CHAPTER 11

Active Filters

LEARNING OBJECTIVES

Upon completion of this chapter on active filters, you will be able to:

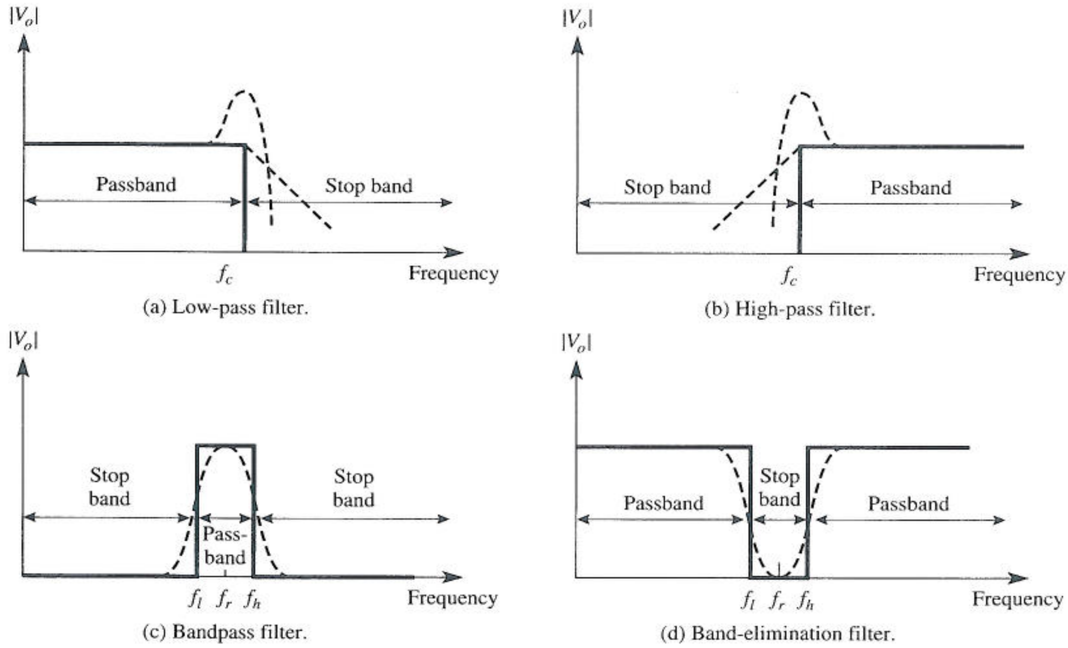
- Name the four general classifications of filters and sketch a frequency–response curve that shows the band of frequencies that they pass and stop.
- Design or analyze circuits for three types of low-pass filters: −20 dB/decade, −40 dB/decade, or −60 dB/decade roll-off.
- Design or analyze circuits for three types of high-pass filters: +20 dB, +40 dB, and +60 dB per decade of roll-off.
- Cascade a low-pass filter with a high-pass filter to make a wide bandpass filter.
- Calculate the lower and upper cutoff frequencies of either a bandpass or a notch filter if you are given (1) bandwidth and resonant frequency, (2) bandwidth and quality factor, or (3) resonant frequency and quality factor.

- Calculate the quality factor, bandwidth, and resonant frequency of a bandpass or notch filter for a given lower and upper cutoff frequency.
- Design a bandpass filter that uses only one op amp.
- Make a notch filter by (1) designing a bandpass filter circuit with the same bandwidth and a resonant frequency equal to the notch frequency, and (2) properly connecting the bandpass circuit to an inverting adder.
- Explain the operation of a stereo equalizer circuit.
- Use PSpice to simulate the performance of filter circuits.

11-0 INTRODUCTION

A *filter* is a circuit that is designed to pass a specified band of frequencies while attenuating all signals outside this band. Filter networks may be either active or passive. *Passive filter networks* contain only resistors, inductors, and capacitors. *Active filters,* which are the only type covered in this text, employ transistors or op amps plus resistors, inductors, and capacitors. Inductors are not often used in active filters, because they are bulky and costly and may have large internal resistive components.

There are four types of filters: *low-pass, high-pass, bandpass,* and *band-elimination* (also referred to as *band-reject* or *notch*) filters. Figure 11-1 illustrates frequency–



(a) Low-pass filter. (b) High-pass filter. (c) Bandpass filter. (d) Band-elimination filter.

FIGURE 11-1 Frequency response for four categories of filters.

response plots for the four types of filters. A low-pass filter is a circuit that has a constant output voltage from dc up to a *cutoff frequency* f_c. As the frequency increases above f_c, the output voltage is attenuated (decreases). Figure 11-1(a) is a plot of the magnitude of the output voltage of a low-pass filter versus frequency. The solid line is a plot for the ideal low-pass filter, while the dashed lines indicate the curves for practical low-pass filters. The range of frequencies that are *transmitted* is known as the *passband*. The range of frequencies that are *attenuated* is known as the *stop band*. The cutoff frequency, f_c, is also called the 0.707 frequency, the -3-dB frequency, the corner frequency, or the break frequency.

High-pass filters attenuate the output voltage for all frequencies below the cutoff frequency f_c. Above f_c, the magnitude of the output voltage is constant. Figure 11-1(b) is the plot for ideal and practical high-pass filters. The solid line is the ideal curve, the dashed curves show how practical high-pass filters deviate from the ideal.

Bandpass filters pass only a band of frequencies while attenuating all frequencies outside the band. Band-elimination filters perform in an exactly opposite way; that is, band-elimination filters reject a specified band of frequencies while passing all frequencies outside the band. Typical frequency–response plots for bandpass and band-elimination filters are shown in Figs. 11-1(c) and (d). Once again, the solid line represents the ideal plot, while dashed lines show the practical curves.

Filters are an integral part of electronic networks and are used in applications from audio circuits to digital signal processing systems.

11-1 BASIC LOW-PASS FILTER

11-1.1 Introduction

The circuit of Fig. 11-2(a) is a commonly used low-pass active filter. The filtering is done by the *RC* network, and the op amp is used as a unity-gain amplifier. The resistor R_f is equal to R and is included for dc offset. [At dc, the capacitive reactance is infinite and the dc resistance path to ground for both input terminals should be equal (see Section 9-4).]

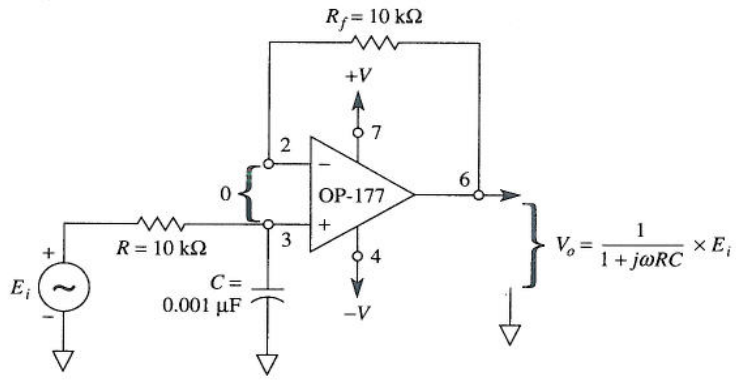
The differential voltage between pins 2 and 3 is essentially 0 V. Therefore, the voltage across capacitor C equals output voltage V_o, because this circuit is a voltage follower. E_i divides between R and C. The capacitor voltage equals V_o and is

$$V_o = \frac{1/j\omega C}{R + 1/j\omega C} \times E_i \tag{11-1a}$$

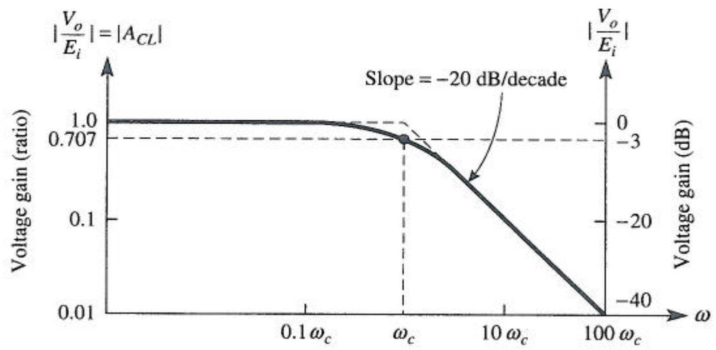
where ω is the frequency of E_i in radians per second ($\omega = 2\pi f$) and j is equal to $\sqrt{-1}$. Rewriting Eq. (11-1a) to obtain the closed-loop voltage gain A_{CL}, we have

$$A_{CL} = \frac{V_o}{E_i} = \frac{1}{1 + j\omega RC} \tag{11-1b}$$

To show that the circuit of Fig. 11-2(a) is a low-pass filter, consider how A_{CL} in Eq. (11-1b) varies as frequency is varied. At very low frequencies, that is, as ω approaches 0, $|A_{CL}| = 1$, and at very high frequencies, as ω approaches infinity, $|A_{CL}| = 0$. (The absolute value sign, $|\cdot|$, indicates magnitude.)



(a) Low-pass filter for a roll-off of −20 dB/decade.



(b) Frequency–response plot for the circuit of part (a).

FIGURE 11-2 Low-pass filter and frequency–response plot for a filter with a −20-dB/decade roll-off.

Figure 11-2(b) is a plot of $|A_{CL}|$ versus ω and shows that for frequencies *greater* than the cutoff frequency ω_c, $|A_{CL}|$ decreases at a rate of 20 dB/decade*. This is the same as saying that the voltage gain is divided by 10 when the frequency of ω is increased by 10.

11-1.2 Designing the Filter

The cutoff frequency ω_c is defined as that frequency of E_i where $|A_{CL}|$ is reduced to 0.707 times its low-frequency value. This important point will be discussed further in Section 11-1.3. The cutoff frequency is evaluated from

$$\omega_c = \frac{1}{RC} = 2\pi f_c \qquad (11\text{-}2a)$$

*$\text{dB} = 20 \log_{10} \frac{Vo}{E_i}$

where ω_c is the cutoff frequency in radians per second, f_c is the cutoff frequency in hertz, R is in ohms, and C is in farads. Equation (11-2a) may be rearranged to solve for R:

$$R = \frac{1}{\omega_c\, C} = \frac{1}{2\pi f_c\, C} \tag{11-2b}$$

Example 11-1

Let $R = 10\ \text{k}\Omega$ and $C = 0.001\ \mu\text{F}$ in Fig. 11-2(a); what is the cutoff frequency?

Solution By Eq. (11-2a),

$$\omega_c = \frac{1}{(10 \times 10^3)(0.001 \times 10^{-6})} = 100\ \text{krad/s}$$

or

$$f_c = \frac{\omega_c}{6.28} = \frac{100 \times 10^3}{6.28} = 15.9\ \text{kHz}$$

Example 11-2

For the low-pass filter in Fig. 11-2(a), calculate R for a cutoff frequency of 2 kHz and $C = 0.005\ \mu\text{F}$.

Solution From Eq. (11-2b),

$$R = \frac{1}{\omega_c\, C} = \frac{1}{(6.28)(2 \times 10^3)(5 \times 10^{-9})} = 15.9\ \text{k}\Omega$$

Example 11-3

Calculate R in Fig. 11-2(a) for a cutoff frequency of 30 krad/s and $C = 0.01\ \mu\text{F}$.

