Eastern Economy Edition

Op-Amps and Linear Integrated Circuits

THIRD EDITION

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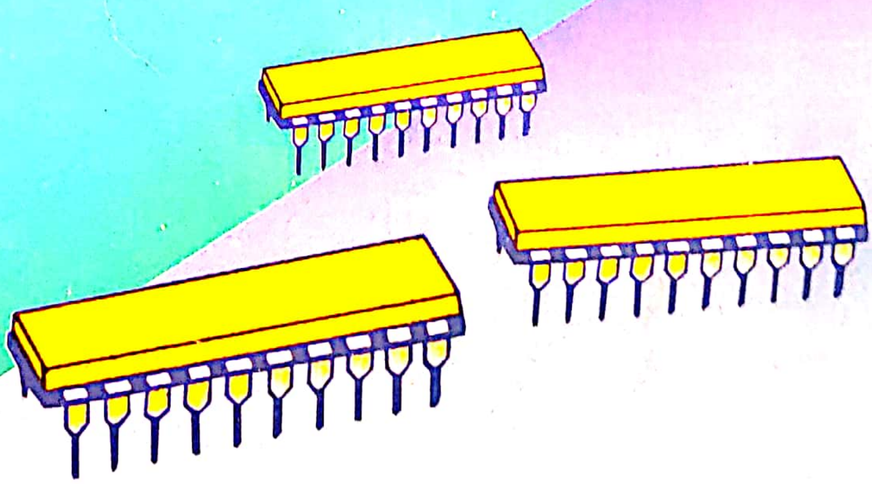

- *Analyze or design an all-pass filter.*
- *Discuss oscillator principles, oscillator types, and frequency stability as it relates to its operation.*
- *Analyze or design a phase shift oscillator.*
- *Analyze or design a Wien bridge and a quadrature oscillators.*
- *Analyze or design a square wave and a triangular wave generators.*
- *Draw the schematic diagram for and analyze the operation of a sawtooth wave generator.*
- *Draw the schematic diagram for and analyze the operation of a voltage-controlled oscillator and make necessary modifications in the circuit to satisfy the given requirements.*

8-1 INTRODUCTION

In Chapter 7 you saw how op-amp circuits are used to provide ac/dc amplification, perform such mathematical operations as summing, averaging, differentiation, and integration, convert *I*-to-*V* and *V*-to-*I* signals, and provide very high input impedance. This chapter presents another important field of application using op-amps: filters and oscillators. The chapter begins with the analysis and design of basic and inexpensive filter types and then discusses the various oscillator circuits. At the end of the chapter, a voltage-controlled oscillator (VCO) using the NE/SE566 integrated circuit is presented.

8-2 ACTIVE FILTERS

An electric filter is often a *frequency-selective* circuit that passes a specified band of frequencies and blocks or attenuates signals of frequencies outside this band. Filters may be classified in a number of ways:

1. Analog or digital
2. Passive or active
3. Audio (AF) or radio frequency (RF)

Analog filters are designed to process analog signals, while *digital* filters process analog signals using digital techniques. Depending on the type of elements used in their construction, filters may be classified as passive or active. Elements used in *passive* filters are resistors, capacitors, and inductors. *Active* filters, on the other hand, employ transistors or op-amps in addition to the resistors and capacitors. The type of element used dictates the operating frequency range of the filter. For example, *RC* filters are commonly used for audio or low-frequency operation, whereas *LC* or crystal filters are employed at RF or high frequencies. Especially because of their high *Q* value (figure of merit), the crystals provide more stable operation at higher frequencies.

First, this chapter presents the analysis and design of analog active-*RC* (audio-frequency) filters using op-amps. In the audio frequencies, inductors are often not used because they are very large, costly, and may dissipate more power. Inductors also emit magnetic fields.

An active filter offers the following advantages over a passive filter:

1. *Gain and frequency adjustment flexibility.* Since the op-amp is capable of providing a gain, the input signal is not attenuated as it is in a passive filter. In addition, the active filter is easier to tune or adjust.
2. *No loading problem.* Because of the high input resistance and low output resistance of the op-amp, the active filter does not cause loading of the source or load.
3. *Cost.* Typically, active filters are more economical than passive filters. This is because of the variety of cheaper op-amps and the absence of inductors.

Although active filters are most extensively used in the field of communications and signal processing, they are employed in one form or another in almost all sophisticated electronic systems. Radio, television, telephone, radar, space satellites, and biomedical equipment are but a few systems that employ active filters.

The most commonly used filters are these:

1. Low-pass filter
2. High-pass filter
3. Band-pass filter
4. Band-reject filter
5. All-pass filter

Each of these filters uses an op-amp as the active element and resistors and capacitors as the passive elements. Although the 741 type op-amp works satisfactorily in these filter circuits, high-speed op-amps such as the LM318 or ICL8017 improve the filter's performance through their increased slew rates and higher unity gain–bandwidths.

Figure 8-1 shows the frequency response characteristics of the five types of filters. The ideal response is shown by dashed curves, while the solid lines indicate the practical filter response. A low-pass filter has a constant gain from 0 Hz to a high cutoff frequency f_H. Therefore, the bandwidth is also f_H. At f_H the gain is down by 3 dB; after that ($f > f_H$) it decreases with the increase in input frequency. The frequencies between 0 Hz and f_H are known as the *passband* frequencies, whereas the range of frequencies, those beyond f_H, that are attenuated includes the *stopband* frequencies.

Figure 8-1(a) shows the frequency response of the low-pass filter. As indicated by the dashed line, an *ideal* filter has a zero loss in its passband and infinite loss in its stopband. Unfortunately, ideal filter response is not practical because linear networks cannot produce the discontinuities. However, it is possible to obtain a practical response that approximates the ideal response by using special

