Audio Applications for Op-Amps, Part III

By Bruce Carter
Advanced Analog Products, Op Amp Applications
Texas Instruments Incorporated

This is the third in a series of articles on single-supply audio circuits. The reader is encouraged to review the introductory material in the first article which concentrated on low-pass and high-pass filters. The second article concentrated on audio notch filter applications and curve-fitting filters. This last article focuses on the use of a simulated inductor as an audio-circuit element.

The Simulated Inductor

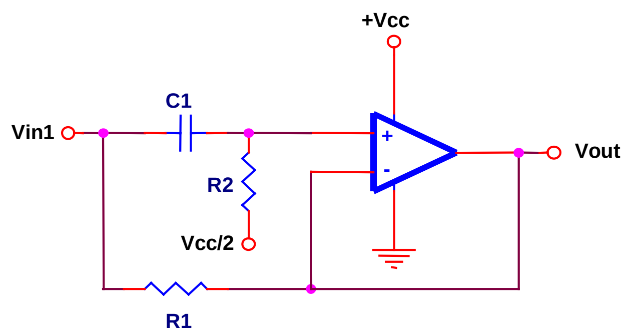

Fig. 1: A Simulated Inductor Circuit

A simulated inductor circuit (see Fig. 1) reverses the operation of a capacitor -- an inductor resists any change in its current, so when a dc voltage is applied to an inductance, the current rises slowly, and the voltage falls as the external resistance becomes more significant.

In practice it is a little different: The fact that one side of the inductor is grounded precludes its use in low-pass and notch filters, leaving only high-pass and bandpass filters as possible applications.

High Pass Filter

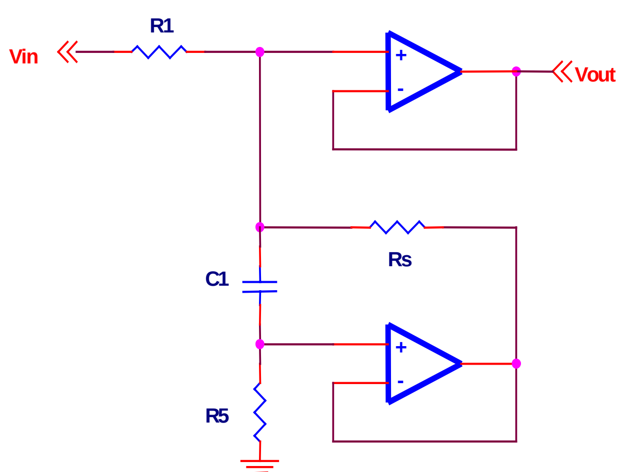

Fig. 2: High-Pass Filter Using A Simulated Inductor

Analyzing the response of this high-pass filter (Fig. 2) shows disappointing results:

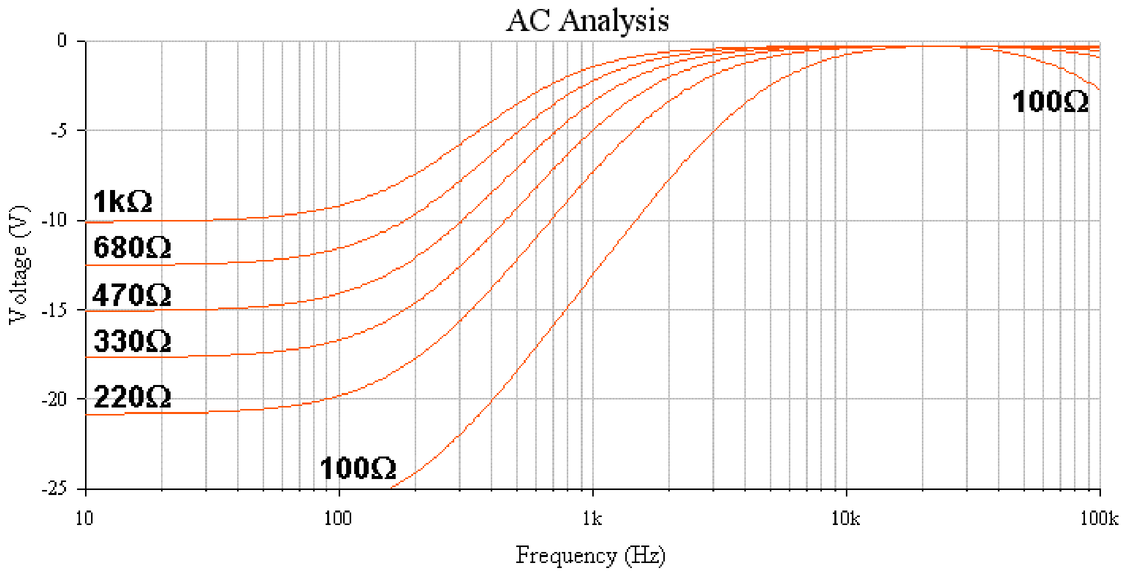

Fig. 3: Response Of Simulated Inductor High-Pass Filter

Various values of Rs were tried but 220 Ω to 470 Ω were the only ones that gave something close to the expected response. Values of 220 Ω and 100 Ω offered the most rejection, but there is an annoying high-frequency roll-off that first shows up at 330 Ω and becomes quite pronounced at 100 Ω. Values of 470 Ω and above have washed out stop-band rejection but at least have flat high-frequency response.

