An audio circuit collection, Part 3

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Introduction

This is the third in a series of articles on single-supply audio circuits. The reader is encouraged to review Parts 1 and 2, which appeared in the November 2000 and February 2001 issues, respectively, of *Analog Applications Journal*. Part 1 concentrated on low-pass and high-pass filters. Part 2 concentrated on audio-notch-filter applications and curve-fitting filters. Part 3 focuses on the use of a simulated inductor as an audio circuit element.

The simulated inductor

The circuit in Figure 1 reverses the operation of a capacitor, simulating an inductor. An inductor resists any change in current, so when a dc voltage is applied to an inductance, the current rises slowly, and the voltage falls as the external resistance increases.

In practice, the simulated inductor operates differently. The fact that one side of the inductor is grounded precludes its use in low-pass and notch filters, leaving high-pass and band-pass filters as the only possible applications.

High-pass filter

Figure 2 shows a 1-kHz high-pass filter using a simulated inductor. The response of this high-pass filter is disappointing, as shown in Figure 3.

R_S is the equivalent series resistance of the inductor and capacitor. Various values of series resistance were tried. Only the R_S values ranging from 220 Ω to 470 Ω gave something close to the expected response. The 220-Ω and 100-Ω resistors provided 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. Resistance

Figure 1. Simulated inductor circuit

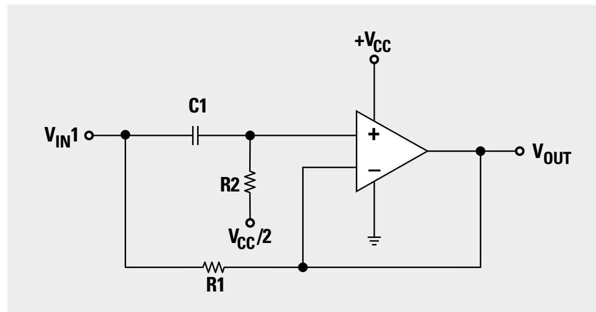


Figure 2. High-pass filter made with a simulated inductor

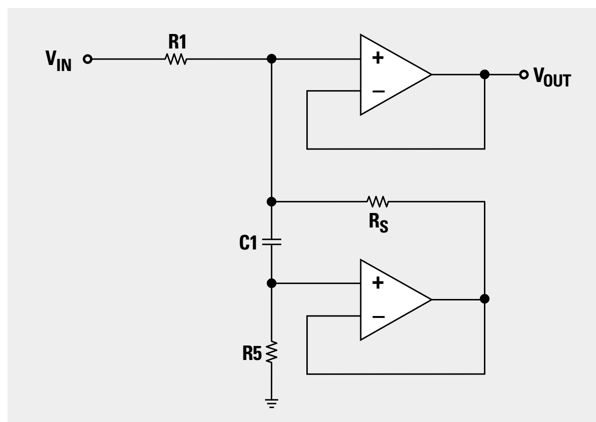
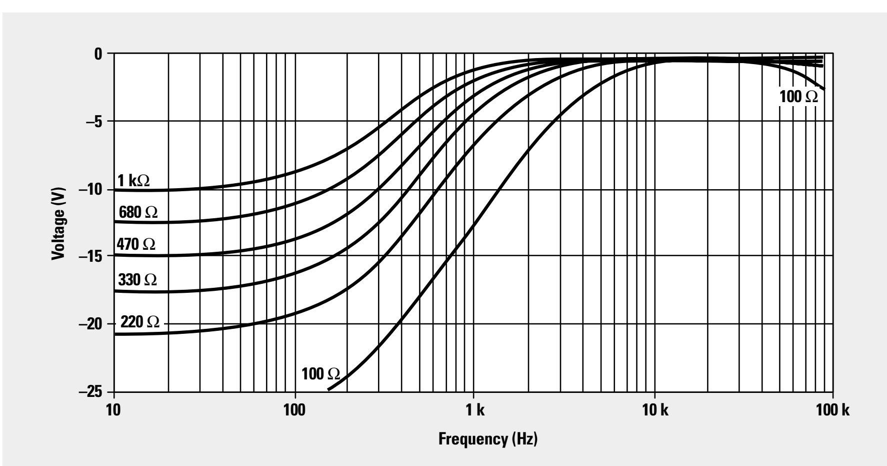


Figure 3. Response of a simulated inductor high-pass filter



values of 470 Ω and above have washed out stop-band rejection, but they at least have a flat high-frequency response.