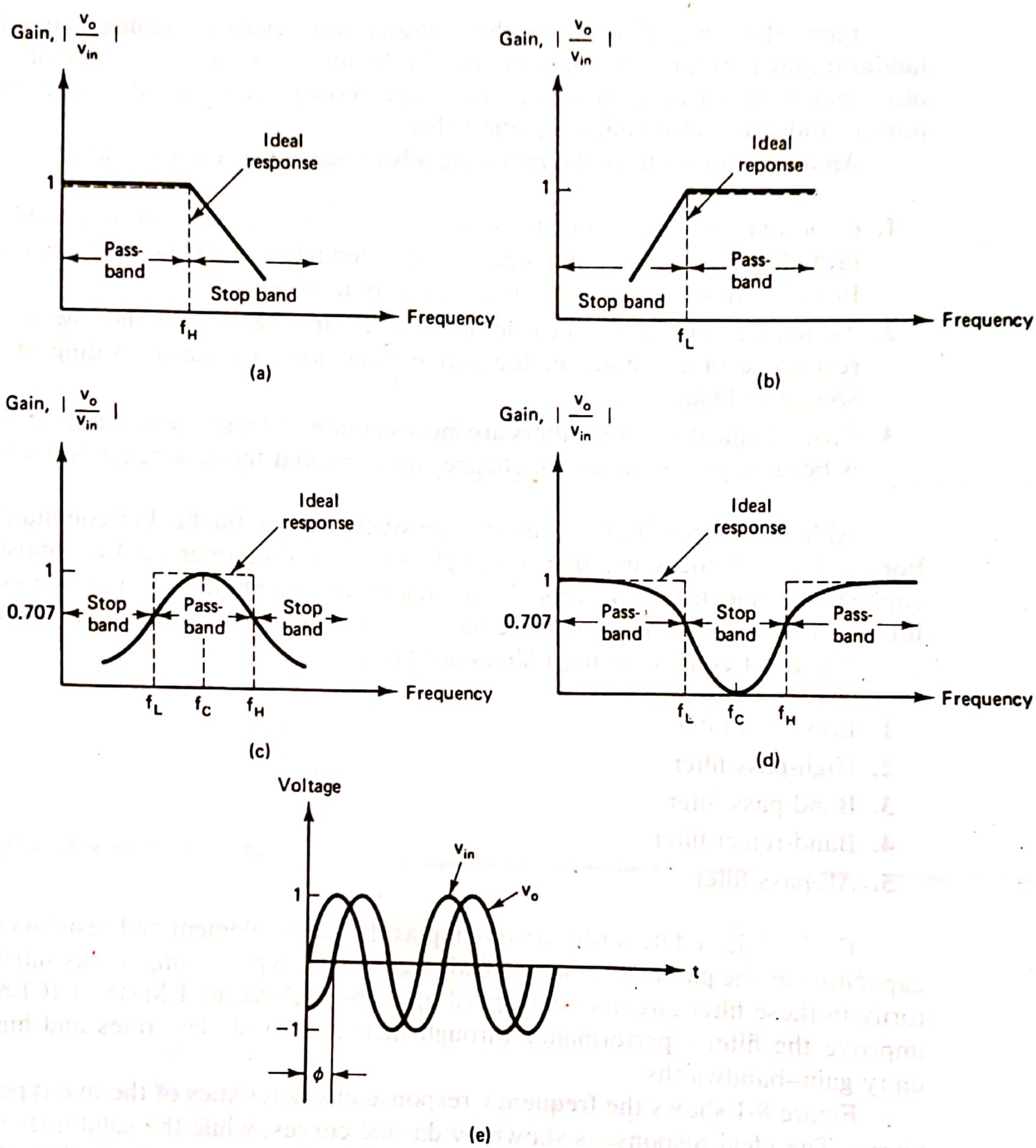

Figure 8–1 Frequency response of the major active filters. (a) Low pass. (b) High pass. (c) Band pass. (d) Band reject. (e) Phase shift between input and output voltages of an all-pass filter.

design techniques, as well as precision component values and high-speed op-amps.

Butterworth, Chebyshev, and Cauer filters are some of the most commonly used practical filters that approximate the ideal response. The key characteristic of the Butterworth filter is that it has a flat passband as well as stopband. For this reason, it is sometimes called a *flat-flat* filter. The Chebyshev filter has a ripple passband and flat stopband, while the Cauer filter has a ripple passband and a ripple stopband. Generally, the Cauer filter gives the best stopband response among the three. Because of their simplicity of design, the low-pass and high-pass Butterworth filters are discussed here.

Figure 8-1(b) shows a high-pass filter with a stopband $0 < f < f_L$ and a passband $f > f_L \cdot f_L$ is the low cutoff frequency, and f is the operating frequency. A band-pass filter has a passband between two cutoff frequencies f_H and f_L, where $f_H > f_L$, and two stop-bands: $0 < f < f_L$ and $f > f_H$. The bandwidth of the band-pass filter, therefore, is equal to $f_H - f_L$. The band-reject filter performs exactly opposite to the band-pass; that is, it has a bandstop between two cutoff frequencies f_H and f_L and two passbands: $0 < f < f_L$ and $f > f_H$. The band-reject is also called a *band-stop* or *band-elimination* filter. The frequency responses of band-pass and band-reject filters are shown in Figure 8-1(c) and (d), respectively. In these figures, f_C is called the center frequency since it is approximately at the center of the passband or stopband.

Figure 8-1(e) shows the phase shift between input and output voltages of an all-pass filter. This filter passes all frequencies equally well; that is, output and input voltages are equal in amplitude for all frequencies, with the phase shift between the two a function of frequency. The highest frequency up to which the input and output amplitudes remain equal is dependent on the unity gain–bandwidth of the op-amp. At this frequency, however, the phase shift between the input and output is maximum.

Before proceeding with specific filter types, let us reexamine the filter characteristics, especially in the stopband region. As shown in Figure 8-1(a)–(d), the actual response curves of the filters in the stopband either steadily decrease or increase or both with increase in frequency. The rate at which the gain of the filter changes in the stopband is determined by the order of the filter. For example, for the first-order low-pass filter the gain rolls off at the rate of 20 dB/decade in the stopband, that is, for $f > f_H$; on the other hand, for the second-order low-pass filter the roll-off rate is 40 dB/decade; and so on. By contrast, for the first-order high-pass filter the gain increases at the rate of 20 dB/decade in the stopband, that is, until $f = f_L$; the increase is 40 dB/decade for the second-order high-pass filter; and so on.

8-3 FIRST-ORDER LOW-PASS BUTTERWORTH FILTER

Figure 8-2 shows a first-order low-pass Butterworth filter that uses an *RC* network for filtering. Note that the op-amp is used in the noninverting configuration; hence it does not load down the *RC* network. Resistors R_1 and R_F determine the gain of the filter.

