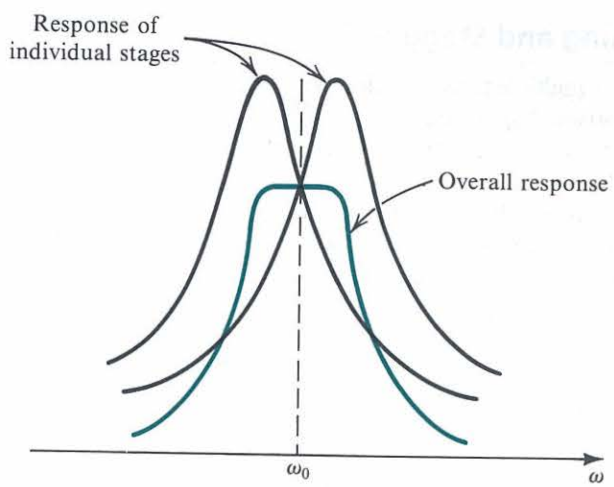

Figure 13.49 Stagger-tuning the individual resonant circuits can result in an overall response with a passband flatter than that obtained with synchronous tuning (Fig. 13.48).

A much better overall response is obtained by stagger-tuning the individual stages, as illustrated in Fig. 13.49. Stagger-tuned amplifiers are usually designed so that the overall response exhibits *maximal flatness* around the center frequency f_0. Such a response can be obtained by transforming the response of a maximally flat (Butterworth) low-pass filter up the frequency axis to ω_0. Appendix H shows how this can be done.

Summary

- A filter is a linear two-port network with a transfer function $T(s) = V_o(s)/V_i(s)$. For physical frequencies, the filter transmission is expressed as $T(j\omega) = |T(j\omega)|e^{j\phi(\omega)}$. The magnitude of transmission can be expressed in decibels using either the gain function $G(\omega) \equiv 20\log|T|$ or the attenuation function $A(\omega) \equiv -20\log|T|$.
- The transmission characteristics of a filter are specified in terms of the edges of the passband(s) and the stopband(s); the maximum allowed variation in passband transmission, A_{max} (dB); and the minimum attenuation required in the stopband, A_{min} (dB). In some applications, the phase characteristics are also specified.
- The filter transfer function can be expressed as the ratio of two polynomials in s; the degree of the denominator polynomial, N, is the filter order. The N roots of the denominator polynomial are the poles (natural modes).
- To obtain a highly selective response, the poles are complex and occur in conjugate pairs (except for one real pole when N is odd). The zeros are placed on the $j\omega$ axis in the stopband(s) including $\omega = 0$ and $\omega = \infty$.
- The Butterworth filter approximation provides a low-pass response that is maximally flat at $\omega = 0$. The transmission decreases monotonically as ω increases, reaching 0 (infinite attenuation) at $\omega = \infty$, where all N transmission zeros lie. Eq. (13.11) gives $|T|$, where ϵ is given by Eq. (13.14) and the order N is determined using Eq. (13.15). The poles are found using the graphical construction of Fig. 13.10, and the transfer function is given by Eq. (13.16).
- The Chebyshev filter approximation provides a low-pass response that is equiripple in the passband with the transmission decreasing monotonically in the stopband. All the transmission zeros are at $s = \infty$. Eq. (13.18) gives $|T|$ in the passband and Eq. (13.19) gives $|T|$ in the stopband, where ϵ is given by Eq. (13.21). The order N can be determined using Eq. (13.22). The poles are given by Eq. (13.23) and the transfer function by Eq. (13.24).
- Figures 13.13 and 13.14 provide a summary of first-order filter functions and their realizations.
- Figure 13.16 provides the characteristics of seven special second-order filtering functions.
- The second-order LCR resonator of Fig. 13.17(a) realizes a pair of complex-conjugate poles with $\omega_0 = 1/\sqrt{LC}$ and $Q = \omega_0 CR$. This resonator can be used to realize the various special second-order filtering functions, as shown in Fig. 13.18.
- By replacing the inductor of an LCR resonator with a simulated inductance obtained using the Antoniou circuit of Fig. 13.20(a), the op amp–RC resonator of Fig. 13.21(b) is obtained. This resonator can be used to realize the various second-order filter functions as shown in Fig. 13.22. The design equations for these circuits are given in Table 13.1.
- Biquads based on the two-integrator-loop topology are the most versatile and popular second-order filter realizations. There are two varieties: the KHN circuit of Fig. 13.24(a), which realizes the LP, BP, and HP functions simultaneously and can be combined with the output summing amplifier of Fig. 13.24(b) to realize the notch and all-pass functions; and the Tow–Thomas circuit of Fig. 13.25(b), which realizes the BP and LP functions simultaneously. Feedforward can be applied to the Tow–Thomas circuit to obtain the circuit of Fig. 13.26, which can be designed to realize any of the second-order functions (see Table 13.2).
- Single-amplifier biquads (SABs) are obtained by placing a bridged-T network in the negative-feedback path of an op amp. If the op amp is ideal, the poles realized are at the same locations as the zeros of the RC network. The complementary transformation can be applied to the feedback loop to obtain another feedback loop having identical poles. Different transmission zeros are realized by feeding the input signal to circuit nodes that are connected to ground. SABs are economic in their use of op amps but are sensitive to the op-amp nonidealities and are thus limited to low-Q applications ($Q \leq 10$).
- The classical sensitivity function