Solution From Eq. (11-2b),

$$R = \frac{1}{\omega_c\, C} = \frac{1}{(30 \times 10^3)(1 \times 10^{-8})} \simeq 3.3\ \text{k}\Omega$$

Design Procedure The design of a low-pass filter similar to Fig. 11-2(a) is accomplished in three steps:

1. Choose the cutoff frequency—either ω_c or f_c.
2. Choose the capacitance C, usually between 0.001 and 0.1 μF.
3. Calculate R from Eq. (11-2b).

11-1.3 Filter Response

The value of A_{CL} at ω_c is found by letting $\omega RC = 1$ in Eq. (11-1b):

$$A_{CL} = \frac{1}{1 + j1} = \frac{1}{\sqrt{2}\ \angle 45^\circ} = 0.707\ \angle{-45^\circ}$$

Therefore, the magnitude of A_{CL} at ω_c is

$$|A_{CL}| = \frac{1}{\sqrt{2}} = 0.707 = -3\ \text{dB}$$

and the phase angle is -45°.

The solid curve in Fig. 11-2(b) shows how the magnitude of the actual frequency response deviates from the straight dashed-line approximation in the vicinity of ω_c. At $0.1\omega_c$, $|A_{CL}| \simeq 1$ (0 dB), and at $10\omega_c$, $|A_{CL}| \simeq 0.1$ (-20 dB). Table 11-1 gives both the magnitude and the phase angle for different values of ω between $0.1\omega_c$ and $10\omega_c$.

Many applications require steeper roll-offs after the cutoff frequency. One common filter configuration that gives steeper roll-offs is the *Butterworth filter.*

TABLE 11-1 MAGNITUDE AND PHASE ANGLE FOR THE LOW-PASS FILTER OF FIG. 11-2(a)

ω	$\lvert A_{CL}\rvert$	Phase angle (deg)
$0.1\omega_c$	1.0	-6
$0.25\omega_c$	0.97	-14
$0.5\omega_c$	0.89	-27
ω_c	0.707	-45
$2\omega_c$	0.445	-63
$4\omega_c$	0.25	-76
$10\omega_c$	0.1	-84

11-2 INTRODUCTION TO THE BUTTERWORTH FILTER

In many low-pass filter applications, it is necessary for the closed-loop gain to be as close to 1 as possible within the passband. The *Butterworth filter* is best suited for this type of application. The Butterworth filter is also called a *maximally flat* or *flat-flat* filter, and all filters in this chapter will be of the Butterworth type. Figure 11-3 shows the ideal (solid line) and the practical (dashed lines) frequency response for three types of Butterworth filters. As the roll-offs become steeper, they approach the ideal filter more closely.

Two active filters similar to Fig. 11-2(a) could be coupled together to give a roll-off of -40 dB/decade. This would not be the most economical design, because it would require two op amps. In Section 11-3.1, it is shown how one op amp can be used to build a Butterworth filter with a single op amp to give a -40-dB/decade roll-off. Then in Section 11-4, a -40-dB/decade filter is cascaded with a -20-dB/decade filter to produce a -60-dB/decade filter.

Butterworth filters are not designed to keep a constant phase angle at the cutoff frequency. A basic low-pass filter of -20 dB/decade has a phase angle of $-45°$ at ω_c. A -40-dB/decade Butterworth filter has a phase angle of $-90°$ at ω_c, and a -60-dB/decade filter has a phase angle of $-135°$ at ω_c. Therefore, for each increase of -20 dB/decade, the phase angle will increase by $-45°$ at ω_c. We now proceed to a Butterworth filter that has a roll-off steeper than -20 dB/decade.

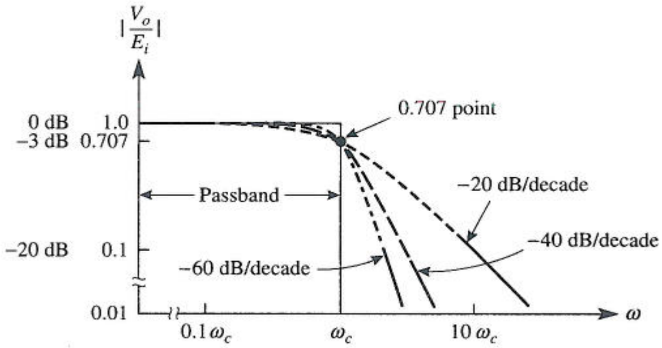


FIGURE 11-3 Frequency–response plots for three types of low-pass Butterworth filters.

11-3 40-DB/DECADE LOW-PASS BUTTERWORTH FILTER

11-3.1 Simplified Design Procedure

The circuit of Fig. 11-4(a) is one of the most commonly used low-pass filters. It produces a roll-off of -40 dB/decade; that is, after the cutoff frequency, the magnitude of A_{CL} decreases by 40 dB as ω increases to $10\omega_c$. The solid line in Fig. 11-4(b) shows the actual frequency–response plot, which is explained in more detail in Section 11-3.2. The op amp is connected for dc unity gain. Resistor R_f is included for dc offset, as explained in Section 9-4. Since the op amp circuit is basically a voltage follower (unity-gain amplifier), the voltage across C_1 equals output voltage, V_o.

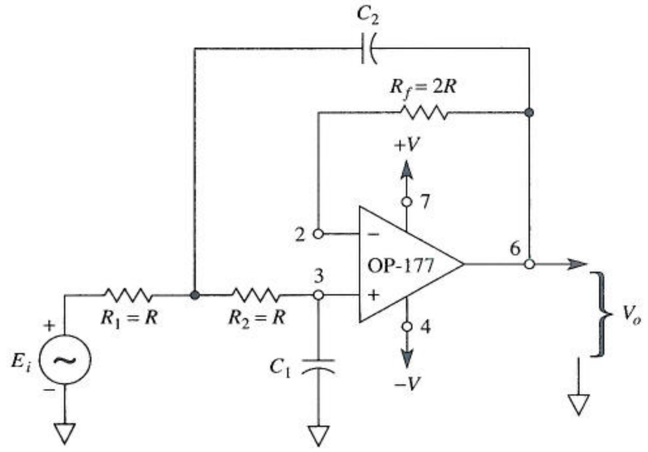
The design of the low-pass filter of Fig. 11-4(a) is greatly simplified by making resistors $R_1 = R_2 = R$. Then there are only five steps in the design procedure.

Design procedure

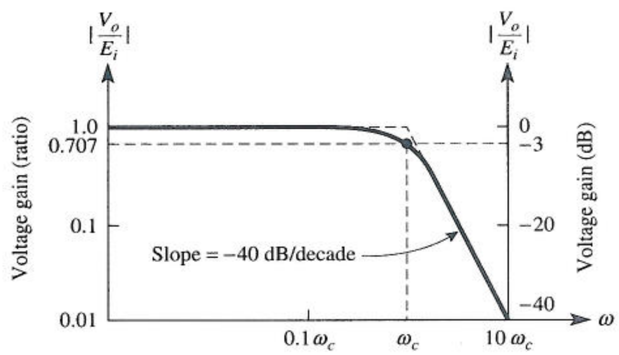
1. Choose the cutoff frequency, ω_c or f_c.
2. Pick C_1; choose a convenient value between 100 pF and 0.1 μF.
3. Make $C_2 = 2C_1$.
4. Calculate

$$R = \frac{0.707}{\omega_c\, C_1} \tag{11-3}$$

5. Choose $R_f = 2R$.



(a) Low-pass filter for a roll-off of −40 dB/decade.



(b) Frequency–response plot for the low-pass filter of part (a).

FIGURE 11-4 Circuit and frequency plot for a low-pass filter of −40 dB/decade.

Example 11-4

Determine R_1 and R_2 in Fig. 11-4(a) for a cutoff frequency of 1 kHz. Let $C_1 = 0.01\ \mu\text{F}$.

Solution Pick $C_2 = 2C_1 = 2(0.01\ \mu\text{F}) = 0.02\ \mu\text{F}$. Select $R_1 = R_2 = R$ from Eq. (11.3):

$$R = \frac{0.707}{(6.28)(1 \times 10^3)(0.01 \times 10^{-6})} = 11{,}258\ \Omega$$

and

$$R_f = 2(11{,}258\ \Omega) = 22{,}516\ \Omega$$

11-3.2 Filter Response

The solid curve in Fig. 11-4(b) shows that the filter of Fig. 11-4(a) not only has a steeper roll-off after ω_c than does Fig. 11-2(a), but also remains at 0 dB almost up to about 0.25 ω_c. The phase angles for the circuit of Fig. 11-4(a) range from 0° at $\omega = 0$ rad/s (dc condition) to $-180°$ as ω approaches ∞ (infinity). Table 11-2 compares magnitude and phase angle for the low-pass filters of Figs. 11-2(a) and 11-4(a) from $0.1\omega_c$ to $10\omega_c$.

The next low-pass filter cascades the filter of Fig. 11-2(a) with the filter of Fig. 11-4(a) to form a roll-off of -60 dB/decade. As will be shown, the resistors are the only values that have to be calculated.

TABLE 11-2 MAGNITUDE AND PHASE ANGLE FOR FIGS. 11-2(a) AND 11-4(a)

	$\lvert A_{CL} \rvert$		Phase angle (deg)	
ω	-20 dB/decade; Fig. 11-2(a)	-40 dB/decade; Fig. 11-4(a)	Fig. 11-2(a)	Fig. 11-4(a)
$0.1\omega_c$	1.0	1.0	-6	-8
$0.25\omega_c$	0.97	0.998	-14	-21
$0.5\omega_c$	0.89	0.97	-27	-43
ω_c	0.707	0.707	-45	-90
$2\omega_c$	0.445	0.24	-63	-137
$4\omega_c$	0.25	0.053	-76	-143
$10\omega_c$	0.1	0.01	-84	-172

11-4 −60-DB/DECADE LOW-PASS BUTTERWORTH FILTER

11-4.1 Simplified Design Procedure

The low-pass filter of Fig. 11-5(a) is built using one low-pass filter of -40 dB/decade cascaded with another of -20 dB/decade to give an overall roll-off of -60 dB/decade. The overall closed-loop gain A_{CL} is the gain of the first filter times the gain of the second filter, or

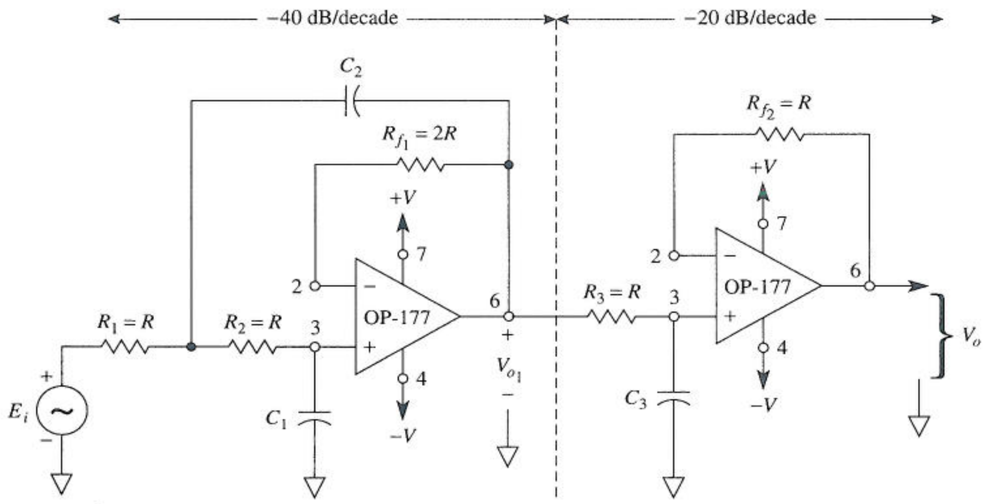
$$A_{CL} = \frac{V_o}{E_i} = \frac{V_{o_1}}{E_i} \times \frac{V_o}{V_{o_1}} \tag{11-4}$$

For a Butterworth filter, the magnitude of A_{CL} must be 0.707 at ω_c. To guarantee that the frequency response is flat in the passband, use the following design steps.