According to the voltage-divider rule, the voltage at the noninverting terminal (across capacitor C) is

$$v_1 = \frac{-jX_C}{R - jX_C} v_{in} \tag{8-1a}$$

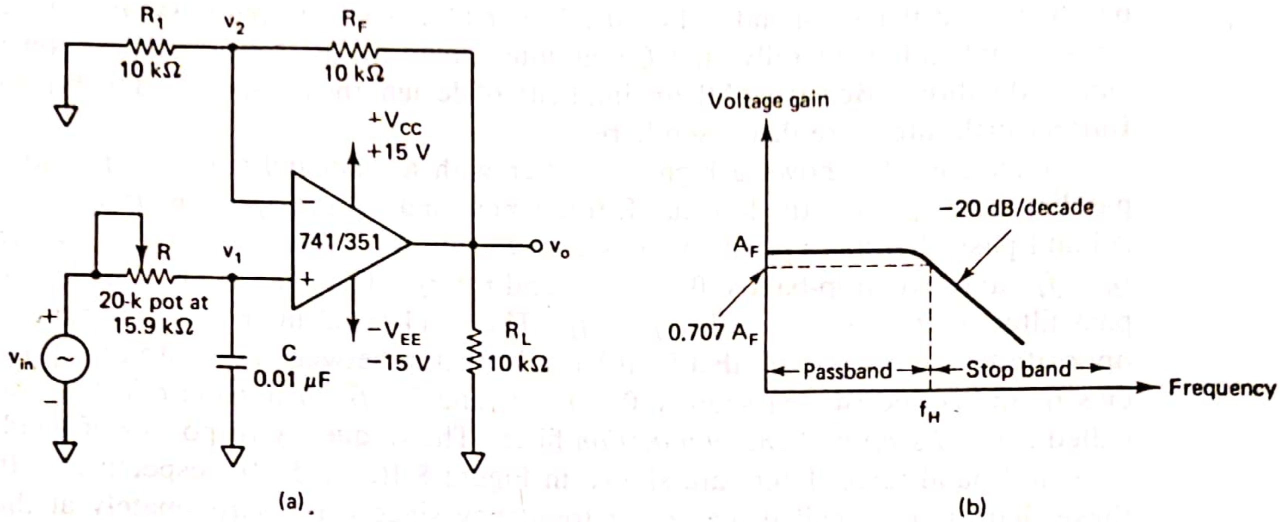

Figure 8–2 First-order low-pass Butterworth filter. (a) Circuit. (b) Frequency response.

where

$$j = \sqrt{-1} \quad \text{and} \quad -jX_C = \frac{1}{j2\pi fC}$$

Simplifying Equation (8-1a), we get

$$v_1 = \frac{v_{in}}{1 + j2\pi fRC}$$

and the output voltage

$$v_o = \left(1 + \frac{R_F}{R_1}\right) v_1$$

That is,

$$v_o = \left(1 + \frac{R_F}{R_1}\right) \frac{v_{in}}{1 + j2\pi fRC}$$

or

$$\frac{v_o}{v_{in}} = \frac{A_F}{1 + j(f/f_H)} \qquad \text{(8-1b)}$$

where $\frac{v_o}{v_{in}}$ = gain of the filter as a function of frequency

$A_F = 1 + \frac{R_F}{R_1}$ = passband gain of the filter

f = frequency of the input signal

$f_H = \frac{1}{2\pi RC}$ = high cutoff frequency of the filter

The gain magnitude and phase angle equations of the low-pass filter can be obtained by converting Equation (8-1b) into its equivalent polar form, as follows:

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1 + (f/f_H)^2}} \tag{8-2a}$$

$$\phi = -\tan^{-1}\left(\frac{f}{f_H}\right) \tag{8-2b}$$

where ϕ is the phase angle in degrees.

The operation of the low-pass filter can be verified from the gain magnitude equation, (8-2a):

1. At very low frequencies, that is, $f < f_H$,

$$\left|\frac{v_o}{v_{in}}\right| \cong A_F$$

2. At $f = f_H$,

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{2}} = 0.707A_F$$

3. At $f > f_H$,

$$\left|\frac{v_o}{v_{in}}\right| < A_F$$

Thus the low-pass filter has a constant gain A_F from 0 Hz to the high cutoff frequency f_H. At f_H the gain is $0.707A_F$, and after f_H it decreases at a constant rate with an increase in frequency [see Figure 8-2(b)]. That is, when the frequency is increased tenfold (one decade), the voltage gain is divided by 10. In other words, the gain decreases 20 dB (= 20 log 10) each time the frequency is increased by 10. Hence the rate at which the gain rolls off after f_H is 20 dB/decade or 6 dB/octave, where octave signifies a twofold increase in frequency. The frequency $f = f_H$ is called the *cutoff frequency* because the gain of the filter at this frequency is down by 3 dB (= 20 log 0.707) from 0 Hz. Other equivalent terms for cutoff frequency are *−3 dB frequency*, *break frequency*, or *corner frequency*.

8-3.1 Filter Design

A low-pass filter can be designed by implementing the following steps:

1. Choose a value of high cutoff frequency f_H.
2. Select a value of C less than or equal to 1 μF. Mylar or tantalum capacitors are recommended for better performance.
3. Calculate the value of R using

$$R = \frac{1}{2\pi f_H C}$$

4. Finally, select values of R_1 and R_F dependent on the desired passband gain A_F using

$$A_F = 1 + \frac{R_F}{R_1}$$

8-3.2 Frequency Scaling

Once a filter is designed, there may sometimes be a need to change its cutoff frequency. The procedure used to convert an original cutoff frequency f_H to a new cutoff frequency f'_H is called *frequency scaling*. Frequency scaling is accomplished as follows. To change a high cutoff frequency, multiply R or C, but not both, by the ratio of the original cutoff frequency to the new cutoff frequency. In filter design the needed values of R and C are often not standard. Besides, a variable capacitor C is not commonly used. Therefore, choose a standard value of capacitor, and then calculate the value of resistor for a desired cutoff frequency. This is because for a nonstandard value of resistor a potentiometer can be used (see Examples 8-1 and 8-2).

EXAMPLE 8-1

Design a low-pass filter at a cutoff frequency of 1 kHz with a passband gain of 2.

SOLUTION Follow the preceding design steps.

1. $f_H = 1$ kHz.
2. Let $C = 0.01\ \mu$F.
3. Then $R = 1/(2\pi)(10^3)(10^{-8}) = 15.9$ kΩ. (Use a 20-kΩ potentiometer.)
4. Since the passband gain is 2, R_1 and R_F must be equal. Therefore, let $R_1 = R_F = 10$ kΩ. The complete circuit with component values is shown in Figure 8-2(a).