$$S_x^y = \frac{\partial y/y}{\partial x/x}$$

is a very useful tool in investigating how tolerant a filter circuit is to the unavoidable inaccuracies in component values and to the nonidealities of the op amps.
- Transconductance-C circuits utilize transconductors and capacitors to realize medium- and high-frequency filters (as high as hundreds of megahertz) that can be implemented in CMOS. The basic building block is the integrator, and the basic filter building block is based on the two-integrator-loop topology.
- Switched-capacitor (SC) filters are based on the principle that a capacitor C, periodically switched between two circuit nodes at a high rate, f_c, is equivalent to a resistance $R = 1/Cf_c$ connecting the two circuit nodes. SC filters can be fabricated in monolithic form using CMOS IC technology.
- Tuned amplifiers utilize LC-tuned circuits as loads, or at the input, of transistor amplifiers. They are used in the design of the RF tuner and the IF amplifier of communication receivers. The cascode and the CC–CB cascade configurations are frequently used in the design of tuned amplifiers. Stagger-tuning the individual tuned circuits results in a flatter passband response (in comparison to that obtained with all the resonant circuits synchronously tuned).

PROBLEMS

Section 13.1: Filter Transmission, Types, and Specification

13.1 The transfer function of a first-order low-pass filter (such as that realized by an RC circuit) can be expressed as $T(s) = \omega_0/(s+\omega_0)$, where ω_0 is the 3-dB frequency of the filter. Give in table form the values of $|T|$, ϕ, G, and A at $\omega = 0$, $0.5\omega_0, \omega_0, 2\omega_0, 5\omega_0, 10\omega_0$, and $100\omega_0$.

13.2 A sinusoid with 1-V peak amplitude is applied at the input of a filter having the transfer function

$$T(s) = \frac{2\pi \times 10^4}{s + 2\pi \times 10^4}$$

Find the peak amplitude and the phase (relative to that of the input sinusoid) of the output sinusoid if the frequency of the input sinusoid is (a) 1 kHz, (b) 10 kHz, (c) 100 kHz, and (d) 1 MHz.

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem

***13.3** A filter has the transfer function $T(s) = 1/[(s+1)(s^2+s+1)]$. Show that $|T| = 1/\sqrt{1+\omega^6}$ and find an expression for its phase response $\phi(\omega)$. Calculate the values of $|T|$ and ϕ for $\omega = 0.1, 1,$ and 10 rad/s and then find the output corresponding to each of the following input signals:

(a) 10 sin $0.1t$ (volts)
(b) 10 sin t (volts)
(c) 10 sin $10t$ (volts)

D 13.4 A low-pass filter is required to pass all signals within its passband, extending from 0 to 4 kHz, with a transmission variation of at most 5% (i.e., the ratio of the maximum to minimum transmission in the passband should not exceed 1.05). The transmission in the stopband, which extends from 5 kHz to ∞, should not exceed 0.05% of the maximum passband transmission. What are the values of A_{max}, A_{min}, and the selectivity factor for this filter?