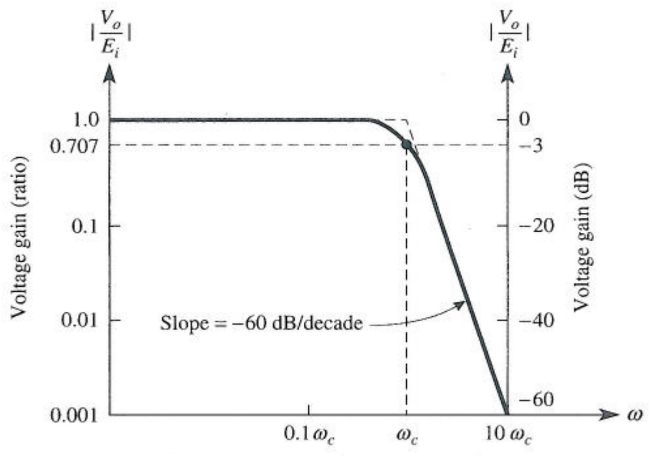
Design procedure

1. Choose the cutoff frequency, ω_c or f_c.
2. Pick C_3; choose a convenient value between 0.001 and 0.1 μF.
3. Make

$$C_1 = \tfrac{1}{2}C_3 \qquad \text{and} \qquad C_2 = 2C_3 \tag{11-5}$$



(a) Low-pass filter for a roll-off of −60 dB/decade.



(b) Plot of frequency response for the circuit of part (a).

FIGURE 11-5 Low-pass filter designed for a roll-off of −60 dB/decade and corresponding frequency–response plot.

4. Calculate

$$R = \frac{1}{\omega_c C_3} \tag{11-6}$$

5. Make $R_1 = R_2 = R_3 = R$.
6. $R_{f_1} = 2R$ and $R_{f_2} = R$. For best results the value of R should be between 10 and 100 kΩ. If the value of R is outside this range, you should go back and pick a new value of C_3.

Example 11-5

For the − 60-dB/decade low-pass filter of Fig. 11-5(a), determine the values of C_1, C_2, and R for a cutoff frequency of 1 kHz. Let $C_3 = 0.01\ \mu F$.

Solution From Eq. (11-5),

$$C_1 = \tfrac{1}{2}C_3 = \tfrac{1}{2}(0.01\ \mu F) = 0.005\ \mu F$$

and

$$C_2 = 2C_3 = 2(0.01\ \mu F) = 0.02\ \mu F$$

From Eq. (11-6),

$$R = \frac{1}{(6.28)(1 \times 10^3)(0.01 \times 10^{-6})} = 15{,}915\ \Omega$$

Example 11-5 shows that the value of R in Fig. 11-5(a) is different from those of Fig. 11-4(a), although the cutoff frequency is the same. This is necessary so that $|A_{CL}|$ remains at 0 dB in the passband until the cutoff frequency is nearly reached; then $|A_{CL}| = 0.707$ at ω_c. 11-5

11-4.2 Filter Response

The solid line in Fig. 11-5(b) is the actual plot of the frequency response for Fig. 11-5(a). The dashed curve in the vicinity shows the straight-line approximation. Table 11-3 compares the magnitudes of A_{CL} for the three low-pass filters presented in this chapter. Note that the $|A_{CL}|$ for Fig. 11-5(a) remains quite close to 1 (0 dB) until the cutoff frequency, ω_c; then the steep roll-off occurs.

TABLE 11-3 $|A_{CL}|$ FOR THE LOW-PASS FILTERS OF FIGS. 11-2(a), 11-4(a), AND 11-5(a)

ω	−20 dB/decade; Fig. 11-2(a)	−40 dB/decade; Fig. 11-4(a)	−60 dB/decade; Fig. 11-5(a)
$0.1\omega_c$	1.0	1.0	1.0
$0.25\omega_c$	0.97	0.998	0.999
$0.5\omega_c$	0.89	0.97	0.992
ω_c	0.707	0.707	0.707
$2\omega_c$	0.445	0.24	0.124
$4\omega_c$	0.25	0.053	0.022
$10\omega_c$	0.1	0.01	0.001

The phase angles for the low-pass filter of Fig. 11-5(a) range from 0° at $\omega = 0$ (dB condition) to $-270°$ as ω approaches ∞. Table 11-4 compares the phase angles for the three low-pass filters.

All digital signal processing systems use a low-pass filter at the front end to attenuate frequencies above the Nyquist frequency, which is one-half the sampling rate.

TABLE 11-4 PHASE ANGLES FOR THE LOW-PASS FILTERS OF FIGS. 11-2(a), 11-4(a), AND 11-5(a)

ω	-20 dB/decade; Fig. 11-2(a)	-40 dB/decade; Fig. 11-4(a)	-60 dB/decade; Fig. 11-5(a)
$0.1\omega_c$	$-6°$	$-8°$	$-12°$
$0.25\omega_c$	$-4°$	$-21°$	$-29°$
$0.5\omega_c$	$-27°$	$-43°$	$-60°$
ω_c	$-45°$	$-90°$	$-135°$
$2\omega_c$	$-63°$	$-137°$	$-210°$
$4\omega_c$	$-76°$	$-143°$	$-226°$
$10\omega_c$	$-84°$	$-172°$	$-256°$

11-5 HIGH-PASS BUTTERWORTH FILTERS

11-5.1 Introduction

A high-pass filter is a circuit that attenuates all signals below a specified cutoff frequency ω_c and passes all signals whose frequency is above the cutoff frequency. Thus a high-pass filter performs the opposite function of the low-pass filter.

Figure 11-6 is a plot of the magnitude of the closed-loop gain versus ω for three types of Butterworth filters. The phase angle for a circuit of 20 dB/decade is $+45°$ at ω_c.

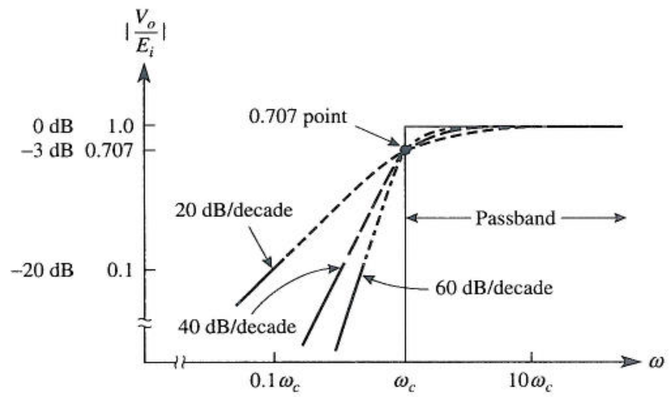


FIGURE 11-6 Comparison of frequency response for three high-pass Butterworth filters.

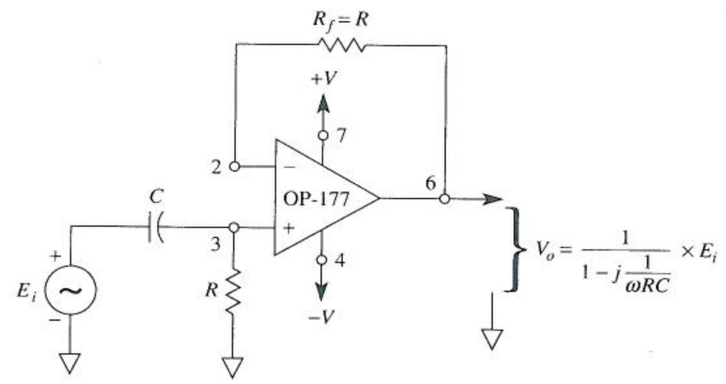
Phase angles at ω_c *increase* by $+45°$ for each *increase* of 20 dB/decade. The phase angles for these three types of high-pass filters are compared in Section 11-5.5.

In this book the design of high-pass filters will be similar to that of the low-pass filters. In fact, the only difference will be the position of the filtering capacitors and resistors.

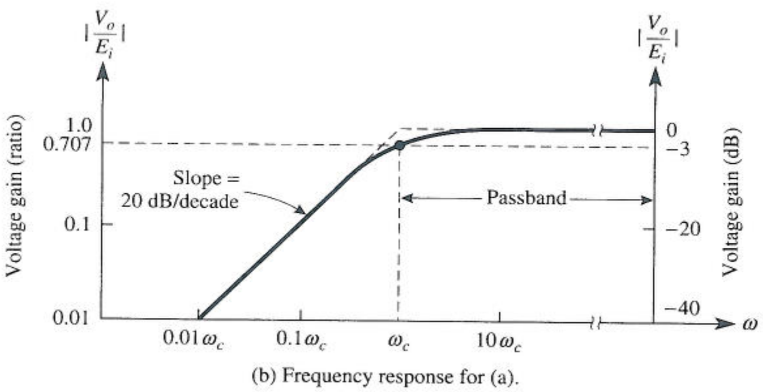
11-5.2 20-dB/Decade Filter

Compare the high-pass filter of Fig. 11-7(a) with the low-pass filter of Fig. 11-2(a) and note that C and R are interchanged. The feedback resistor R_f is included to minimize dc offset. Since the op amp is connected as a unity-gain follower in Fig. 11-7(a), the output voltage V_o equals the voltage across R and is expressed by

$$V_o = \frac{1}{1 - j(1/\omega RC)} \times E_i \tag{11-7}$$



(a) High-pass filter with a roll-off of 20 dB/decade.



(b) Frequency response for (a).

FIGURE 11-7 Basic high-pass filter, 20 dB/decade.

When ω approaches 0 rad/s in Eq. (11-7), V_o approaches 0 V. At high frequencies, as ω approaches infinity, V_o equals E_i. Since the circuit is not an ideal filter, the frequency response is not ideal, as shown by Fig. 11-7(b). The solid line is the actual response; the dashed lines show the straight-line approximation. The magnitude of the closed-loop gain equals 0.707 when $\omega RC = 1$. Therefore, the cutoff frequency ω_c is given by

$$\omega_c = \frac{1}{RC} = 2\pi f_c \tag{11-8a}$$

or

$$R = \frac{1}{\omega_c C} = \frac{1}{2\pi f_c C} \tag{11-8b}$$

The reason for solving for R and not C in Eq. (11-8b) is that it is easier to adjust R than it is C. The steps needed in designing Fig. 11-7(a) are as follows:

Design procedure for 20-dB/decade high-pass

1. Choose the cutoff frequency, ω_c or f_c.
2. Choose a convenient value of C, usually between 0.001 and 0.1 μF.
3. Calculate R from Eq. (11-8b).
4. Choose $R_f = R$.

Example 11-6

Calculate R in Fig. 11-7(a) if $C = 0.002\ \mu$F and $f_c = 10$ kHz.