EXAMPLE 8-2

Using the frequency scaling technique, convert the 1-kHz cutoff frequency of the low-pass filter of Example 8-1 to a cutoff frequency of 1.6 kHz.

SOLUTION To change a cutoff frequency from 1 kHz to 1.6 kHz, we multiply the 15.9-kΩ resistor by

$$\frac{\text{original cutoff frequency}}{\text{new cutoff frequency}} = \frac{1\text{ kHz}}{1.6\text{ kHz}} = 0.625$$

Therefore, new resistor $R = (15.9\ \text{k}\Omega)(0.625) = 9.94\ \text{k}\Omega$. However, 9.94 kΩ is not a standard value. Therefore, use $R = 10\ \text{k}\Omega$ potentiometer and adjust it to 9.94 kΩ. Thus the new cutoff frequency is

$$f_H = \frac{1}{(2\pi)(0.01\ \mu\text{F})(9.94\ \text{k}\Omega)}$$

$$= 1.6\ \text{kHz}$$

EXAMPLE 8-3

Plot the frequency response of the low-pass filter of Example 8-1.

SOLUTION To plot the frequency response, we have to use Equation (8-2a). The data of Table 8-1 are, therefore, obtained by substituting various values for f in this equation. Equation (8-2a) will be repeated here for convenience:

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1 + (f/f_H)^2}}$$

where $A_F = 2$ and $f_H = 1$ kHz. The data of Table 8-1 are plotted as shown in Figure 8-3.

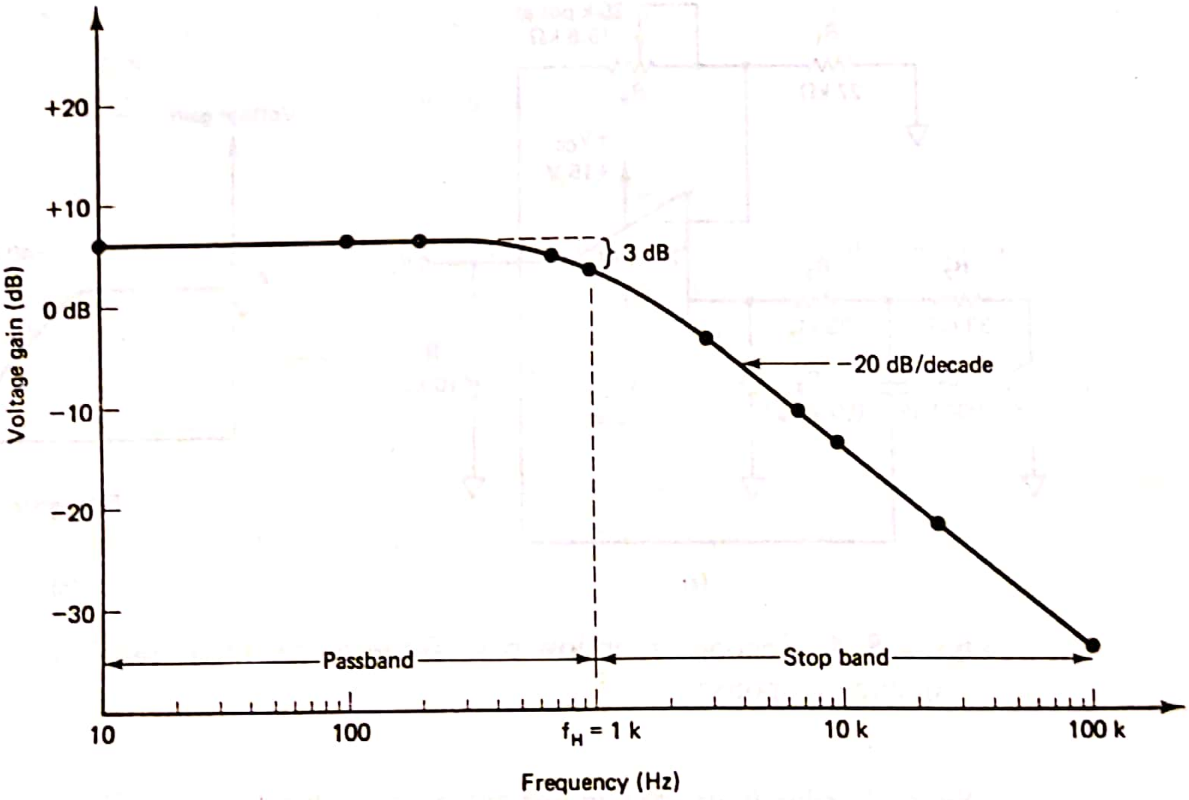

Figure 8–3 Frequency response for Example 8–3.

TABLE 8-1 FREQUENCY RESPONSE DATA FOR EXAMPLE 8-3

Input frequency, f (Hz)	Gain magnitude, $\lvert v_o/v_{in} \rvert$	Magnitude (dB) = $20 \log \lvert v_o/v_{in} \rvert$
10	2	6.02
100	1.99	5.98
200	1.96	5.85
700	1.64	4.29
1,000	1.41	3.01
3,000	0.63	−3.98
7,000	0.28	−10.97
10,000	0.20	−14.02
30,000	0.07	−23.53
100,000	0.02	−33.98

8-4 SECOND-ORDER LOW-PASS BUTTERWORTH FILTER

A stop-band response having a 40-dB/decade roll-off is obtained with the second-order low-pass filter. A first-order low-pass filter can be converted into a second-order type simply by using an additional *RC* network, as shown in Figure 8-4.