The value of Rs that gives the most inductive response is 330 Ω although it rolls off slightly more than 3 dB at 1kHz and is not 20 dB down a decade away. If high-frequency roll-off is not desirable 470 Ω can be used, but the maximum attenuation will only be about 15 dB. So, a high-pass filter constructed from a simulated inductor has poor performance and is not practical leaving only bandpass filters as potential applications.

Bandpass Filters And Graphic Equalizers

An Rs value of 220 Ω to 470 Ω is relatively high, meaning that only relatively low Q bandpass filters can be constructed with simulated inductors. But there is an application that can use low Q bandpass filters: Graphic equalizers.

Graphic equalizers are used to compensate for irregularities in a listening environment, or to tailor audio to a listener's preferences; they are commonly available as dual-octave (5 bands) or single-octave (10 or 11 bands) while professional sound reinforcement systems use ⅓-octave equalizers (about 30 bands.)

[For the non-musically inclined, an octave is a repeating pattern of pitch used in musical scales. To the ear a tone played at any given frequency has the same pitch as a tone at half or double that frequency, except for any obvious difference in frequency. Western cultures have octaves (8 notes) while, correspondingly, Eastern cultures use pentatonic (5 note) scales.]

The center frequencies for a ⅓-octave equalizer are not equally spaced as the human ear hears pitch logarithmically, and so the center frequencies must be determined by using the cube root of 2 (1.26). (The center frequencies are listed in Appendix A.)

Graphic equalizers do not have to be constructed on octave intervals and any set of center frequencies can be used. Musical content, however, tends to stay within octaves -- so graphic equalizers that do not follow the octave scale may produce objectionable level shifts when artists play or sing different notes within the octave. One of the latest trends is to compensate for the poor audio response in small systems by moving the high- and low-frequency settings in from the extremes and placing the equalization frequencies at 100, 300, 1000, 3000, and 10000 Hz. It looks nicer on the front panel and makes more efficient use of the limited capabilities of such systems -- although musically incorrect.

Two strategies can be used to create graphic equalizers: the simulated inductor method (being described here) and the MFB (multiple feedback) bandpass filter method (see Ref. 1.) (Construction of MFB filters can be done on TI's Filter Design Database -- see Ref. 3.)

Building The Equalizer

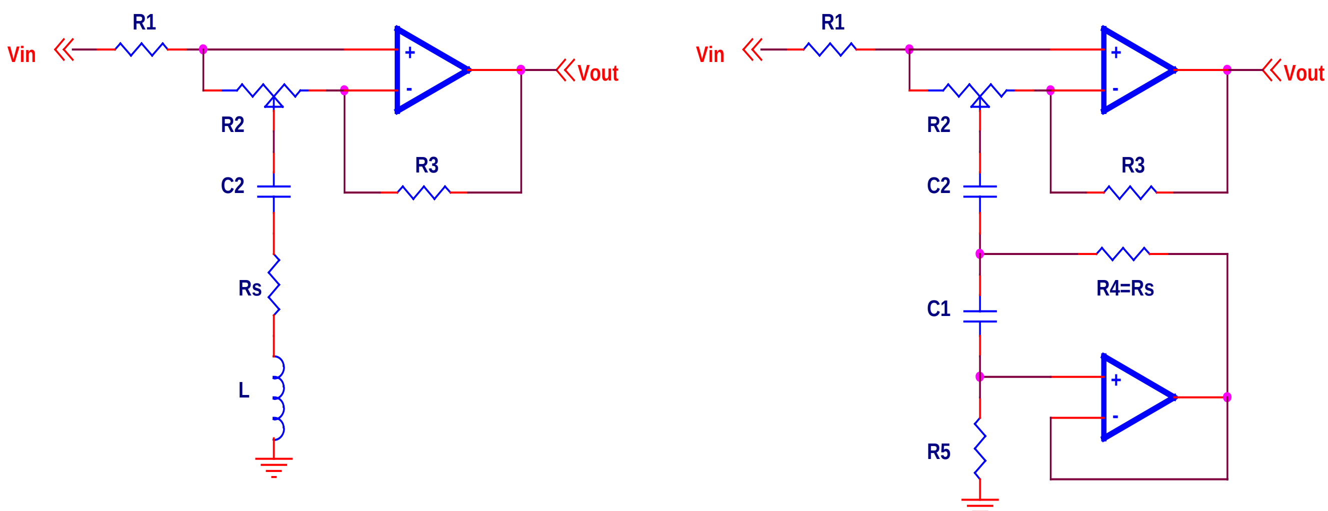

Fig. 4: Graphic Equalizer (Physical Inductor On Left, Simulated Inductor On Right)

A graphic equalizer can be built with a physical inductor (Fig. 4, left) but obtaining inductors of the correct values would be difficult and it is much easier to use the simulated inductor implementation (Fig. 4, right.)