Solution From Eq. (11-8b),

$$R = \frac{1}{(6.28)(10 \times 10^3)(0.002 \times 10^{-6})} = 8\ \text{k}\Omega$$

Example 11-7

In Fig 11-7(a) if $R = 22\ \text{k}\Omega$ and $C = 0.01\ \mu$F, calculate (a) ω_c; (b) f_c.

Solution (a) From Eq. (11-8a),

$$\omega_c = \frac{1}{(22 \times 10^3)(0.01 \times 10^{-6})} = 4.54\ \text{krad/s}$$

(b)

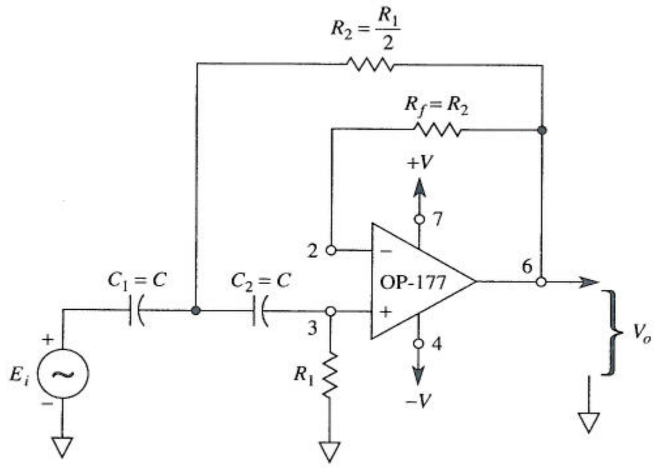
$$f_c = \frac{\omega_c}{2\pi} = \frac{4.54 \times 10^3}{6.28} = 724\ \text{Hz}$$

11-5.3 40-dB/Decade Filter

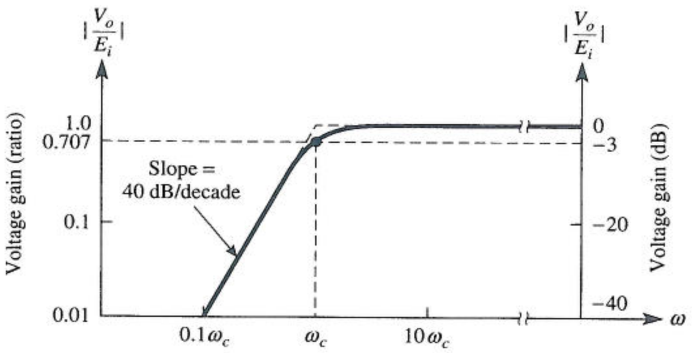
The circuit of Fig. 11-8(a) is to be designed as a high-pass Butterworth filter with a roll-off of 40 dB/decade below the cutoff frequency, ω_c. To satisfy the Butterworth criteria, the frequency response must be 0.707 at ω_c and be 0 dB in the pass band. These conditions will be met if the following design procedure is followed:

Design procedure for 40-dB/decade high-pass

1. Choose a cutoff frequency, ω_c or f_c.
2. Let $C_1 = C_2 = C$ and choose a convenient value.



(a) High-pass filter with a roll-off of 40 dB/decade.



(b) Frequency response for circuit of part (a).

FIGURE 11-8 Circuit and frequency response for a 40-dB/decade high-pass Butterworth filter.

3. Calculate R_1 from

$$R_1 = \frac{1.414}{\omega_c\, C} \tag{11-9}$$

4. Select

$$R_2 = \tfrac{1}{2}R_1 \tag{11-10}$$

5. To minimize dc offset, let $R_f = R_1$.

Example 11-8

In Fig. 11-8(a), let $C_1 = C_2 = 0.01\ \mu F$. Calculate (a) R_1 and (b) R_2 for a cutoff frequency of 1 kHz.

Solution (a) From Eq. (11-9),

$$R_1 = \frac{1.414}{(6.28)(1 \times 10^3)(0.01 \times 10^{-6})} = 22.5\ k\Omega$$

(b) $R_2 = \frac{1}{2}(22.5\ k\Omega) = 11.3\ k\Omega$.

Example 11-9

Calculate (a) R_1 and (b) R_2 in Fig. 11-8(a) for a cutoff frequency of 80 krad/s. $C_1 = C_2 =$ 125 pF.

Solution (a) From (11-9),

$$R_1 = \frac{1.414}{(80 \times 10^3)(125 \times 10^{-12})} = 140\ k\Omega$$

(b)

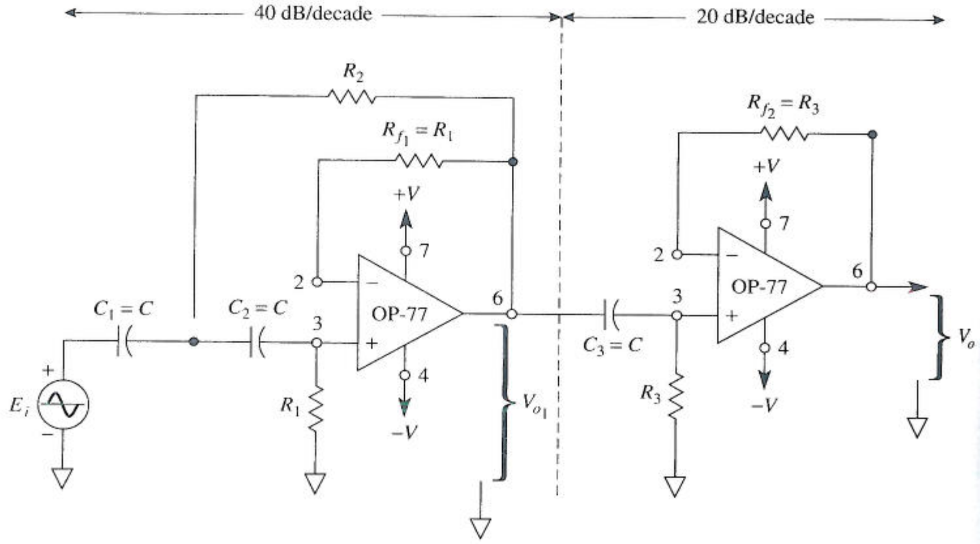
$$R_2 = \tfrac{1}{2}(140\ k\Omega) = 70\ k\Omega.$$

11-5.4 60-dB/Decade Filter

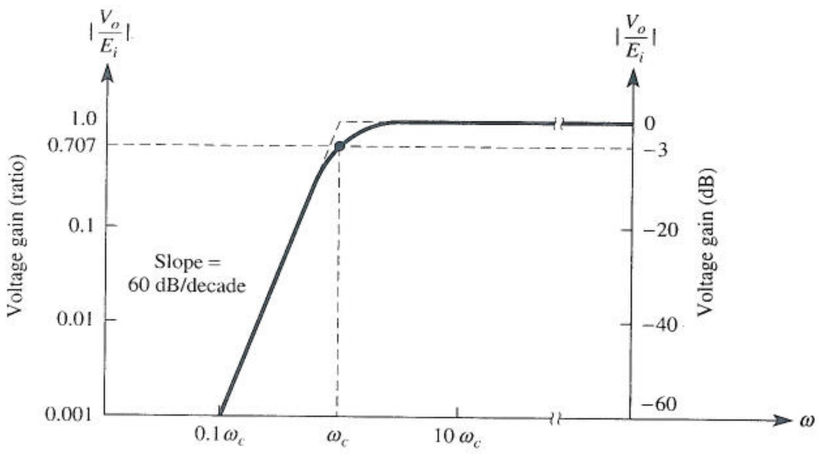
As with the low-pass filter of Fig. 11-5, a high-pass filter of +60 dB/decade can be constructed by cascading a +40-dB/decade filter with a +20-dB/decade filter. This circuit (like the other high- and low-pass filters) is designed as a Butterworth filter to have the frequency response in Fig. 11-9(b). The design steps for Fig. 11-9(a) are as follows:

Design procedure for 60-dB/decade high-pass

1. Choose the cutoff frequency, ω_c or f_c.
2. Let $C_1 = C_2 = C_3 = C$ and choose a convenient value between 100 pF and 0.1 μF.



(a) High-pass filter for a 60 dB/decade slope.



(b) Frequency–response for the circuit of part (a).

FIGURE 11-9 Circuit and frequency response for a 60-dB/decade Butterworth high-pass filter.

3. Calculate R_3 from

$$R_3 = \frac{1}{\omega_c C} \tag{11-11}$$

4. Select

$$R_1 = 2R_3 \tag{11-12}$$

5. Select

$$R_2 = \tfrac{1}{2}R_3 \tag{11-13}$$

6. To minimize dc offset current, let $R_{f_1} = R_1$ and $R_{f_2} = R_3$.

Example 11-10

For Fig. 11-9(a), let $C_1 = C_2 = C_3 = C = 0.1\ \mu\text{F}$. Determine (a) R_3, (b) R_1, and (c) R_2 for $\omega_c = 1$ krad/s. ($f_c = 159$ Hz.)

Solution (a) By Eq. (11-11),

$$R_3 = \frac{1}{(1 \times 10^3)(0.1 \times 10^{-6})} = 10\ \text{k}\Omega$$

(b) $R_1 = 2R_3 = 2(10\ \text{k}\Omega) = 20\ \text{k}\Omega$.
(c) $R_2 = \frac{1}{2}R_3 = \frac{1}{2}(10\ \text{k}\Omega) = 5\ \text{k}\Omega$.

Example 11-11

Determine (a) R_3, (b) R_1, and (c) R_2 in Fig. 11-9(a) for a cutoff frequency of 60 kHz. Let $C_1 = C_2 = C_3 = C = 220$ pF.

Solution (a) From Eq. (11-11),

$$R_3 = \frac{1}{(6.28)(60 \times 10^3)(220 \times 10^{-12})} = 12\ \text{k}\Omega$$

(b) $R_1 = 2R_3 = 2(12\ \text{k}\Omega) = 24\ \text{k}\Omega$.
(c) $R_2 = \frac{1}{2}R_3 = \frac{1}{2}(12\ \text{k}\Omega) = 6\ \text{k}\Omega$.

If desired, the 20-dB/decade section can come before the 40-dB/decade section, because the op amps provide isolation and do not load one another.

11-5.5 Comparison of Magnitudes and Phase Angles

Table 11-5 compares the magnitudes of the closed-loop gain for the three high-pass filters. For each increase of 20 dB/decade, the circuit not only has a steeper roll-off below ω_c but also remains closer to 0 dB or a gain of 1 above ω_c.

The phase angle for a 20-dB/decade Butterworth high-pass filter is 45° at ω_c. For a 40-dB/decade filter it is 90°, and for a 60-dB/decade filter it is 135°. Other phase angles in the vicinity of ω_c for the three filters are given in Table 11-6.