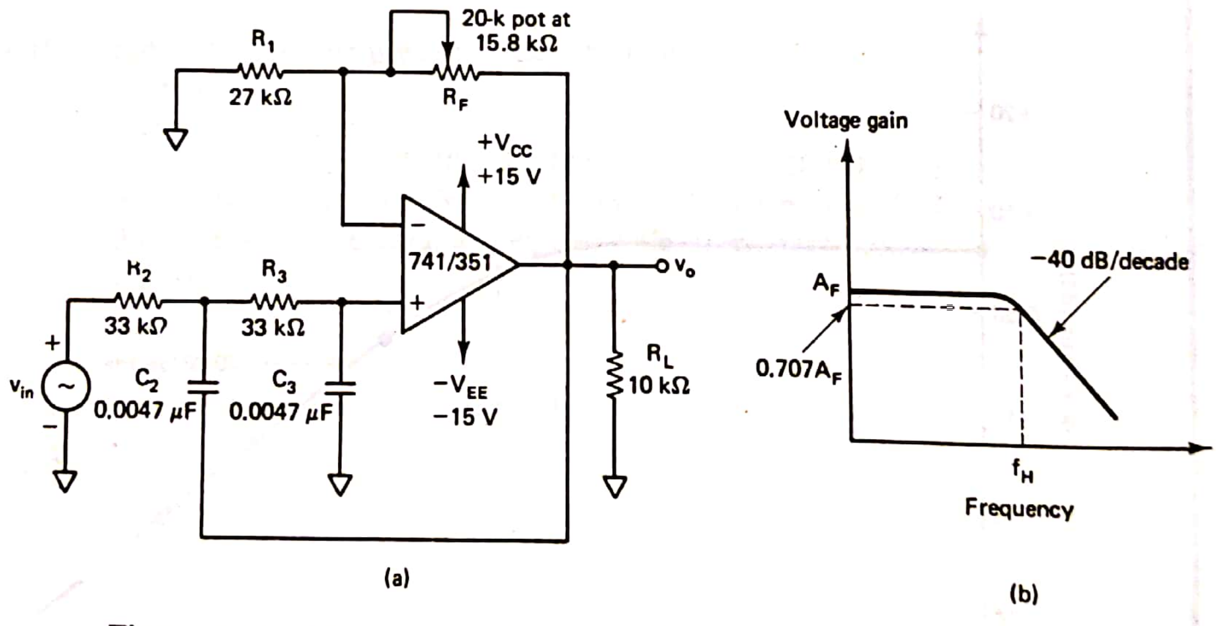

Figure 8–4 Second-order low-pass Butterworth filter. (a) Circuit. (b) Frequency response.

Second-order filters are important because higher-order filters can be designed using them. The gain of the second-order filter is set by R_1 and R_F, while the high cutoff frequency f_H is determined by R_2, C_2, R_3, and C_3, as follows:

$$f_H = \frac{1}{2\pi\sqrt{R_2R_3C_2C_3}} \tag{8-3}$$

For the derivation of f_H, refer to Appendix C.

Furthermore, for a second-order low-pass Butterworth response, the voltage gain magnitude equation is

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1 + (f/f_H)^4}} \tag{8-4}$$

where $A_F = 1 + \dfrac{R_F}{R_1}$ = passband gain of the filter

f = frequency of the input signal (Hz)

$f_H = \dfrac{1}{2\pi\sqrt{R_2R_3C_2C_3}}$ = high cutoff frequency (Hz)

8-4.1 Filter Design

Except for having twice the roll-off rate in the stopband, the frequency response of the second-order low-pass filter is identical to that of the first-order type. Therefore, the design steps of the second-order filter are identical to those of the first-order filter, as follows:

1. Choose a value for the high cutoff frequency f_H.
2. To simplify the design calculations, set $R_2 = R_3 = R$ and $C_2 = C_3 = C$. Then choose a value of $C \leq 1\ \mu$F.
3. Calculate the value of R using Equation (8-3):

$$R = \frac{1}{2\pi f_H C}$$

4. Finally, because of the equal resistor ($R_2 = R_3$) and capacitor ($C_2 = C_3$) values, the passband voltage gain $A_F = (1 + R_F/R_1)$ of the second-order low-pass filter has to be equal to 1.586. That is, $R_F = 0.586R_1$. This gain is necessary to guarantee Butterworth response. Hence choose a value of $R_1 \leq 100$ kΩ and calculate the value of R_F.

As outlined in Section 8-3.2, the frequency scaling method of the first-order filter is also applicable to the second-order low-pass filter.

EXAMPLE 8-4

(a) Design a second-order low-pass filter at a high cutoff frequency of 1 kHz.
(b) Draw the frequency response of the network in part (a).

SOLUTION (a) To design the second-order low-pass filter, simply follow the steps just presented:

1. $f_H = 1$ kHz.
2. Let $C_2 = C_3 = 0.0047\ \mu$F.
3. Then

$$R_2 = R_3 = \frac{1}{(2\pi)(10^3)(47)(10^{-10})} = 33.86\ \text{k}\Omega$$

(Use $R_2 = R_3 = 33$ kΩ.)

4. Since R_F must be equal to $0.586R_1$, let R_1 equal 27 kΩ. Therefore,

$$R_F = (0.586)(27\ \text{k}\Omega) = 15.82\ \text{k}\Omega$$

(Use $R_F = 20$ kΩ pot.) Thus the required components are

$R_2 = R_3 = 33$ kΩ

$C_2 = C_3 = 0.0047\ \mu$F

$R_1 = 27$ kΩ and $R_F = 15.8$ kΩ (20k − Ω pot)

Another method to design the second-order low-pass filter is to use the same values of resistor and capacitor obtained for the first-order filter in Example 8-1. This is because the cutoff frequency of both the second-order and first-order filters is 1 kHz. Therefore, we may use $R_2 = R_3 = 15.9$ kΩ and $C_2 = C_3 = 0.01\ \mu$F. However, the values of R_1 and R_F must be chosen such that $R_F = 0.586R_1$. Therefore, use $R_1 = 27$ kΩ and $R_F = 15.8$ kΩ.

(b) The frequency response data shown in Table 8-2 are obtained from the magnitude equation, (8-4), by substituting various values from 10 Hz to 100 kHz for f. Equation (8-4) is repeated here for convenience:

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1 + (f/f_H)^4}}$$

where $A_F = 1.586$ and $f_H = 1$ kHz. The frequency response of the second-order low-pass filter of Example 8-4 is shown in Figure 8-5.