Rs is the equivalent series resistance of the inductor and capacitor and in the simulated inductor version it is approximately equal to R4 (which does not include a negligible contribution from capacitor C2.)

Gain of the Equalizer

Starting with Rs ≈ 470 Ω the gain of the circuit can now be calculated, but that value constrains the input and feedback resistor of the graphic equalizer stage. Several sources use a gain of 17dB but this will only appear when the surrounding stages are also adjusted to their maximum level. Otherwise, gain at the resonant stage will experience roll-off from adjacent stages according to their proximity and Q.

The potentiometer (Fig. 4, again) is connected across the inverting and non-inverting inputs of the op-amp, and is in parallel with the differential input resistance. It does not, therefore, enter into the gain calculations for the op amp stage, but Rs does. We need to look at the equivalent circuits of Fig. 4 with the potentiometer at each end of its travel is.

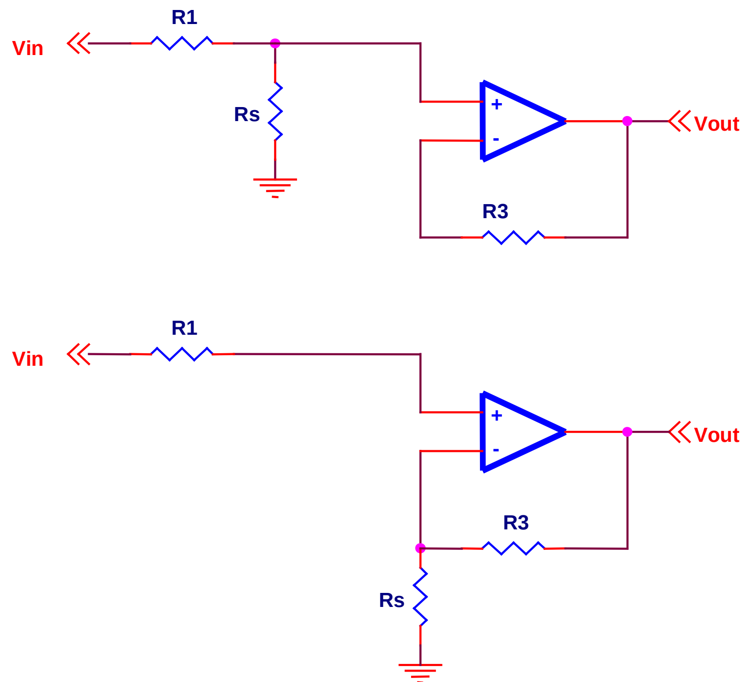

Fig. 5: Gain Circuit at Either End of Potentiometer Travel

The top circuit (in Fig. 5) acts like a unity-gain buffer, with a voltage divider on the input voltage. The gain will be at its minimum value of -17 dB (1/7). For Rs = 470 Ω, R1 can be calculated:

- $R1 = (Rs \div A) - Rs = (470 * 7) - 470 = 2820\ \Omega$

The bottom circuit acts like a non-inverting gain stage, with the input resistance R1 being ignored. The gain will be at its maximum value of 17 dB (7). For Rs = 470 Ω, the feedback resistor R3 is:

- $R3 = Rs(A-1) = 470\Omega \times (7-1) = 2820\Omega$

This is the same value, which simplifies design, and a standard E-6 value of 3.3 kΩ is selected for both because the absolute value of gain is unimportant.

Potentiometer Action

The gain at positions in between the ends of the potentiometer wiper is more difficult to calculate. It will combine both non-inverting and inverting gains and although, superficially, the circuit looks like a differential amplifier stage, the resistor values are not balanced for differential operation. This leads to an unusual taper for the potentiometer. At one value of potentiometer resistance, in this case 20 kΩ,. has a ½ gain/loss at the 5% and 95% settings, respectively. This then requires a potentiometer with two logarithmic (audio) tapers joined in the center -- non-standard and hard to obtain.

A partial solution to this is to reduce the potentiometer's value, and at 10 kΩ the logarithmic effects are lessened. Reducing the potentiometer's value to 5 kΩ results in less improvement and starts to limit the bandwidth of the op amp. 10 kΩ is probably the best compromise.