TABLE 11-5 COMPARISON OF $|A_{CL}|$ FOR FIGS. 11-7(a), 11-8(a), AND 11-9(a)

ω	20 dB/decade; Fig. 11-7(a)	40 dB/decade; Fig. 11-8(a)	60 dB/decade; Fig. 11-9(a)
$0.1\omega_c$	0.1	0.01	0.001
$0.25\omega_c$	0.25	0.053	0.022
$0.5\omega_c$	0.445	0.24	0.124
ω_c	0.707	0.707	0.707
$2\omega_c$	0.89	0.97	0.992
$4\omega_c$	0.97	0.998	0.999
$10\omega_c$	1.0	1.0	1.0

TABLE 11-6 COMPARISON OF PHASE ANGLES FOR FIGS. 11-7(a), 11-8(a), AND 11-9(a)

ω	20 dB/decade; Fig. 11-7(a)	40 dB/decade; Fig. 11-8(a)	60 dB/decade; Fig. 11-9(a)
$0.1\omega_c$	84°	172°	256°
$0.25\omega_c$	76°	143°	226°
$0.5\omega_c$	63°	137°	210°
ω	45°	90°	135°
$2\omega_c$	27°	43°	60°
$4\omega_c$	14°	21°	29°
$10\omega_c$	6°	8°	12°

11-6 INTRODUCTION TO BANDPASS FILTERS

11-6.1 Frequency Response

A bandpass filter is a frequency selector. It allows one to select or pass only one particular band of frequencies from all other frequencies that may be present in a circuit. Its normalized frequency response is shown in Fig. 11-10. This type of filter has a maximum gain at a resonant frequency f_r. In this chapter all bandpass filters will have a gain of 1 or 0 dB at f_r. There is one frequency below f_r where the gain falls to 0.707. It is the *lower cutoff frequency, f_l*. At the *higher cutoff frequency, f_h*, the gain also equals 0.707, as in Fig. 11-10.

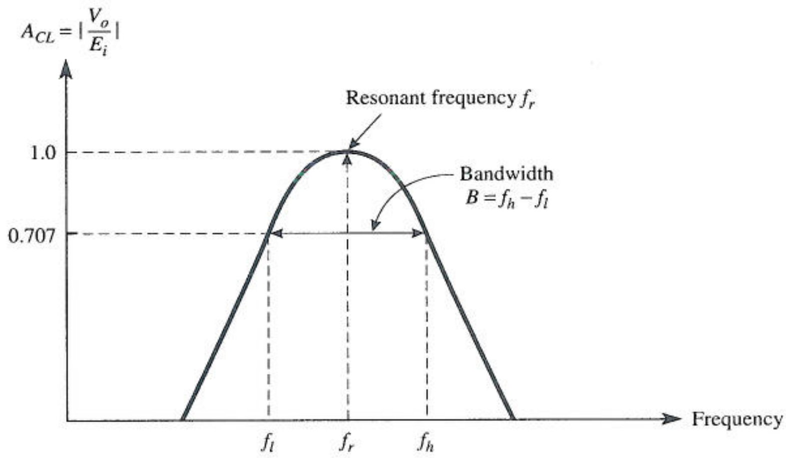


FIGURE 11-10 A bandpass filter has a maximum gain at resonant frequency f_r. The band of frequencies transmitted lies between f_l and f_h.

11-6.2 Bandwidth

The range of frequencies between f_l and f_h is called *bandwidth B,* or

$$B = f_h - f_l \tag{11-14}$$

The bandwidth is not exactly centered on the resonant frequency. (It is for this reason that we use the historical name "resonant frequency" rather than "center frequency" to describe f_r.)

If you know the values for f_l and f_h, the resonant frequency can be found from

$$f_r = \sqrt{f_l f_h} \tag{11-15}$$

If you know the resonant frequency, f_r, and bandwidth, B, cutoff frequencies can be found from

$$f_l = \sqrt{\frac{B^2}{4} + f_r^2} - \frac{B}{2} \tag{11-16a}$$

$$f_h = f_l + B \tag{11-16b}$$

Example 11-12

A bandpass voice filter has lower and upper cutoff frequencies of 300 and 3000 Hz. Find (a) the bandwidth; (b) the resonant frequency.

Solution (a) From Eq. (11-14),

$$B = f_h - f_l = (3000 - 300) = 2700 \text{ Hz}$$

(b) From Eq. (11-15),

$$f_r = \sqrt{f_l f_h} = \sqrt{(300)(3000)} = 948.7 \text{ Hz}$$

Note: f_r is always *below* the center frequency of $(3000 + 300)/2 = 1650$ Hz.

Example 11-13

A bandpass filter has a resonant frequency of 950 Hz and a bandwidth of 2700 Hz. Find its lower and upper cutoff frequencies.

Solution From Eq. (11-16a),

$$f_l = \sqrt{\frac{B^2}{4} + f_r^2} - \frac{B}{2} = \sqrt{\frac{(2700)^2}{4} + (950)^2} - \frac{2700}{2}$$
$$= 1650 - 1350 = 300 \text{ Hz}$$

From Eq. (11-16b), $f_h = 300 + 2700 = 3000$ Hz.

11-6.3 Quality Factor

The *quality factor* Q is defined as the ratio of resonant frequency to bandwidth, or

$$Q = \frac{f_r}{B} \tag{11-17}$$

Q is a measure of the bandpass filter's *selectivity.* A high Q indicates that a filter selects a smaller band of frequencies (more selective).

11-6.4 Narrowband and Wideband Filters

A *wideband* filter has a bandwidth that is two or more times the resonant frequency. That is, $Q \le 0.5$ for wideband filters. In general, wideband filters are made by cascading a low-pass filter circuit with a high-pass filter circuit. This topic is covered in the next section. A narrowband filter ($Q > 0.5$) can usually be made with a single stage. This type of filter is presented in Section 11-8.

Example 11-14

Find the quality factor of a voice filter that has a bandwidth of 2700 Hz and a resonant frequency of 950 Hz (see Examples 11-12 and 11-13).

Solution From Eq. (11-7),

$$Q = \frac{f_r}{B} = \frac{950}{2700} = 0.35$$

This filter is classified as wideband because $Q < 0.5$.

11-7 BASIC WIDEBAND FILTER

11-7.1 Cascading

When the output of one circuit is connected in series with the input of a second circuit, the process is called *cascading* gain stages. In Fig. 11-11, the first stage is a 3000-Hz low-pass filter (Section 11-3). Its output is connected to the input of a 300-Hz high-pass filter (Section 11-5.3). The cascaded pair of active filters now form a bandpass filter from input E_i to output V_o. Note that it makes no difference if the high-pass is connected to the low-pass, or vice versa. Note: Each op amp circuit in Fig. 11-11 has unity gain.

11-7.2 Wideband Filter Circuit

In general, a wideband filter ($Q \leq 0.5$) is made by cascading a low- and a high-pass filter (see Fig. 11-11). Cutoff frequencies of the low- and high-pass sections *must not overlap,* and each must have the same passband gain. Furthermore, the low-pass filter's cutoff frequency must be 10 or more times the high-pass filter's cutoff frequency.

For cascaded low- and high-pass filters, the resulting wideband filter will have the following characteristics:

1. The lower cutoff frequency, f_l, will be determined only by the high-pass filter.
2. The high cutoff frequency, f_h, will be set only by the low-pass filter.
3. Gain will be maximum at resonant frequency, f_r, and equal to the passband gain of either filter.

These principles are illustrated next.

11-7.3 Frequency Response

In Fig. 11-11 the frequency response of a basic −40-dB/decade 3000-Hz low-pass filter is plotted as a dashed line. The frequency response of a 300-Hz high-pass filter is plotted as a solid line. The 40-dB/decade roll-off of the high-pass filter is seen to determine f_l. The −40-dB/decade roll-off of the low-pass sets f_h. Both roll-off curves make up the frequency response of the bandpass filter, V_o versus f. Observe that the resonant, low, and high cutoff frequencies plus bandwidth agree exactly with the values calculated in

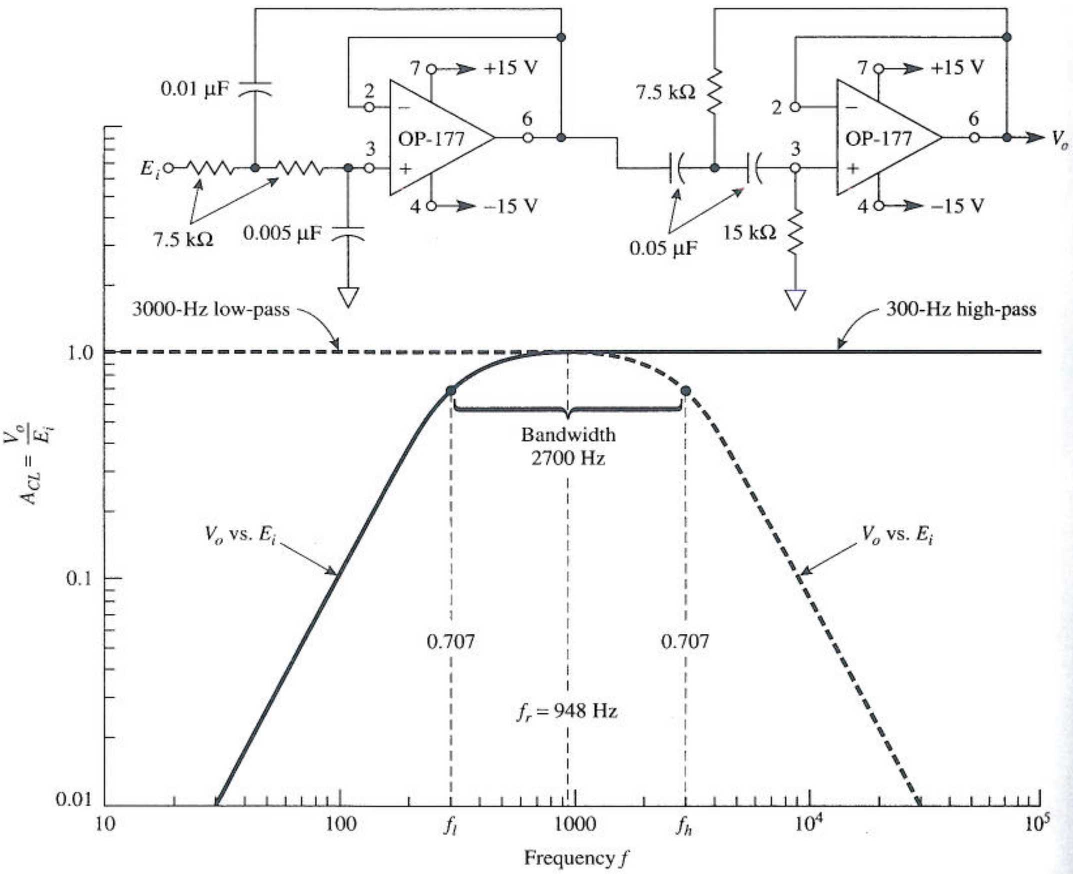
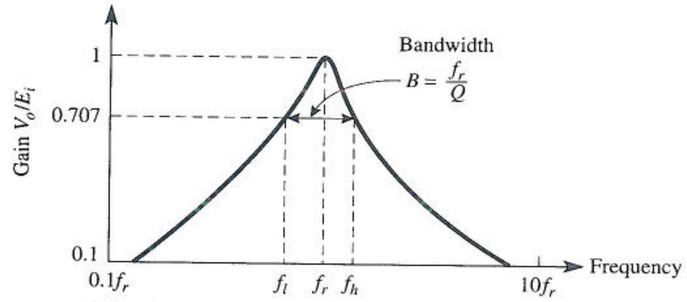


FIGURE 11-11 A 3000-Hz second-order low-pass filter is cascaded with a 300-Hz high-pass filter to form a 300- to 3000-Hz bandpass voice filter.