TABLE 8-2 FREQUENCY RESPONSE DATA FOR EXAMPLE 8-4

Frequency, f (Hz)	Gain magnitude, $\lvert v_o/v_{in}\rvert$	Magnitude (dB) = $20 \log\lvert v_o/v_{in}\rvert$
10	1.59	4.01
100	1.59	4.01
200	1.58	4.00
700	1.42	3.07
1,000	1.12	1.00
3,000	0.18	−15.13
7,000	0.03	−29.80
10,000	0.02	−35.99
30,000	1.76×10^{-3}	−55.08
100,000	1.59×10^{-4}	−75.99

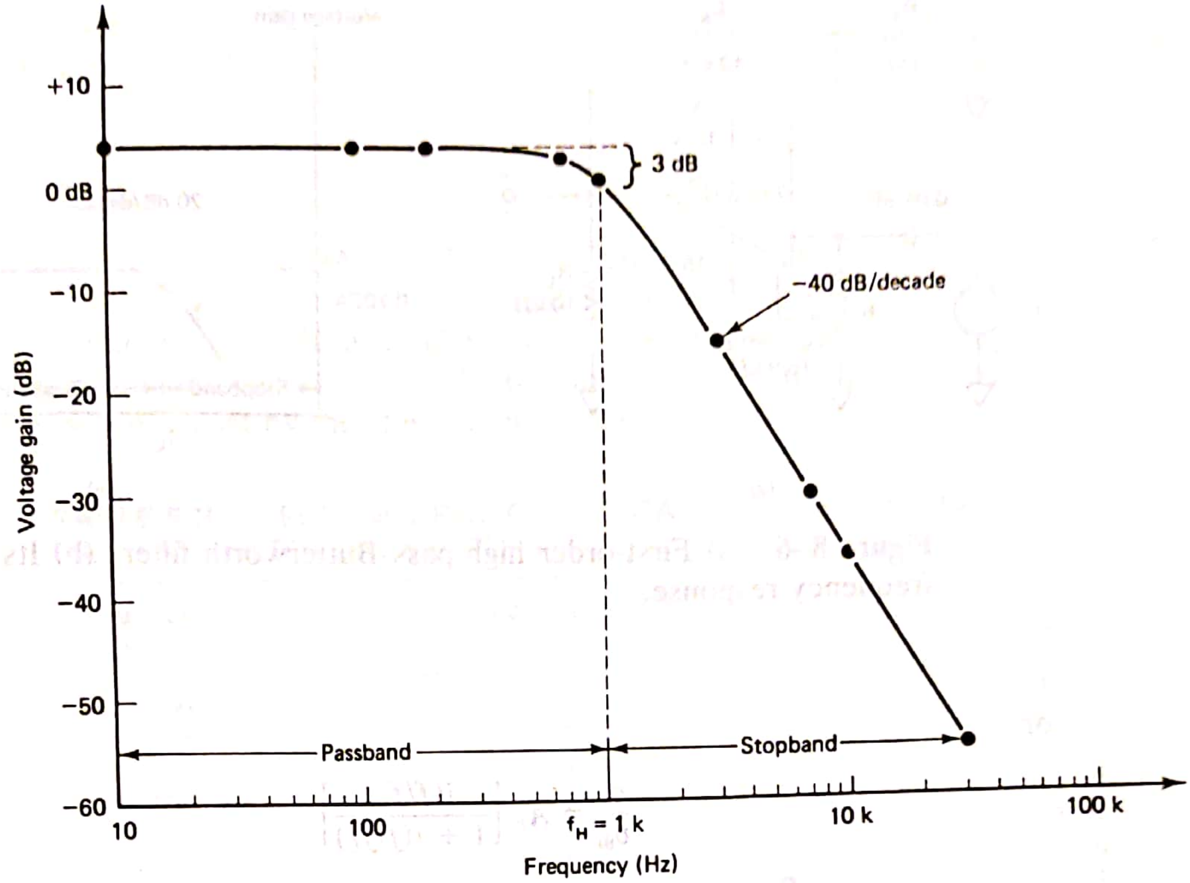

Figure 8–5 Frequency response for Example 8-4.

8-5 FIRST-ORDER HIGH-PASS BUTTERWORTH FILTER

High-pass filters are often formed simply by interchanging frequency-determining resistors and capacitors in low-pass filters. That is, a first-order high-pass filter is formed from a first-order low-pass type by interchanging components R and C. Similarly, a second-order high-pass filter is obtained from a second-order low-pass filter if R and C are interchanged, and so on. Figure 8-6 shows a first-order high-pass Butterworth filter with a low cutoff frequency of f_L. This is the frequency at which the magnitude of the gain is 0.707 times its passband value. Obviously, all frequencies higher than f_L are passband frequencies, with the highest frequency determined by the closed-loop bandwidth of the op-amp.

Note that the high-pass filter of Figure 8-6(a) and the low-pass filter of Figure 8-2(a) are the same circuits, except that the frequency-determining components (R and C) are interchanged.

For the first-order high-pass filter of Figure 8-6(a), the output voltage is

$$v_o = \left(1 + \frac{R_F}{R_1}\right) \frac{j2\pi fRC}{1 + j2\pi fRC} v_{in}$$

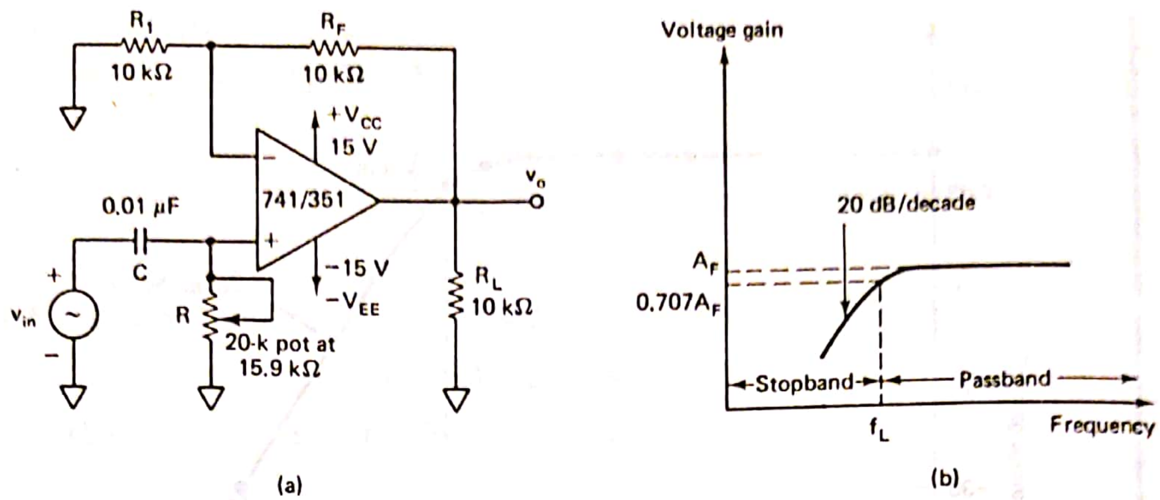

Figure 8–6 (a) First-order high-pass Butterworth filter. (b) Its frequency response.

or

$$\frac{v_o}{v_{in}} = A_F\left[\frac{j(f/f_L)}{1 + j(f/f_L)}\right] \tag{8-5}$$

where $A_F = 1 + \dfrac{R_F}{R_1}$ = passband gain of the filter

f = frequency of the input signal (Hz)

$f_L = \dfrac{1}{2\pi RC}$ = low cutoff frequency (Hz)

Hence the magnitude of the voltage gain is

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F(f/f_L)}{\sqrt{1 + (f/f_L)^2}} \tag{8-6}$$

Since high-pass filters are formed from low-pass filters simply by interchanging R's and C's, the design and frequency scaling procedures of the low-pass filters are also applicable to the high-pass filters (see Sections 8-3.1 and 8-3.2).