The value of R_S that gives the most inductive response is 330 Ω, although it rolls off slightly more than 3 dB at 1 kΩ and is not 20 dB down a decade away. If high-frequency roll-off is not desirable, 470 Ω should be used, but maximum attenuation will be only about 15 dB. A high-pass filter constructed from a simulated inductor has poor performance and is not practical. This leaves band-pass filters as the only potential application for simulated inductors.

Band-pass filters and graphic equalizers

A series resistance of 220 Ω to 470 Ω is relatively high, which means that only relatively low-Q band-pass filters can be constructed with simulated inductors. There is an application that can use low-Q band-pass filters—graphic equalizers.

Graphic equalizers are used to compensate for irregularities in the listening environment or to tailor sound to a listener's preferences. Graphic equalizers are commonly available as 2-octave (5 bands) or 1-octave (10 or 11 bands). Professional sound re-enforcement systems utilize ⅓-octave equalizers (about 30 bands).

An octave is a repeating pattern of pitch used in musical scales. To the ear, a tone played at a given frequency has the same pitch as a tone at half or double the frequency, except for an obvious difference in frequency. Western cultures have divided octaves into 8 notes, Eastern cultures into 5 notes.

The center frequencies for a ⅓-octave equalizer are not equally spaced. The ear hears pitch logarithmically, 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. Any set of center frequencies can be utilized. Musical content, however, tends to stay within octaves; so graphic equalizers that do not follow the octave scale may produce objectionable volume shifts when artists play or sing different notes within the octave. One of the latest trends is to compensate for poor response in small audio systems by moving the high- and low-frequency settings in from their extremes and placing the equalization frequencies at 100, 300, 1000, 3000, and 10000 Hz. It looks nicer on the front panel, makes more efficient use of the limited capabilities of such systems, but is musically incorrect.

Two strategies can be used to create graphic equalizers—the simulated inductor method and the MFB band-pass filter method. Reference 1 describes the MFB method in detail; this article is concerned with the use of simulated inductors and their use in a graphic equalizer.

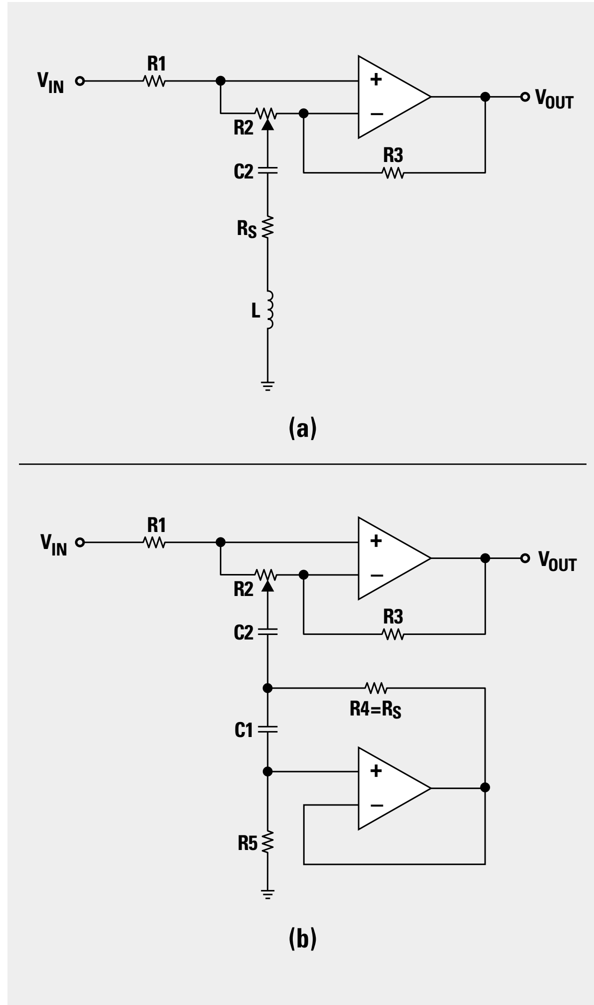
Building the equalizer

Start with $R_S \cong 470\ \Omega$.