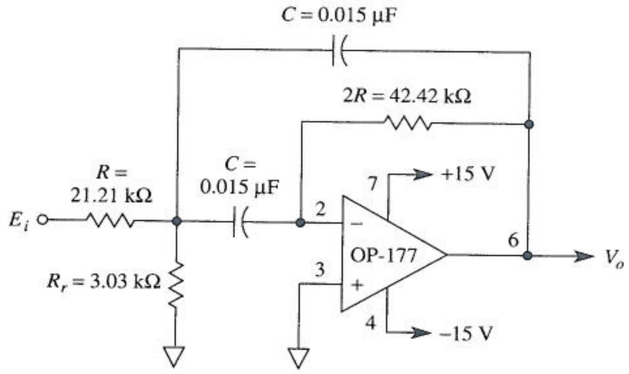
Examples 11-12 and 11-13. Narrow bandpass filters will be introduced in Section 11-8. Discussion of notch filters is deferred until Sections 11-9 and 11-10.

11-8 NARROWBAND BANDPASS FILTERS

Narrowband filters exhibit the typical frequency response shown in Fig. 11-12(a). The analysis and construction of narrowband filters is considerably simplified if we stipulate that the narrowband filter will have a maximum gain of 1 or 0 dB at the resonant frequency f_r. Equations (11-14) through (11-17) and bandpass terms were presented in Section 11-6. They gave an introduction to (cascaded pair) wideband filters. These equations and terms also apply to the narrowband filters that follow.



(a) Typical frequency response curve of a narrowband filter.



(b) Narrowband filter.

FIGURE 11-12 Narrow bandpass filter circuit and its frequency response for the component values shown; $f_r = 100$ Hz, $B = 500$ Hz, $Q = 2$, $f_l = 780$ Hz, and $f_h = 1280$ Hz. (a) Typical frequency response of a bandpass filter; (b) narrow bandpass filter circuit.

11-8.1 Narrowband Filter Circuit

A narrowband filter circuit uses only one op amp, as shown in Fig. 11-12. (Compare with the two-op-amp wideband filters in Fig. 11-11.) The filter's input resistance is established approximately by resistor R. If the feedback resistor ($2R$) is made two times the input resistor R, the filter's maximum gain will be 1 or 0 dB at resonant frequency f_r. By adjusting R_r one can change (or exactly trim) the resonant frequency *without changing the bandwidth or gain.*

11-8.2 Performance

The performance of the *unity*-gain narrowband filter in Fig. 11-12 is determined by only a few simple equations. The bandwidth B in hertz is determined by resistor R and the two (matched) capacitors C by

$$B = \frac{0.1591}{RC} \tag{11-18a}$$

where

$$B = \frac{f_r}{Q} \tag{11-18b}$$

Gain is a maximum of 1 at f_r provided that feedback resistor $2R$ is twice the value of input resistor R.

The resonant frequency f_r is determined by resistor R_r according to

$$R_r = \frac{R}{2Q^2 - 1} \tag{11-19}$$

If you are given component values for the circuit, its resonant frequency can be calculated from

$$f_r = \frac{0.1125}{RC}\sqrt{1 + \frac{R}{R_r}} \tag{11-20}$$

11-8.3 Stereo-Equalizer Octave Filter

A stereo equalizer has 10 bandpass filters per channel. They separate the audio spectrum from approximately 30 Hz to 16 kHz into 10 separate octaves of frequency. Each octave can then be cut or boosted with respect to the other to achieve special sound effects, equalize room response, or equalize an automotive compartment to make the radio sound like it is playing in a large hall. The construction of one such equalizer will be analyzed by an example.

Example 11-15

Octave equalizers have resonant frequencies at approximately 32, 64, 128, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz. Q of each filter is chosen to have values between 1.4 and 2. Let's make a unity-gain narrowband filter to select the sixth octave. Specifically, make a filter with $f_r = 1000$ Hz and $Q = 2$.

Solution From Eq. (11-18b),

$$B = \frac{f_r}{Q} = \frac{1000}{2} = 500 \text{ Hz}$$

[*Note:* From Eq. (11-16), $f_l = 80$ and $f_h = 1280$ Hz.] Choose $C = 0.015\ \mu$F. Find R from Eq. (11-18a).

$$R = \frac{0.1591}{BC} = \frac{0.1591}{(500)(0.015 \times 10^{-6}\text{ F})} = 21.21\text{ k}\Omega$$

The feedback resistor will be $2R = 42.42\ \text{k}\Omega$. Find R_r from Eq. (11-19).

$$R_r = \frac{R}{2Q^2 - 1} = \frac{21.21\ \text{k}\Omega}{2(2)^2 - 1} = \frac{21.21\ \text{k}\Omega}{7} = 3.03\ \text{k}\Omega$$

Example 11-16

Given a bandpass filter circuit with the component values in Fig. 11-12, find (a) the resonant frequency; (b) the bandwidth.

Solution (a) From Eq. (11-12),

$$f_r = \frac{0.1125}{RC}\sqrt{1 + \frac{R}{R_r}} = \frac{0.1125}{(21.21 \times 10^3)(0.015 \times 10^{-6})}\sqrt{1 + \frac{21.21\ \text{k}\Omega}{3.03\ \text{k}\Omega}}$$

$$= (353.6\ \text{Hz})\sqrt{1 + 7} = 353.6\ \text{Hz} \times 2.83 \simeq 1000\ \text{Hz}$$

(b) From Eq. (11-18a),

$$B = \frac{0.1591}{RC} = \frac{0.1591}{(21.21 \times 10^3)(0.015 \times 10^{-6})} = 500\ \text{Hz}$$

11-9 NOTCH FILTERS

11-9.1 Introduction

The notch or band-reject filter is named for the characteristic shape of its frequency–response curve in Fig. 11-13. Unwanted frequencies are attenuated in the stopband B. The desired frequencies are transmitted in the passband that lies on either side of the notch.

Notch filters usually have a passband gain of unity or 0 dB. The equations for Q, B, f_l, f_h, and f_r are identical to those of its associated bandpass filter. The reasons for this last statement are presented next.

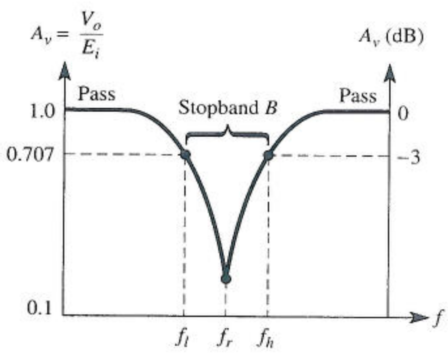


FIGURE 11-13 A notch filter transmits frequencies in the passband and rejects undesired frequencies in the stopband.

11-9.2 Notch Filter Theory

As shown in Fig. 11-14, a notch filter is made by subtracting the output of a bandpass filter from the original signal. For frequencies in the notch filter's passband, the output of the bandpass filter section approaches zero. Therefore, input E_i is transmitted via adder input resistor R_1 to drive V_o to a value equal to $-E_i$. Thus $V_o = -E_i$ in both lower and upper passbands of the notch filter.

Suppose that the frequency of E_i is adjusted to resonant frequency f_r of the narrow bandpass filter component. (*Note:* f_r of the bandpass sets the notch frequency.) E_i will exit from the bandpass as $-E_i$ and then is inverted by R_1 and R to drive V_o to $+E_i$. However, E_i is transmitted via R_2 to drive V_o to $-E_i$. Thus V_o responds to both inputs of the adder and becomes $V_o = E_i - E_i = 0$ V at f_r.

In practice, V_o approaches zero only at f_r. The depth of the notch depends on how closely the resistors and capacitors are matched in the bandpass filter and judicious fine adjustment of resistor R_1 at the inverting adder's onput. This procedure is explained in Section 11-10.3.

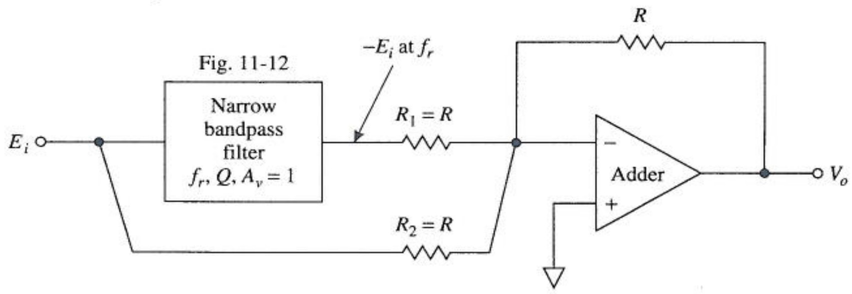


FIGURE 11-14 A notch filter is made by a circuit that subtracts the output of a bandpass filter from the original signal.

11-10 120-HZ NOTCH FILTER

11-10.1 Need for a Notch Filter

In applications where low-level signals must be amplified, there may be present one or more of an assortment of unwanted noise signals. Examples are 50-, 60-, or 400-Hz frequencies from power lines, 120-Hz ripple from full-wave rectifiers, or even higher frequencies from regulated switching-type power supplies or clock oscillators. If both signals and a signal-frequency noise component are passed through a notch filter, only the desired signals will exit from the filter. The noise frequency is "notched out." As an example, let us make a notch filter to eliminate 120-Hz hum.

11-10.2 Statement of the Problem

The problem is to make a notch filter with a notch (resonant) frequency of f_r = 120 Hz. Let us select a stopband of B = 12 Hz. The gain of the notch filter in the passband will be unity (0 dB) so that the desired signals will be transmitted without attenuations. We use Eq. (11-17) to determine a value for Q that is required by the notch filter:

$$Q = \frac{f_r}{B} = \frac{120}{12} = 10$$

This high value of Q means that (1) the notch and component bandpass filter will have narrow bands with very sharp frequency–response curves, and (2) the bandwidth is essentially centered on the resonant frequency. Accordingly, this filter will transmit all frequencies from 0 to (120 − 6) = 114 Hz and all frequencies above (120 + 6) = 126 Hz. The notch filter will stop all frequencies between 114 and 126 Hz.

11-10.3 Procedure to Make a Notch Filter

A notch filter is made in two steps:

1. Make a bandpass filter that has the same resonant frequency, bandwidth, and consequently Q as the notch filter.
2. Connect the inverting adder of Fig. 11-15 by selecting equal resistors for R. Usually, R = 10 kΩ. (A practical fine-tuning procedure is presented in the next section.)

11-10.4 Bandpass Filter Components

The first step in making a 120-Hz notch filter is best illustrated by an example (see Fig. 11-15).

Design Example 11-17

Design a bandpass filter with a resonant frequency of f_r = 120 Hz and a bandwidth of 12 Hz so that Q = 10. Thus gain of the bandpass section will be 1 at f_r and approach zero at the output of the notch labeled V_o.

Solution Choose C = 0.33 μF. From Eq. (11-18a),

$$R = \frac{0.1591}{BC} = \frac{0.1591}{(12)(0.33 \times 10^{-6})} = 40.2\ \text{k}\Omega$$

Then the bandpass feedback resistor will be $2R$ equals 80.4 kΩ. From Eq. (11-19),

$$R_r = \frac{R}{2Q^2 - 1} = \frac{40.2\ \text{k}\Omega}{2(10)^2 - 1} = \frac{40.2\ \text{k}\Omega}{199} = 201\ \Omega$$

This bandpass filter component is built first and f_r is fine-tuned by adjusting R_r (see Section 11-8.2 and Fig. 11-15).