EXAMPLE 8-5

(a) Design a high-pass filter at a cutoff frequency of 1 kHz with a passband gain of 2.
(b) Plot the frequency response of the filter in part (a).

SOLUTION (a) Use the same values of R and C that were determined for the low-pass filter of Example 8-1, since $f_L = f_H = 1$ kHz. That is, $C = 0.01\ \mu F$ and $R = 15.9\ k\Omega$. Similarly, use $R_1 = R_F = 10\ k\Omega$, since $A_F = 2$.

(b) The data for the frequency response plot can be obtained by substituting for the input frequency f values from 100 Hz to 100 kHz in Equation (8-6). These data are included in Table 8-3. Equation (8-6) is repeated here for convenience:

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F(f/f_L)}{\sqrt{1+(f/f_L)^2}}$$

where $A_F = 2$ and $f_L = 1$ kHz. The frequency response data of Table 8-3 are plotted in Figure 8-7. In the stopband (from 100 Hz to 1 kHz) the gain increases at the rate of 20 dB/decade. However, in the passband (after $f = f_L = 1$ kHz) the gain remains constant at 6.02 dB. Moreover, the upper-frequency limit of the passband is set by the closed-loop bandwidth of the op-amp.

TABLE 8-3 FREQUENCY RESPONSE DATA FOR THE FIRST-ORDER HIGH-PASS FILTER OF EXAMPLE 8-5

Frequency, f (Hz)	Gain magnitude, $\lvert v_o/v_{in}\rvert$	Magnitude (dB) = $20 \log\lvert v_o/v_{in}\rvert$
100	0.20	−14.02
200	0.39	−8.13
400	0.74	−2.58
700	1.15	1.19
1,000	1.41	3.01
3,000	1.90	5.56
7,000	1.98	5.93
10,000	1.99	5.98
30,000	2	6.02
100,000	2	6.02

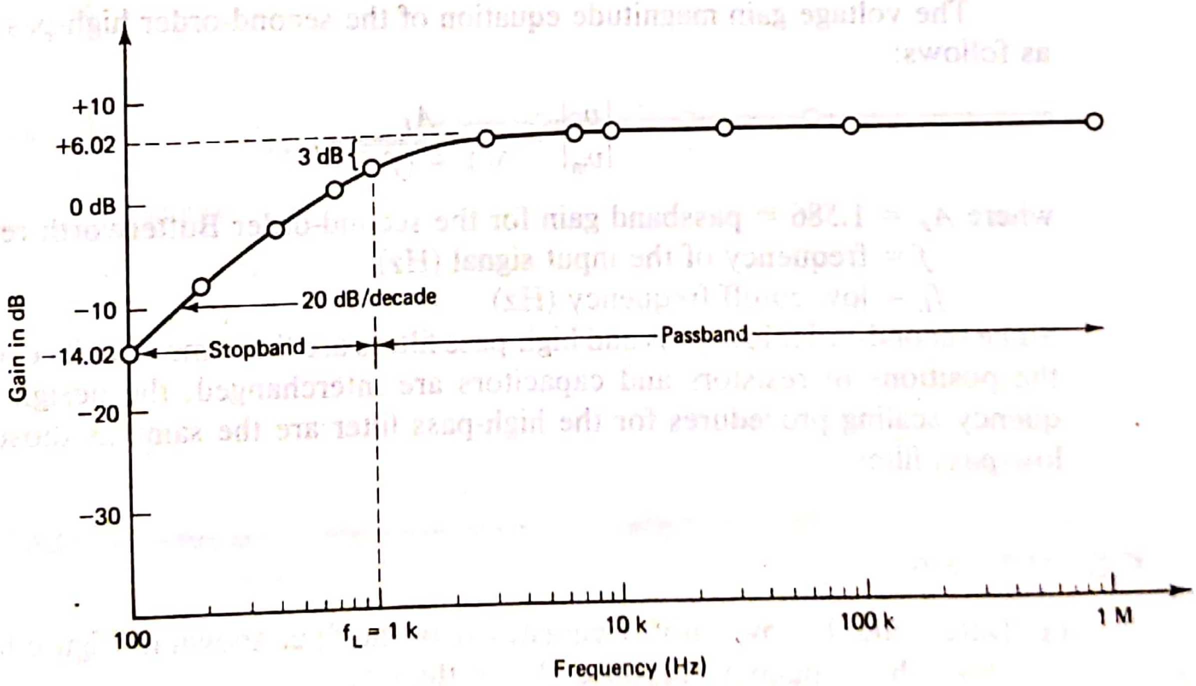

Figure 8–7 Frequency response for Example 8-5.

8-6 SECOND-ORDER HIGH-PASS BUTTERWORTH FILTER

As in the case of the first-order filter, a second-order high-pass filter can be formed from a second-order low-pass filter simply by interchanging the frequency-determining resistors and capacitors. Figure 8-8(a) shows the second-order high-pass filter.