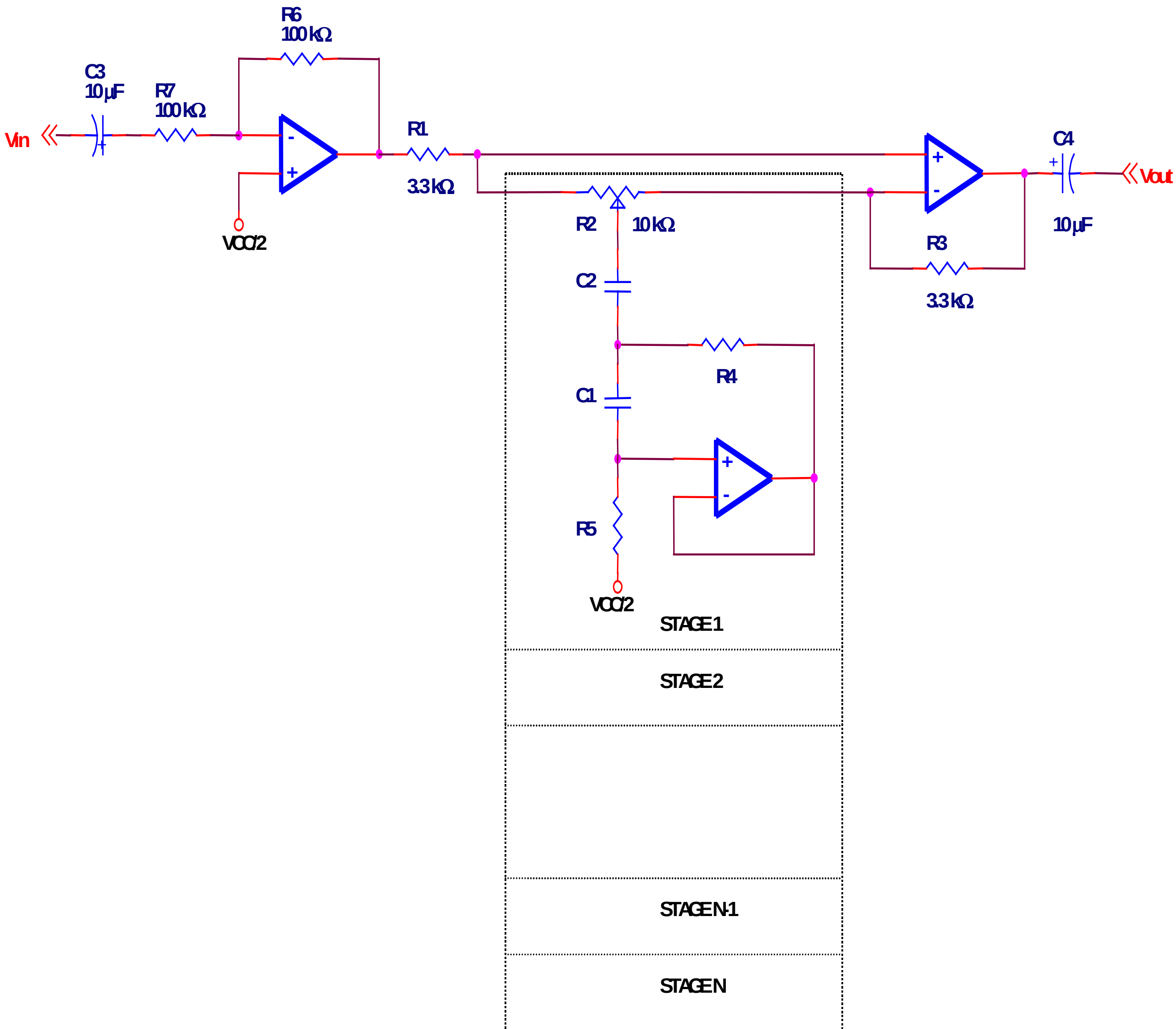

Fig. 6: Graphic Equalizer Schematic

In the schematic of the equalizer (see Fig. 6) C3 and C4 ac couple the input and output, respectively. The first stage is an inverting unity-gain buffer that ensure drive to a large number of stages, and it also allows easy injection of the half supply voltage to the equalization stages. The equalization stages are shown in the dotted lines. R5 is selected to be 100 kΩ but there may be some slight variation of R4 and R5 values to make capacitor values reasonable. The component values of the equalization stages are given in Appendix A.

Q Factor
At this point, the designer needs to know the Q, which is based on how many bands the equalizer will have and will determine the bandwidth of a bandpass filter.

Different references suggest different values of Q -- based on the ripple that is tolerable when all the controls are set at their maximum or minimum values. This ripple is not desirable -- if an end-user is adjusting all the controls to maximum, they need a pre-amplifier, not an equalizer. Nevertheless, the maximum and minimum positions provide a good way to demonstrate the response capability of the unit.

Ref. 2 recommends a Q of 1.7 for an octave equalizer which gives a ripple of 2.5 dB, reasonable for this type of device. Extrapolating, the Q of a two-octave equalizer should then be 0.85, and that of a ⅓-octave equalizer should be 5.1.