11-10.5 Final Assembly

Refer to Fig. 11-15. Simply connect an inverting adder with equal 1% input and feedback 10-kΩ resistors as shown. The resultant notch filter (from E_i to V_o) exhibits a respectable performance that is an acceptable solution to the problem. The notch depth can be increased by fine trimming R_1 or R_2.

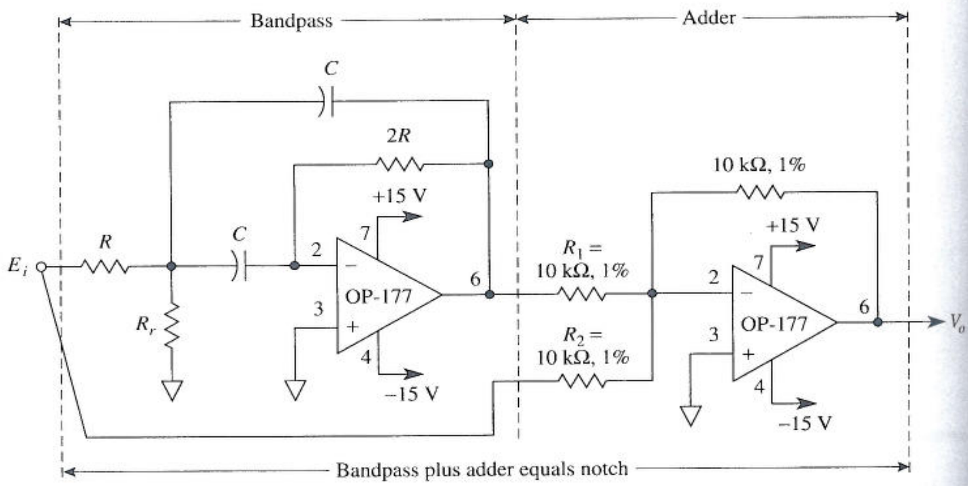


FIGURE 11-15 This two-op-amp notch filter is made from a bandpass filter plus an inverting adder. If $C = 0.33\ \mu\text{F}$, $R = 40.2\ \text{k}\Omega$, and $R_f = 201\ \Omega$, the notch frequency will be 120 Hz and reject a bandwidth of 12 Hz.

11-11 SIMULATION OF ACTIVE FILTER CIRCUITS USING PSPICE

We will simulate the performance of three filter circuits using PSpice: a −40 dB/decade low-pass filter, a +40 dB/decade high-pass filter, and a wide bandpass filter.

11-11.1 Low-Pass Filter

Refer to Fig. 11-4(a) and create the PSpice model of the circuit using a 741 op amp if you are using the evaluation software package. The input voltage source will be **VAC** and will be set for a 1-V magnitude. We want a plot of V_o versus frequency. To begin, place the following parts in the work area.

Draw => Get New Part

Part	Number	Library
=> **uA741**	1	**eval.slb**
=> **VAC**	1	**source.slb**
=> **VDC**	2	**source.slb**
=> **R**	4	**analog.slb**
=> **C**	2	**analog.slb**
=> **GLOBAL**	4	**port.slb**
=> **AGND**	5	**port.slb**

Note: We are using **VAC** as the input source instead of **VSIN** as we have in previous chapters. The **VAC** symbol requires only that magnitude and phase be set. The frequency range will be set in the Analysis Setup menu. Arrange the parts as shown in Fig. 11-4(a). Change the attributes of the parts to those values given in Example 11-4. Set up the **VAC** sine wave attributes by double-clicking the symbol; in the pop-up window change phase and magnitude.

ACPHASE => 0 => Save Attr
ACMAG => 1V => Save Attr => Change Display => Both name and value

Double-click on the lead from the output terminal of the op amp and label it **Vo** (see Fig. 11-16). To obtain a plot of V_o versus frequency, we must initialize the AC Sweep menu.

Analysis => Setup => Enable AC Sweep
Open AC Sweep => Decade
=> Pts/Decade => 10
=> Start Freq => 10Hz
=> End Freq => 10kHz

Save the circuit as a file with the **.SCH** extension. Run the simulation

Analysis => Simulate

In the Probe window, we need to select both Plot and Trace options from the menu bar.

Plot => Y Axis Settings => Scale => Log
Trace => Add => V[Vo]

Label the plots and obtain a printout as shown in Fig. 11-17.

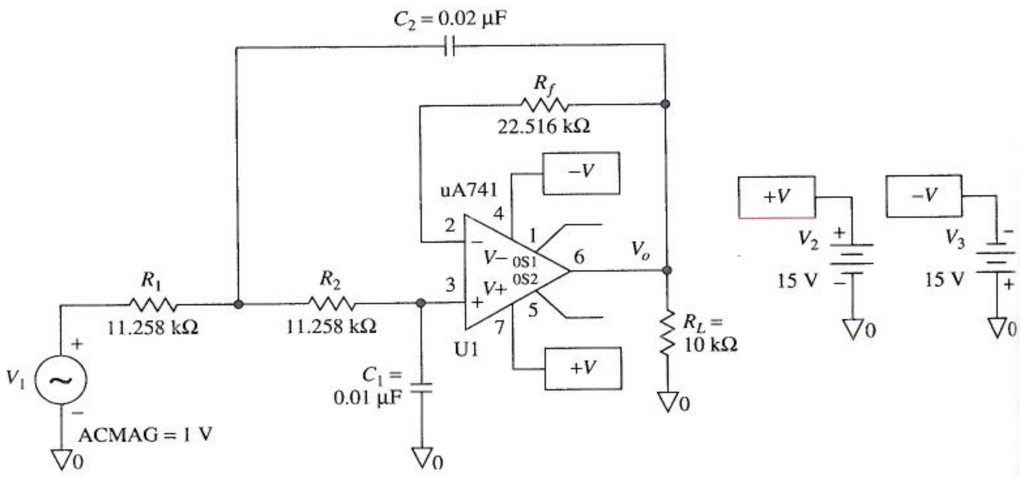


FIGURE 11-16 PSpice model of Fig. 11-4(a).

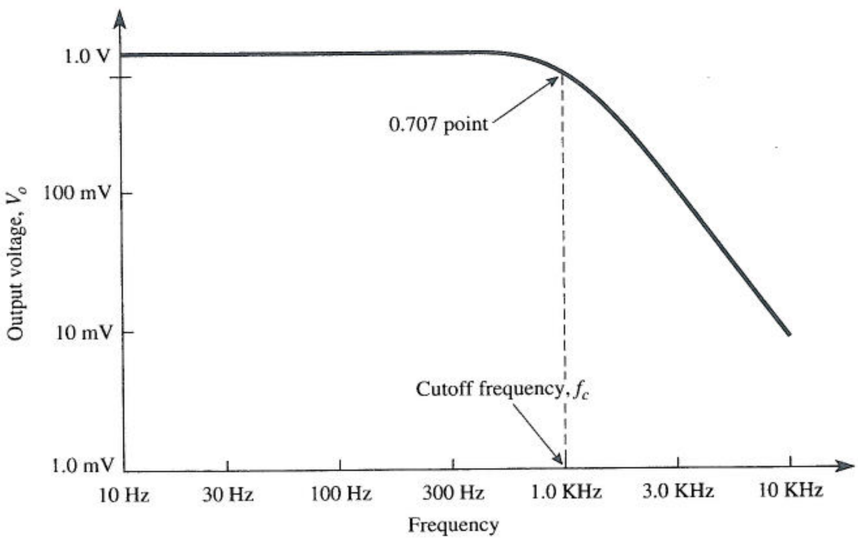


FIGURE 11-17 Frequency–response plot of a low-pass filter.

11-11.2 High-Pass Filter

The procedure for modeling and simulating a high-pass filter is similar to that for the low-pass filter previously described. Refer to Fig. 11-8(a) and create the PSpice model of the circuit using a 741 op amp. The input voltage source will be **VAC** and will be set for a 1-V magnitude. Obtain a plot of V_o versus frequency. To begin, place the following parts in the work area.

Draw => Get New Part

Part	Number	Library
=> **uA741**	1	**eval.slb**
=> **VAC**	1	**source.slb**
=> **VDC**	2	**source.slb**
=> **R**	4	**analog.slb**
=> **C**	2	**analog.slb**
=> **GLOBAL**	4	**port.slb**
=> **AGND**	5	**port.slb**

As previously mentioned we are using **VAC** as the input source instead of **VSIN** so that we may vary frequency through a range, because the **VAC** symbol requires only magnitude and phase to be set. The frequency range is set in the Analysis Setup menu. Arrange the parts as shown in Fig. 11-8(a). Change the attributes of the parts to those values given in Example 11-8. Set up the **VAC** sine wave attributes by double-clicking the symbol; in the pop-up window change phase and magnitude.

ACPHASE => 0 => Save Attr
ACMAG => 1V => Save Attr => Change Display => Both name and value

Double-click on the lead from the output terminal of the op amp and label it **Vo** (see Fig. 11-18). To obtain a plot of V_o versus frequency, we must initialize the AC Sweep menu.

Analysis => Setup => Enable AC Sweep
Open AC Sweep => Decade
=> Pts/Decade => 10
=> Start Freq => 100Hz
=> End Freq => 100kHz

Save the circuit as a file with the **.SCH** extension. Run the simulation

Analysis => Simulate

In the Probe window, we need to select both Plot and Trace options from the menu bar.

Plot => Y Axis Settings => Scale => Log
Trace => Add => V[Vo]

Label the plots and obtain a printout as shown in Fig. 11-19.

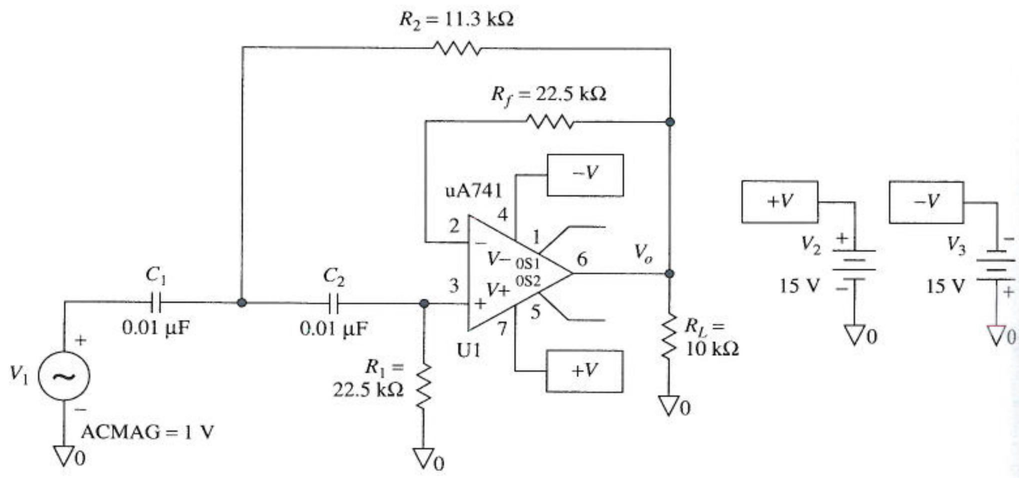


FIGURE 11-18 PSpice model of Fig. 11-8(a).