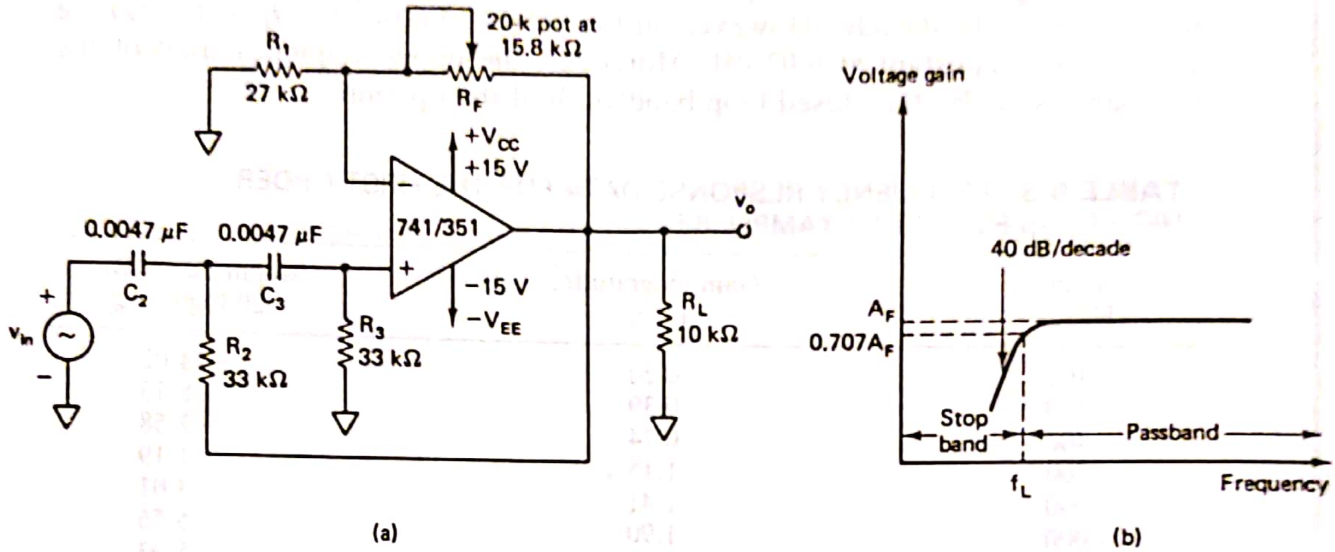

Figure 8–8 (a) Second-order high-pass Butterworth filter. (b) Its frequency response.

The voltage gain magnitude equation of the second-order high-pass filter is as follows:

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1 + (f_L/f)^4}} \tag{8-7}$$

where A_F = 1.586 = passband gain for the second-order Butterworth response
f = frequency of the input signal (Hz)
f_L = low cutoff frequency (Hz)

Since second-order low-pass and high-pass filters are the same circuits except that the positions of resistors and capacitors are interchanged, the design and frequency scaling procedures for the high-pass filter are the same as those for the low-pass filter.

EXAMPLE 8-6

(a) Determine the low cutoff frequency f_L of the filter shown in Figure 8-8(a).
(b) Draw the frequency response plot of the filter.

SOLUTION (a)

$$f_L = \frac{1}{2\pi\sqrt{R_2R_3C_2C_3}}$$

$$= \frac{1}{2\pi\sqrt{(33\text{ k}\Omega)^2(0.0047\ \mu\text{F})^2}} \cong 1\text{ kHz}$$

(b) The frequency response data in Table 8-4 are obtained from the voltage gain magnitude equation, (8-7), which is repeated here for convenience:

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1 + (f_L/f)^4}}$$

where $A_F = 1.586$ and $f_L = 1$ kHz. The resulting frequency response plot is shown in Figure 8-9.

TABLE 8-4 FREQUENCY RESPONSE DATA FOR SECOND-ORDER HIGH-PASS FILTER OF EXAMPLE 8-6

Input frequency, f(Hz)	Gain magnitude, $\lvert v_o/v_{in}\rvert$	Magnitude (dB) = $20\log\lvert v_o/v_{in}\rvert$
100	0.01586	−35.99
200	0.0634	−23.96
700	0.6979	−3.124
1,000	1.1215	0.9960
3,000	1.5763	3.953
7,000	1.5857	4.004
10,000	1.5859	4.006
30,000	1.5860	4.006
100,000	1.5860	4.006

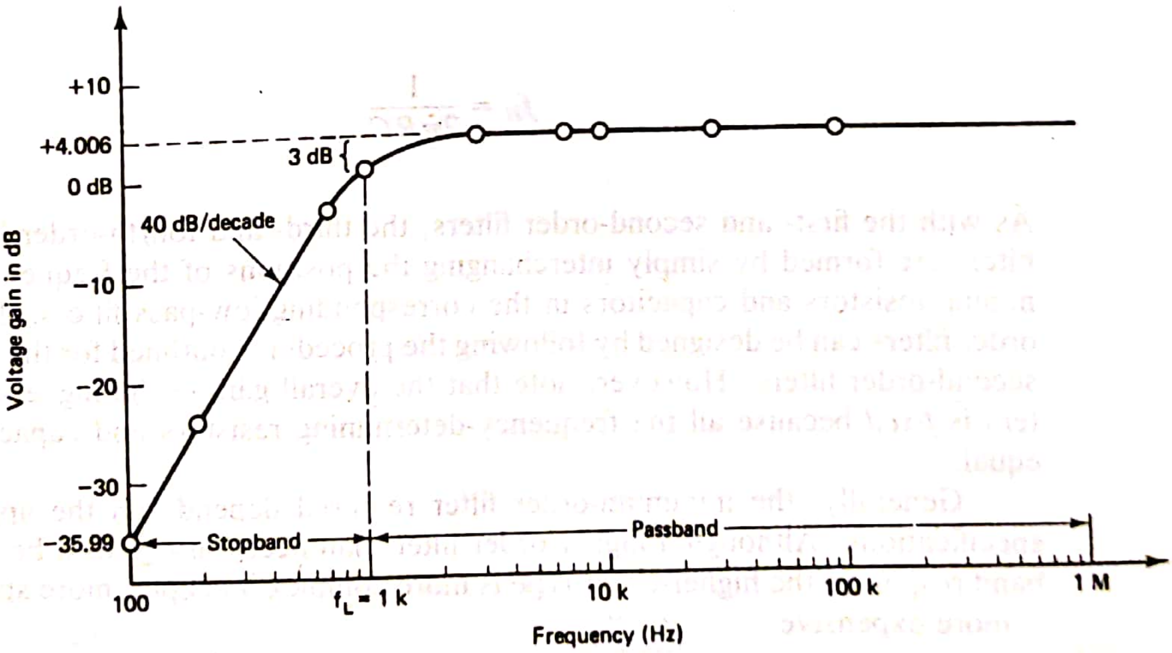

Figure 8–9 Frequency response for Example 8-6.