A graphic equalizer can be built with stages based on the circuits shown in Figure 4.

Obtaining real inductors of the correct values would be difficult. It is much easier to use the simulated inductor implementation shown in Figure 4b, where R_S is approximately equal to R4. R4 does not include a negligible contribution from capacitor C2.

Figure 4. Graphic equalizer



Gain of the equalizer

Now the gain of the circuit can be calculated. Selecting $R_S \cong 470\ \Omega$ constrains the input and feedback resistor of the graphic equalizer stage. Several sources use a gain of 17 dB. This gain, however, will appear only when the surrounding stages are also adjusted to their maximum level. Otherwise, the gain at the resonant stage will experience roll-off from adjacent stages according to their proximity and Q.

The potentiometer in Figure 4 is connected across the inverting and non-inverting inputs of the op amp and is in parallel with r_{id}, the differential input resistance. Therefore, it does not enter into the gain calculations for the op amp

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stage. R_S does, however. The equivalent circuit with the potentiometer at each end of its travel is shown in Figure 5.

The circuit in Figure 5a 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 R_S = 470 Ω, R1 can be calculated:

$$R1 = \frac{R_S}{A} - R_S = \frac{470\ \Omega}{7} - 470\ \Omega = 2820\ \Omega.$$

The circuit in Figure 5b 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 R_S = 470 Ω, the feedback resistor R3 is

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

This is the same value, which simplifies design. 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 points between the ends of the potentiometer wiper travel is more difficult to calculate. It will combine both non-inverting and inverting gains. Superficially, the circuit looks like a differential amplifier stage, but the resistor values are not balanced for differential operation. This leads to an unusual taper for the potentiometer. One value of resistance for the potentiometer, in this case 20 kΩ, has ½ gain/loss at the 5% and 95% settings,