13.5 For the filter whose magnitude response is sketched (as the blue curve) in Fig. 13.3, find $|T|$ at $\omega = 0$, $\omega = \omega_p$, and $\omega = \omega_s$. $A_{max} = 0.2$ dB, and $A_{min} = 60$ dB.

13.6 A low-pass filter is specified to have $f_p = 5$ kHz and a selectivity factor of 10. The specifications are just met by a first-order transfer function

$$T(s) = \frac{2\pi \times 10^4}{s + 2\pi \times 10^4}$$

What must A_{max} and A_{min} be?

13.7 Sketch transmission specifications for a high-pass filter having a passband defined by $f \geq 3$ kHz and a stopband defined by $f \leq 2$ kHz. $A_{max} = 0.4$ dB, and $A_{min} = 60$ dB.

13.8 Sketch transmission specifications for a bandstop filter that is required to pass signals over the bands $0 \leq f \leq 10$ kHz and $20 \text{ kHz} \leq f \leq \infty$ with A_{max} of 0.5 dB. The stopband extends from $f = 12$ kHz to $f = 18$ kHz, with a minimum required attenuation of 50 dB.

Section 13.2: The Filter Transfer Function

13.9 Consider a fifth-order filter whose poles are all at a radial distance from the origin of 10^4 rad/s. One pair of complex-conjugate poles is at 18° angles from the $j\omega$ axis, and the other pair is at 54° angles. Give the transfer function in each of the following cases.

(a) The transmission zeros are all at $s = \infty$ and the dc gain is unity.

(b) The transmission zeros are all at $s = 0$ and the high-frequency gain is unity.

What type of filter results in each case?

13.10 A second-order low-pass filter has poles at $-0.25 \pm j$ and a transmission zero at $\omega = 2$ rad/s. If the dc gain is unity, give the transfer function $T(s)$. What is the gain at ω approaching infinity?

13.11 A third-order low-pass filter has transmission zeros at $\omega = 2$ rad/s and $\omega = \infty$. Its natural modes are at $s = -1$ and $s = -0.5 \pm j0.8$. The dc gain is unity. Find $T(s)$.

13.12 Find the order N and the form of $T(s)$ of a bandpass filter having transmission zeros as follows: one at $\omega = 0$, one at $\omega = 10^3$ rad/s, one at 3×10^3 rad/s, one at 6×10^3 rad/s, and one at $\omega = \infty$. If this filter has a monotonically decreasing passband transmission with a peak at the center frequency of 2×10^3 rad/s, and equiripple response in the stopbands, sketch the shape of its $|T|$.

***13.13** Analyze the RLC network of Fig. P13.13 to determine its transfer function $V_o(s)/V_i(s)$ and hence its poles and zeros. (*Hint:* Begin the analysis at the output and work your way back to the input.)

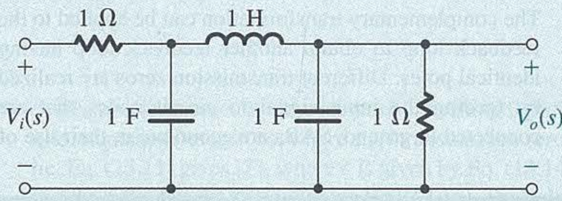

Figure P13.13

Section 13.3: Butterworth and Chebyshev Filters

D 13.14 Determine the order N of the Butterworth filter for which $A_{max} = 0.5$ dB, $A_{min} \geq 20$ dB, and the selectivity ratio $\omega_s/\omega_p = 1.7$. What is the actual value of minimum stopband attenuation realized? If A_{min} is to be exactly 20 dB, to what value can A_{max} be reduced?

13.15 Show that the order N of a Butterworth filter can be obtained from the approximate expression

$$N \geq \frac{A_{min} - 20 \log \epsilon}{20 \log(\omega_s/\omega_p)}$$

Hint: Use Eq. (13.15) and neglect the unity term.

13.16 Calculate the value of attenuation obtained at a frequency 1.8 times the 3-dB frequency of a seventh-order Butterworth filter.

13.17 Find the natural modes of a Butterworth filter having a 0.5-dB bandwidth of 10^3 rad/s and $N = 5$.

13.18 Sketch the transfer function magnitude for a low-pass Chebyshev filter of (a) sixth order and (b) seventh order.

D 13.19 Design a Butterworth filter that meets the following low-pass specifications: $f_p = 10$ kHz, $A_{max} = 3$ dB, $f_s = 20$ kHz, and $A_{min} = 20$ dB. Find N, the natural modes, and $T(s)$. What is the attenuation provided at 30 kHz?