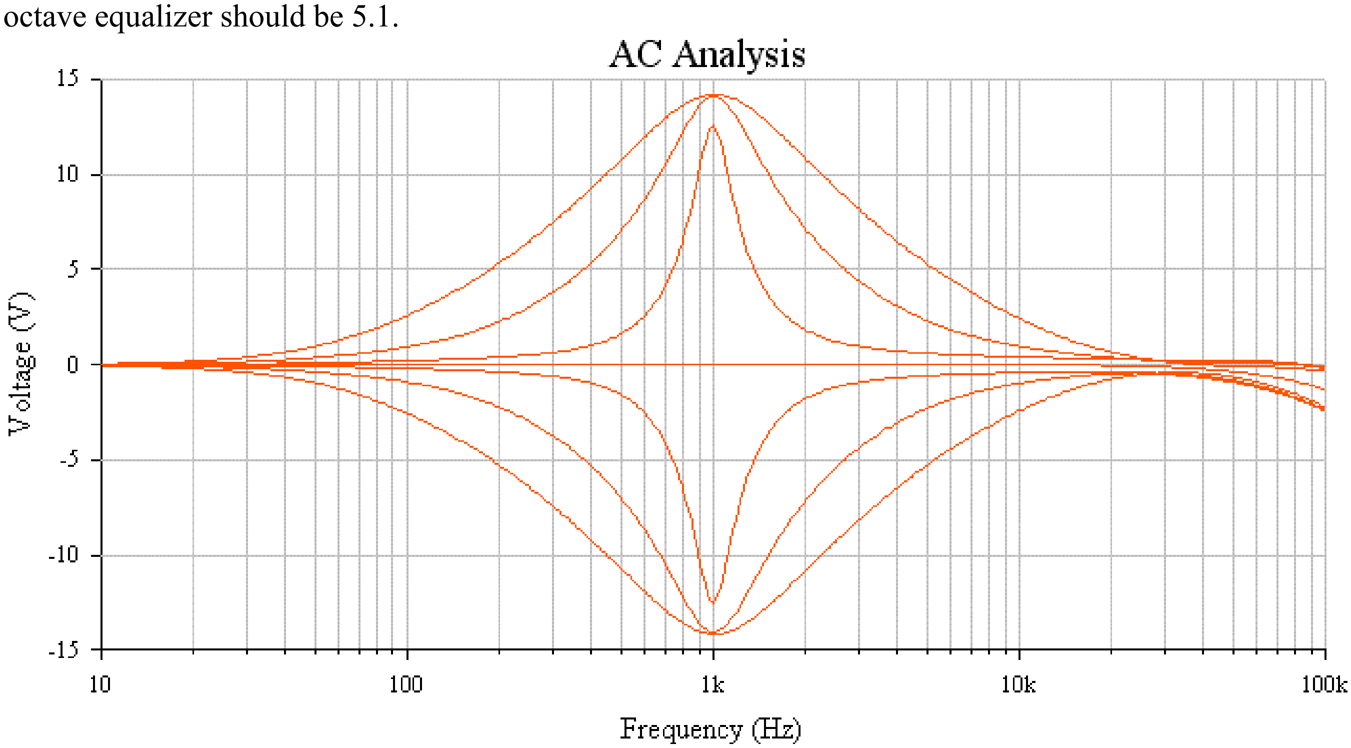

Fig. 7: Effect Of Q On Bandwidth In A Graphic Equalizer

A filter with a Q of 1.7 (middle curve of Fig.7) will have a bandwidth that is 1/1.7, (or 0.588 of the center frequency) so the 1000 Hz filter shown has a bandwidth of 588 Hz. The -3 dB points, therefore, would be logarithmically equidistant from the center peak at 1 kHz, at approximately 750 Hz and 1350Hz. Beyond the -3dB points the response of the filter flattens out to a first-order response of -6 dB per octave, eventually flattening to a limiting value. Increasing the Q does nothing to change this, as can be seen. What increasing the Q accomplishes is to narrow the -3 dB bandwidth.

Capacitor Values
The relationships that are known at this point are:

- Inductive Reactance: $X_L = 2\pi \times f_o \times L$
- Definition of Q: $Q = \frac{X_L}{R}$ where R is R4
- Resonant Frequency Calculation: $f_o = \frac{1}{2\pi\sqrt{LC}}$, where C is C2
- Formula for simulated inductor: $L = (R5 - R4) \times R4 \times C1$

After deriving the following from the expressions above, the value of C1 and C2 can now be determined in terms of f_o, R4, and R5:

- $C1 = \frac{Q \times R4}{2\pi \times f_o \times (R5 - R4)}$
- $C2 = \frac{1}{2\pi \times f_o \times R4}$

The values of C1 and C2 for each value of frequency are shown in Appendix A.

Response
The response curves for equalizers with potentiometers at each extreme are shown below.