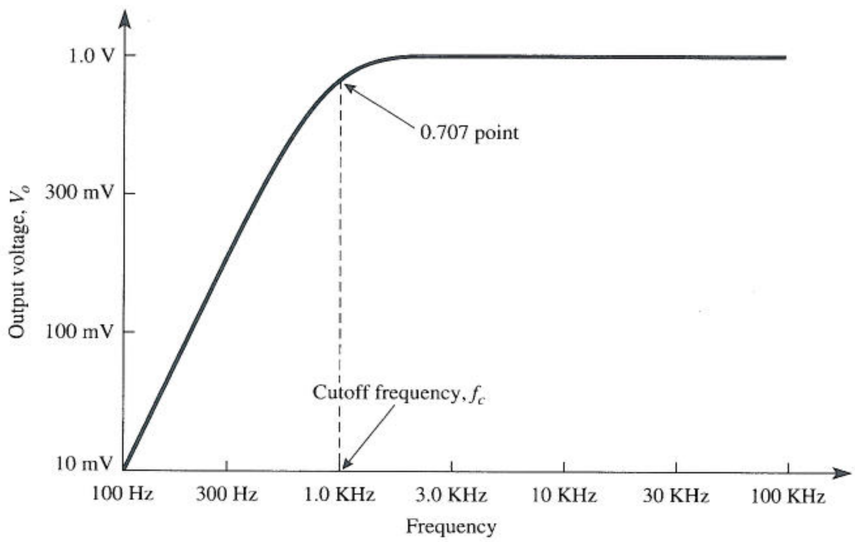


FIGURE 11-19 Frequency response of a high-pass filter.

11-11.3 Bandpass Filter

In this section, we want to model and simulate the bandpass filter shown in Fig. 11-11. This circuit is a wide bandpass filter designed by cascading a −40 dB/decade low-pass filter with a +40 dB/decade high-pass filter. Since we have already created both of these circuits in PSpice, we will create the model of the bandpass filter by copying the circuit of Fig. 11-16 and Fig. 11-18 onto a new work area, deleting some parts, changing the at-

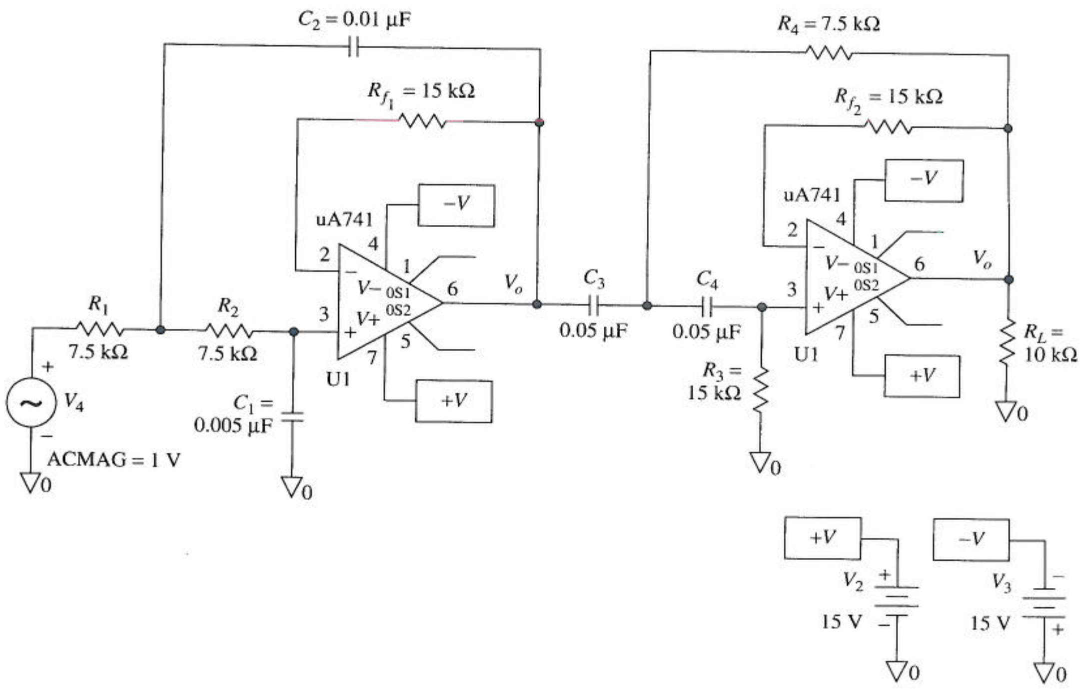


FIGURE 11-20 PSpice model of Fig. 11-11.

tributes of other parts, and saving the schematic as a new file. The model for the band-pass filter is shown in Fig. 11-20. The Analysis Setup menu has to be set as in the previous two designs. A printout from the Probe window is shown in Fig. 11-21.

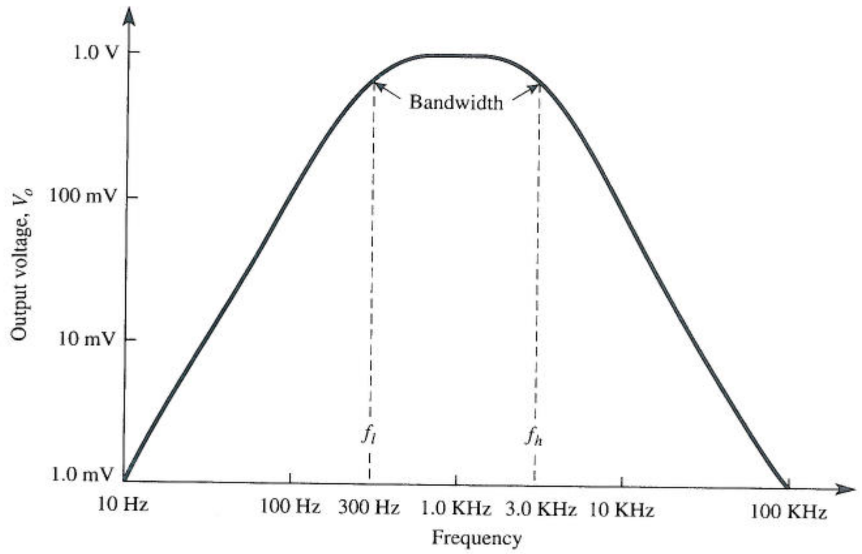


FIGURE 11-21 Frequency response of wide bandpass filter.

PROBLEMS

11-1. List the four types of filters.

11-2. What type of filter has a constant output voltage from dc up to the cutoff frequency?

11-3. What is a filter called that passes a band of frequencies while attenuating all frequencies outside the band?

11-4. In Fig. 11-2(a), if $R = 100\ \text{k}\Omega$ and $C = 0.02\ \mu\text{F}$, what is the cutoff frequency?

11-5. The low-pass filter of Fig. 11-2(a) is to be designed for a cutoff frequency of 4.5 kHz. If $C = 0.005\ \mu\text{F}$, calculate R.

11-6. Calculate the cutoff frequency for each value of C in Fig. P11-6.

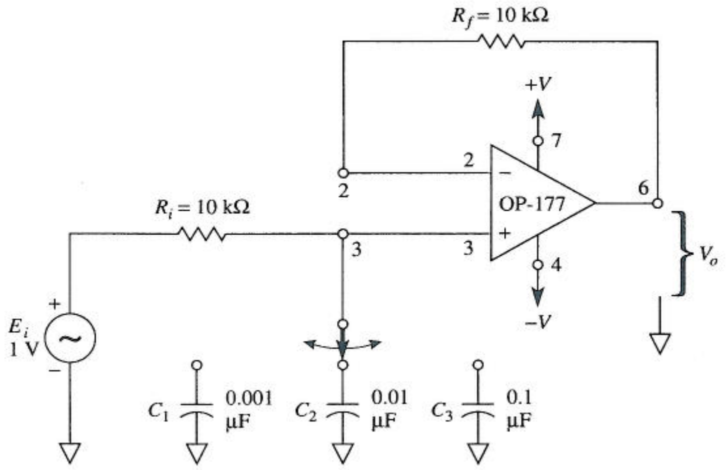


FIGURE P11-6

11-7. What are the two characteristics of a Butterworth filter?

11-8. Design a -40-dB/decade low-pass filter at a cutoff frequency of 10 krad/s. Let $C_1 = 0.02\ \mu\text{F}$.

11-9. In Fig. 11-4(a), if $R_1 = R_2 = 10\ \text{k}\Omega$, $C_1 = 0.01\ \mu\text{F}$, and $C_2 = 0.002\ \mu\text{F}$, calculate the cutoff frequency f_c.

11-10. Calculate **(a)** R_3, **(b)** R_1, and **(c)** R_2 in Fig. 11-5(a) for a cutoff frequency of 10 krad/s. Let $C_3 = 0.005\ \mu\text{F}$.

11-11. If $R_1 = R_2 = R_3 = 20\ \text{k}\Omega$, $C_1 = 0.002\ \mu\text{F}$, $C_2 = 0.008\ \mu\text{F}$, and $C_3 = 0.004\ \mu\text{F}$ in Fig. 11-5(a), determine the cutoff frequency ω_c.

11-12. In Fig. 11-5(a), $C_1 = 0.01\ \mu\text{F}$, $C_2 = 0.04\ \mu\text{F}$, and $C_3 = 0.02\ \mu\text{F}$. Calculate R for a cutoff frequency of 1 kHz.

11-13. Calculate R in Fig. 11-7(a) if $C = 0.04\ \mu\text{F}$ and $f_c = 500$ Hz.

11-14. In Fig. 11-7(a) calculate **(a)** ω_c and **(b)** f_c if $R = 10\ \text{k}\Omega$ and $C = 0.01\ \mu\text{F}$.

11-15. Design a 40-dB/decade high-pass filter for $\omega_c = 5$ krad/s. $C_1 = C_2 = 0.02\ \mu\text{F}$.

11-16. Calculate **(a)** R_1 and **(b)** R_2 in Fig. 11-8(a) for a cutoff frequency of 40 krad/s. $C_1 = C_2 =$ 250 pF.

11-17. For Fig. 11-9(a), let $C_1 = C_2 = C_3 = 0.05\ \mu\text{F}$. Determine **(a)** R_3, **(b)** R_1, and **(c)** R_2 for a cutoff frequency of 500 Hz.

11-18. The circuit of Fig. 11-9(a) is designed with the values $C_1 = C_2 = C_3 = 400$ pF, $R_1 =$ 100 kΩ, $R_2 = 25$ kΩ, and $R_3 = 50$ kΩ. Calculate the cutoff frequency f_c.

11-19. Find the **(a)** bandwidth, **(b)** resonant frequency, and **(c)** quality factor of a bandpass filter with lower and upper cutoff frequencies of 55 and 65 Hz.

11-20. A bandpass filter has a resonant frequency of 1000 Hz and a bandwidth of 2500 Hz. Find the lower and upper cutoff frequencies.

11-21. Use the capacitor and resistor values of the high-pass filter in Fig. 11-11 to prove $f_c =$ 3000 Hz.

11-22. Use the capacitor and resistor values of the high-pass filter in Fig. 11-11 to prove that $f_c = 300$ Hz.

11-23. Find Q for the bandpass filter of Fig. 11-11.

11-24. Design a narrow bandpass filter using one op amp. The resonant frequency is 128 Hz and $Q = 1.5$. Select $C = 0.1\ \mu\text{F}$ in Fig. 10-12.

11-25. **(a)** How would you convert the bandpass filter of Problem 11-24 into a notch filter with the same resonant frequency and Q? **(b)** Calculate f_l and f_h for the notch filter.