Figure 5. Equivalent circuits with gain at either end of potentiometer travel

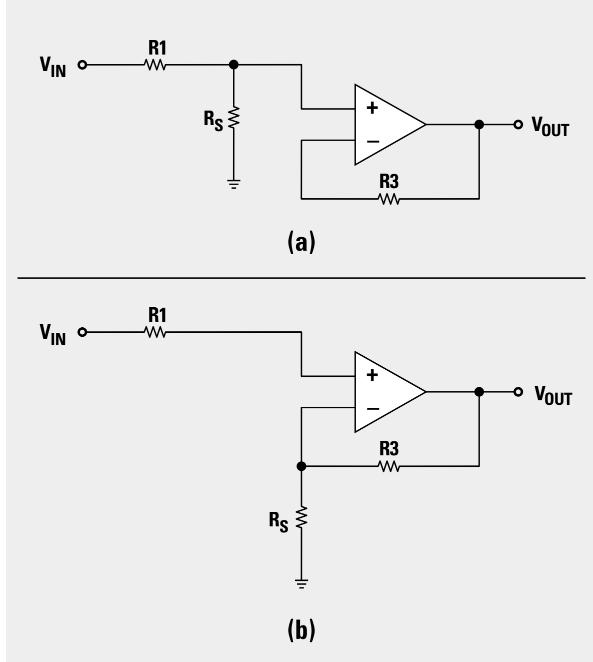
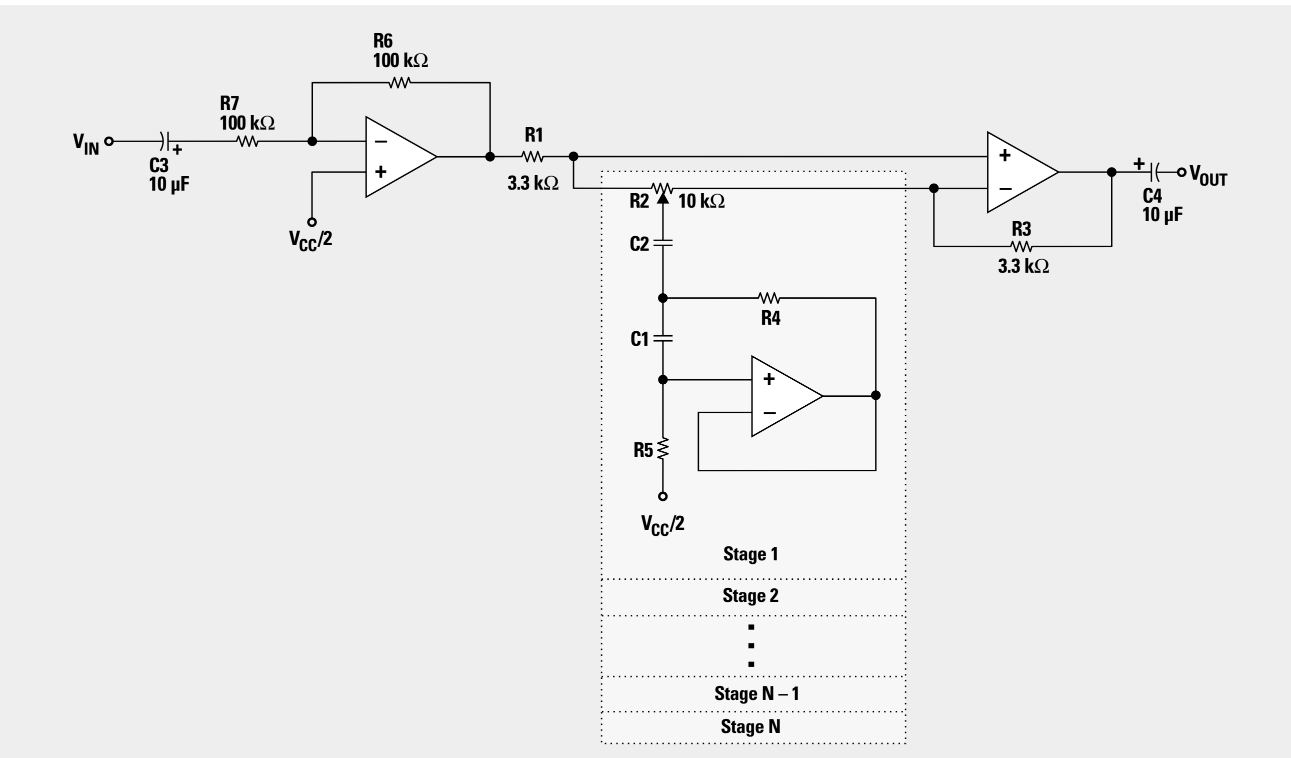


Figure 6. Graphic equalizer schematic

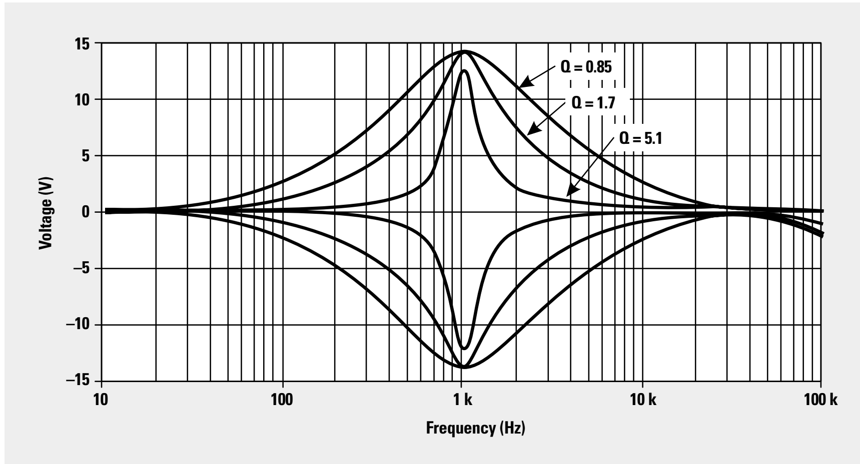


respectively. This requires a potentiometer with two logarithmic (audio) tapers joined in the center. This taper is non-standard and hard to obtain.