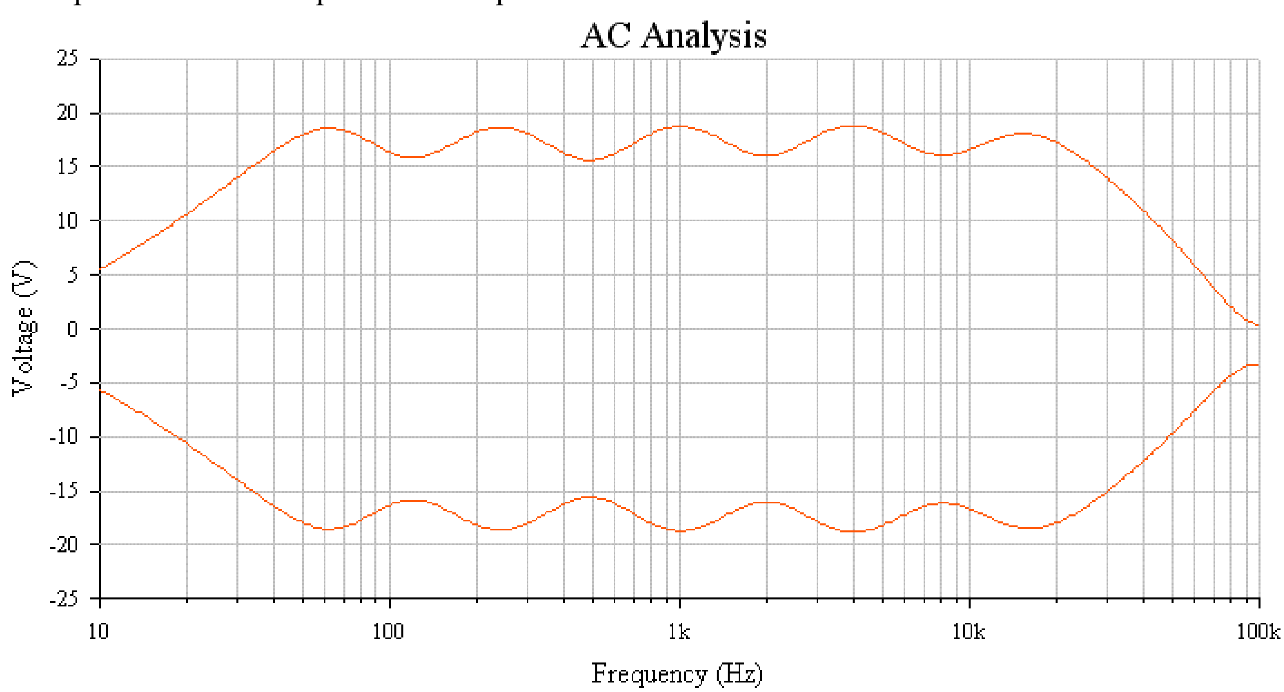

Fig. 8: Frequency Response Of A 2-Octave Equalizer

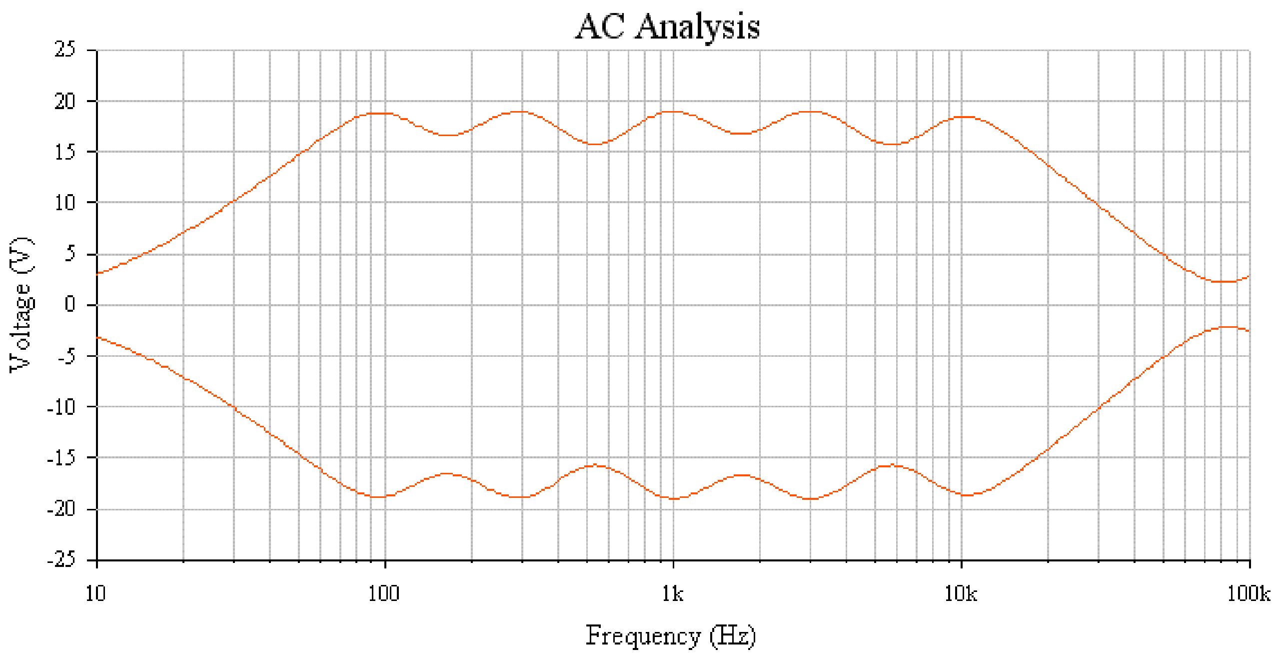

Fig. 9: Frequency Response Of A Pseudo 2 Octave Equalizer

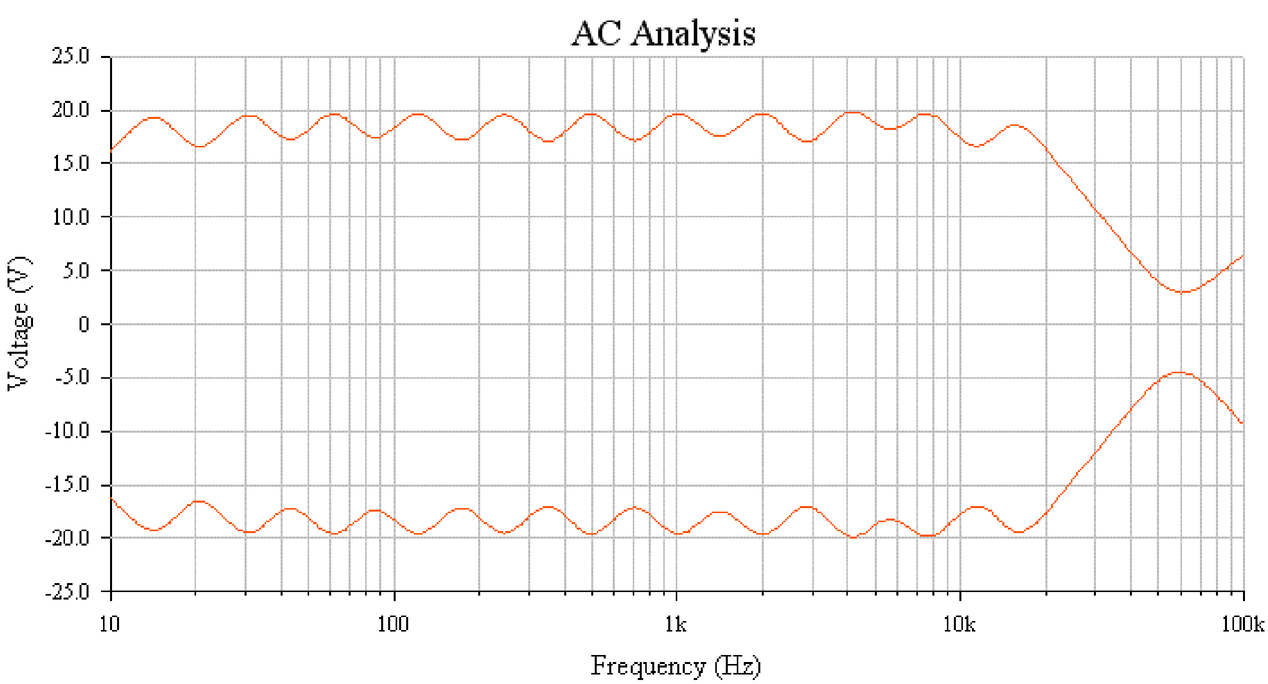

