empirically derived; optimal phase compensation without substantial degradation of the two-pole response slope. The range of acceptable indexes or ratios is 1.75 to 2.75 times the corner frequency for bass boost and cut.

For the treble filter, the index or ratio is divided into the corner frequency. Thus in placing the compensating zero for the treble filter shown in Fig. 1 that has a corner frequency of 7.0 kHz, the 7.0 kHz is divided by the selected ratio within the range of 1.75 to 2.75. For this example, using an index ratio of 2.2, the zero would be placed at 7.0 kHz divided by 2.2, or 3.18 kHz. It is observed that the placement of the zero in the treble network is at a frequency less than the corner frequency and hence toward the midband, as it is in this area, where the phase shift starts to produce cancellation effects if a double pole without the zero compensation is used.

5 SUMMARY

A new bass and treble audio tone-control circuit for changing amplitude versus frequency response in low and high bands, respectively, is presented whereby the amplitude versus frequency response of the midband frequencies is substantially unaffected by changes in settings of the bass and treble controls.

Each high and low end band filter network has multiple poles and offset zeros located at a frequency so as to restrict the maximum phase shift of the filter to within a safe level not greater than about 90°. It has been shown that by using multiple-pole filters with optimally placed compensating zeros, the steepness of the conventional bass and treble tone-control equalizers can be substantially increased, and that these accelerated slopes are unconditionally stable and offer enhanced aural benefits due to lack of center frequency disturbances. Thus the true purpose of bass and treble tone controls comes closer to reality: Accelerated Slope Tone Controls alter bass and treble frequencies without changing the critical midband frequencies.

8 REFERENCES

[1] D. Bohn, *Ed., Audio Handbook (National Semiconductor Corp.,* 1976).

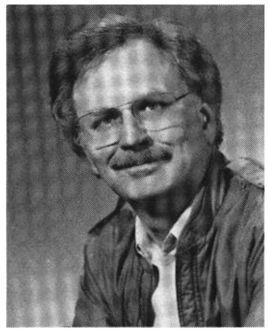
[2] D. Bohn, "Audio Signal Equalizer Having Accelerated Slope Phase Shift Compensated Filters," U.S. Patent 5,046,105 (1991 Sept.).

[3] P. Baxandall, "Negative Feedback Tone Control-Independent Variation of Bass and Treble Without Switches," *Wire & World, vol. 58, p. 402* (1952 Oct.):

[4] D. Bohn, "Reciprocal, Subtractive, Audio Spectrum Equalizer," U.S. Patent 4,891,841 (1990 Jan.).

[5] K. Gundry, "Adjustable Equalizers Useable in Audio Spectrum," U.S. Patent 3,921,104 (1975 Nov.).

THE AUTHOR



Dennis A. Bohn was born in San Fernando, California, in 1942. He received B.S.E.E. and M.S.E.E. degrees from the University of California at Berkeley in 1972 and 1974, respectively. Between undergraduate and graduate schools, he worked as a research and development engineer for the Hewlett-Packard Company developing thin-film high-speed oscillators. Upon completion of his M.S.E.E., he accepted a position with National Semiconductor Corporation as a linear application engineer specializing in audio. While at National Semiconductor, he created the *Audio Handbook,* acting as technical editor and contributing author. In 1976, he accepted the position of senior design engineer for Phase Linear Corporation, where he was involved in designing several consumer audio products. Promoted to engineering manager in 1978, he was responsible for developing the professional audio products division.

In 1982 Mr. Bohn's strong interest in professional audio products prompted him to leave Phase Linear and accept the position of vice president of engineering for Rane Corporation. In 1984, he became a principal of Rane Corporationand assumed the position of vice president in charge of research and development, where he now designs and develops advanced analog and digital products for the professional audio industry.

Mr. Bohn is a member of the AES, the IEEE, and Tau Beta Pi, and is listed in the First Edition of *Who's Who* In Science *and Engineering.* He has designed more than 30 consumer and professional audio products and authored over 100 articles in national and international magazines, including his many convention papers delivered before the Audio Engineering Society. He has published three articles in the AES Journal and holds two U.S. patents. Recently, Mr. Bohn wrote the entry *on* equalizers for the *McGraw-Hill Encyclopedia of Science & Technology, 7th edition.*