A partial solution to this is to reduce the value of the potentiometer. A value of 10 kΩ will diminish the logarithmic effects somewhat. Reducing the potentiometer to 5 kΩ will result in less improvement and will start to limit the bandwidth of the op amp. The best compromise is probably 10 kΩ.

Figure 6 shows the schematic of the equalizer. Capacitors C3 and C4 ac-couple the input and output, respectively. The first stage is an inverting unit gain buffer that insures that the input is buffered to drive a large number of stages. It also allows easy injection of the half-supply voltage to the equalization stages. The equalization stages are shown by the dotted lines. R5 is selected to be 100 kΩ. 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.

Figure 7. Effect of Q on bandwidth for a graphic equalizer



Q and bandwidth

At this point, the designer needs to know the Q, which is based on how many bands the equalizer will have. The Q determines the bandwidth of a band-pass filter.

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

Reference 2 recommends a Q of 1.7 for an octave equalizer. This value does give a ripple of 2.5 dB, which is reasonable for this type of device. Extending the line of reasoning, the Q of a 2-octave equalizer should be 0.85, and that of a ⅓-octave equalizer should be 5.1. The response of an equalizer stage with these Q values is shown in Figure 7.

A filter with a Q of 1.7 (Figure 7) will have a bandwidth that is 1/1.7, or 0.588 of the center frequency. Thus, the 1000-Hz filter with a Q of 1.7 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 1350 Hz, respectively. Beyond the –3-dB 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 Figure 7 demonstrates. The only thing that 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:

$$Q = \frac{X_L}{R}, \quad \text{where R is R4}$$

Resonant frequency calculation:

$$f_o = \frac{1}{2\pi\sqrt{LC}}, \quad \text{where C is C2}$$

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 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 in Figures 8–11.

References

1. Elliott Sound Products, Projects 28 and 64, http://sound.au.com
2. *Audio/Radio Handbook*, National Semiconductor (1980).

Related Web sites

www.ti.com/sc/opamps
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Figure 8. Response of a 2-octave equalizer