Fig. 10: Frequency Response Of A 1-Octave Equalizer

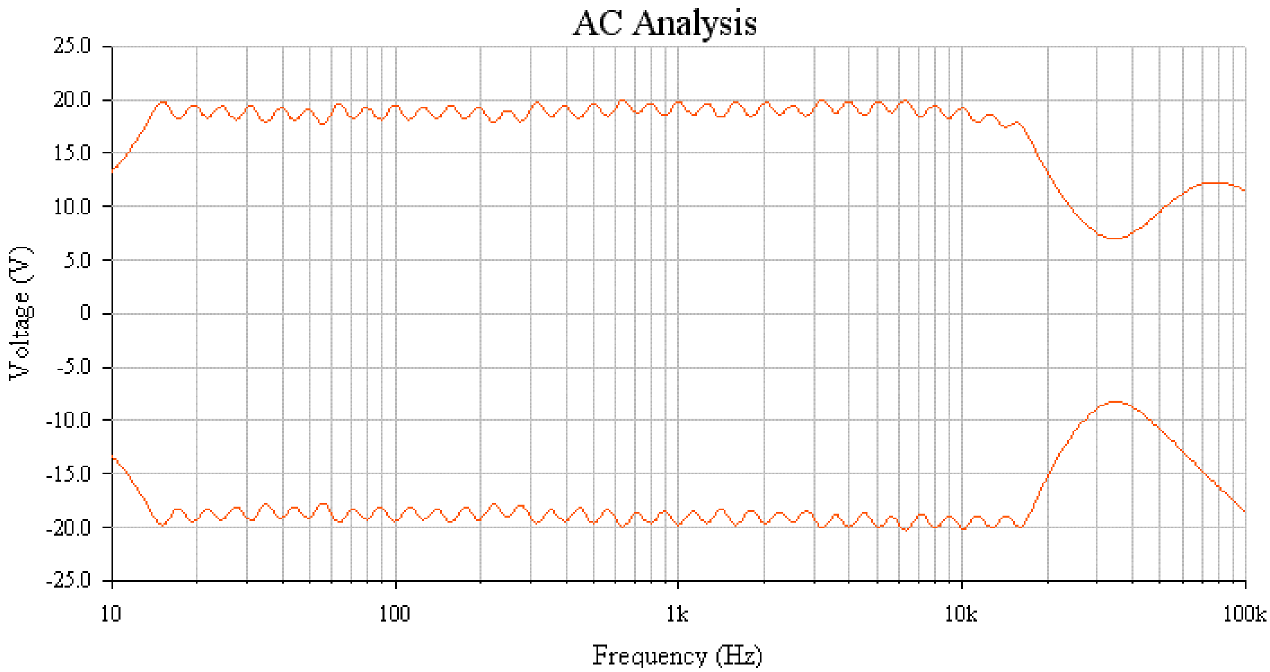

Fig. 11: Frequency Response Of A ⅓-Octave Equalizer

Appendix A Component Values For Graphic Equalizers

Use standard E-24 capacitor values nearest to the value calculated in the tables.

Component values for a 2-octave equalizer:

Freq	R5	R4	Q	L	C1	C2
60	100000	510	0.85	1.150	2.3E-08	6.1E-06
250	100000	470	0.85	0.254	5.4E-09	1.6E-06
1000	100000	470	0.85	0.064	1.4E-09	4.0E-07
4000	100000	470	0.85	0.016	3.4E-10	1.0E-07
16000	100000	470	0.85	0.004	8.5E-11	2.5E-08

Component values for a pseudo 2-octave equalizer:

Freq	R5	R4	Q	L	C1	C2
100	100000	470	1	0.748	1.6E-08	3.4E-06
300	100000	470	1	0.249	5.3E-09	1.1E-06
1000	100000	470	1	0.075	1.6E-09	3.4E-07
3000	100000	470	1	0.025	5.3E-10	1.1E-07
10000	100000	470	1	0.007	1.6E-10	3.4E-08

Component Values for a 1 Octave Equalizer:

Freq	R5	R4	Q	L	C1	C2
16	110000	470	1.7	7.948	1.5E-07	1.2E-05
31	110000	470	1.7	4.102	8.0E-08	6.4E-06
63	100000	470	1.7	2.018	4.3E-08	3.2E-06
125	100000	470	1.7	1.017	2.2E-08	1.6E-06
250	100000	470	1.7	0.509	1.1E-08	8.0E-07
500	100000	470	1.7	0.254	5.4E-09	4.0E-07
1000	100000	470	1.7	0.127	2.7E-09	2.0E-07
2000	100000	470	1.7	0.064	1.4E-09	1.0E-07
4000	100000	470	1.7	0.032	6.8E-10	5.0E-08
8000	100000	470	1.7	0.016	3.4E-10	2.5E-08
16000	100000	470	1.7	0.008	1.7E-10	1.2E-08

Component values for a ⅓-octave equalizer:

Freq	R5	R4	Q	L	C1	C2
16	100000	499	5.1	25.315	5.1E-07	3.9E-06
20	105000	475	5.1	19.278	3.9E-07	3.3E-06
25	100000	511	5.1	16.591	3.3E-07	2.4E-06
31	97600	499	5.1	13.066	2.7E-07	2.0E-06
40	100000	499	5.1	10.126	2.0E-07	1.6E-06
50	100000	499	5.1	8.101	1.6E-07	1.3E-06
63	100000	487	5.1	6.274	1.3E-07	1.0E-06
80	100000	511	5.1	5.185	1.0E-07	7.6E-07
100	100000	499	5.1	4.050	8.2E-08	6.3E-07
125	105000	487	5.1	3.162	6.2E-08	5.1E-07
160	100000	499	5.1	2.531	5.1E-08	3.9E-07
200	105000	475	5.1	1.928	3.9E-08	3.3E-07
250	100000	511	5.1	1.659	3.3E-08	2.4E-07
315	97600	499	5.1	1.286	2.7E-08	2.0E-07
400	100000	499	5.1	1.013	2.0E-08	1.6E-07
500	100000	499	5.1	0.810	1.6E-08	1.3E-07
630	100000	487	5.1	0.627	1.3E-08	1.0E-07
800	100000	475	5.1	0.482	1.0E-08	8.2E-08
1000	100000	499	5.1	0.405	8.2E-09	6.3E-08
1200	100000	511	5.1	0.346	6.8E-09	5.1E-08
1600	100000	499	5.1	0.253	5.1E-09	3.9E-08
2000	105000	475	5.1	0.193	3.9E-09	3.3E-08
2500	100000	511	5.1	0.166	3.3E-09	2.4E-08
3200	105000	499	5.1	0.127	2.4E-09	2.0E-08
4000	100000	499	5.1	0.101	2.0E-09	1.6E-08
5000	100000	499	5.1	0.081	1.6E-09	1.3E-08
6300	100000	487	5.1	0.063	1.3E-09	1.0E-08
8000	100000	475	5.1	0.048	1.0E-09	8.2E-09
10000	100000	499	5.1	0.041	8.2E-10	6.3E-09
12000	100000	511	5.1	0.035	6.8E-10	5.1E-09
16000	100000	499	5.1	0.025	5.1E-10	3.9E-09
20000	105000	475	5.1	0.019	3.9E-10	3.3E-09

Some ⅓-octave equalizers omit the 16- and 20-Hz bands; others omit the 20-kHz band. The frequencies are so close that 1% resistors are mandatory for this design.

References:

1. Elliot Sound Products, Projects 28 and 64, http://sound.au.com
2. "Audio/Radio Handbook", National Semiconductor, 1980. Scanned copies of the pages for a basic 3-band audio equalizer and a multiband octave audio equalizer from this text can be found at http://www.wavefront.mcmail.com/scans.htm
3. Additional resource: "Using the Texas Instruments Filter Design Database," By Bruce Carter, Texas Instruments Incorporated.