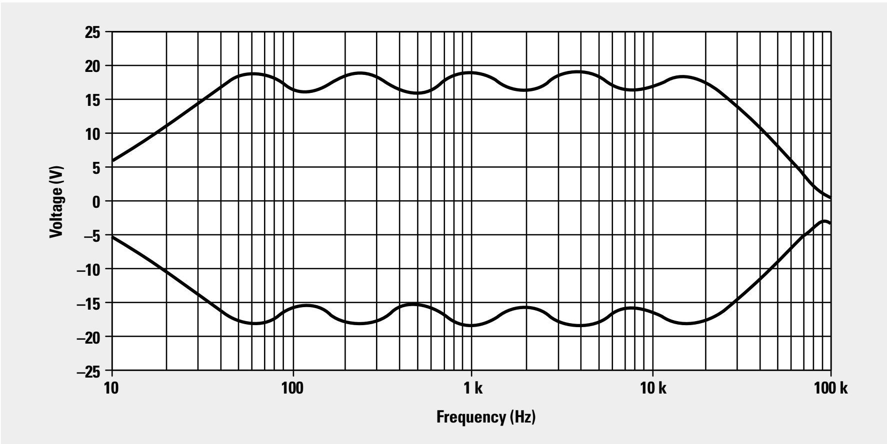


Figure 9. Response of a pseudo 2-octave equalizer

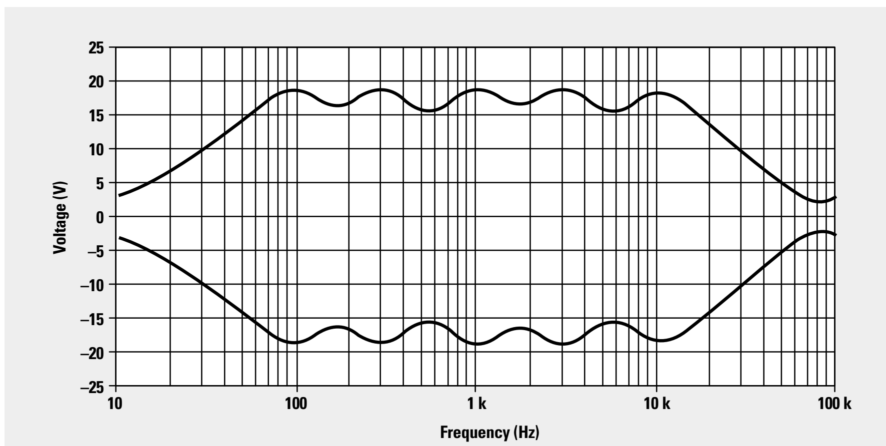


Figure 10. Response of a 1-octave equalizer

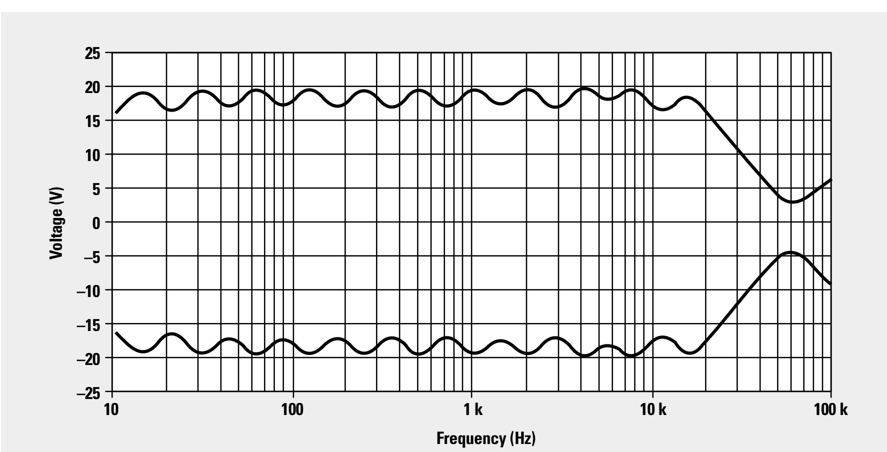
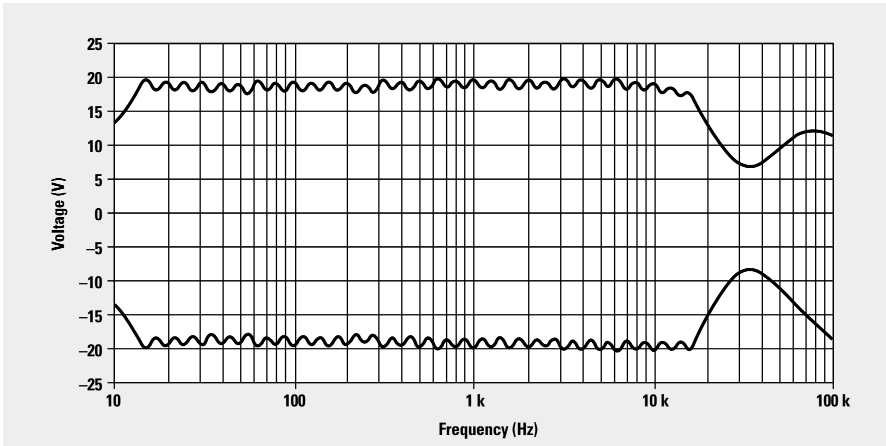


Figure 11. Response of a ⅓-octave equalizer



Appendix A. Component values for graphic equalizers

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

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.

Table 1. 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

Table 2. 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

Table 3. 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

Table 4. 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

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