13.20 On the same diagram, sketch the magnitude of the transfer function of a Butterworth and a Chebyshev low-pass filter of fifth order and having the same ω_p and A_{max}. At the stopband edge, ω_s, which filter gives greater attenuation?

***13.21** Sketch $|T|$ for a seventh-order low-pass Chebyshev filter with $\omega_p = 1$ rad/s and $A_{max} = 0.5$ dB. Use Eq. (13.18) to determine the values of ω at which $|T| = 1$ and the values of ω at which $|T| = 1/\sqrt{1+\epsilon^2}$. Indicate these values on your sketch. Use Eq. (13.19) to determine $|T|$ at $\omega = 2$ rad/s, and indicate this point on your sketch. For large values of ω, at what rate (in dB/octave) does the transmission decrease?

D *13.22 It is required to design a low-pass filter to meet the following specifications: $f_p = 3.4$ kHz, $A_{max} = 1$ dB, $f_s = 4$ kHz, $A_{min} = 35$ dB.

(a) Find the required order of Chebyshev filter. What is the excess (above 35 dB) stopband attenuation obtained?
(b) Find the poles and the transfer function.

Section 13.4: First-Order and Second-Order Filter Functions

D 13.23 Use the information displayed in Fig. 13.13 to design a first-order op amp–RC low-pass filter having a 3-dB frequency of 5 kHz, a dc gain magnitude of 10, and an input resistance of 12 kΩ.

D 13.24 Use the information given in Fig. 13.13 to design a first-order op amp–RC high-pass filter with a 3-dB frequency of 200 Hz, a high-frequency input resistance of 120 kΩ, and a high-frequency gain magnitude of unity.

13.25 Derive an expression for the transfer function of the op amp–RC circuit that is shown in Fig. 13.13(c). Give expressions for the frequency of the transmission zero ω_Z, the frequency of the pole ω_P, the dc gain, and the high-frequency gain.

D *13.26 Use the information given in Fig. 13.13 to design a first-order op amp–RC spectrum-shaping network with a transmission zero frequency of 100 Hz, a pole frequency of 10 kHz, and a dc gain magnitude of unity. The low-frequency input resistance is to be 10 kΩ. What is the high-frequency gain that results? Sketch the magnitude of the transfer function versus frequency.

D *13.27 By cascading a first-order op amp–RC low-pass circuit with a first-order op amp–RC high-pass circuit, one can design a wideband bandpass filter. Provide such a design for the case in which the midband gain is 12 dB and the 3-dB bandwidth extends from 50 Hz to 50 kHz. Select appropriate component values under the constraints that no resistors higher than 100 kΩ are to be used and that the input resistance is to be as high as possible.

D 13.28 Derive $T(s)$ for the op amp–RC circuit in Fig. 13.14. Find $|T(j\omega)|$ and $\phi(\omega)$. We wish to use this circuit as a variable phase shifter by adjusting R. If the input signal frequency is 5×10^3 rad/s and if $C = 10$ nF, find the values of R required to obtain phase shifts of –30°, –60°, –90°, –120°, and –150°.

13.29 Show that by interchanging R and C in the op amp–RC circuit of Fig. 13.14, the resulting phase shift covers the range 0 to 180° (with 0° at high frequencies and 180° at low frequencies).

D *13.30 Use two first-order op amp–RC all-pass circuits in cascade to design a circuit that provides a set of three-phase 60-Hz voltages, each separated by 120° and equal in magnitude, as shown in the phasor diagram of Fig. P13.30. These voltages simulate those used in three-phase power transmission systems. Use 1-μF capacitors.

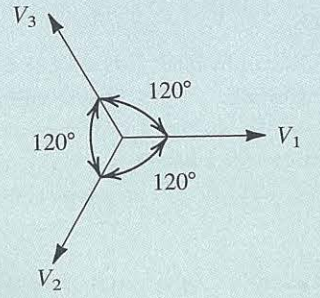

Figure P13.30

13.31 Use the information in Fig. 13.16(a) to obtain the transfer function of a second-order low-pass filter with $\omega_0 = 10^4$ rad/s, $Q = 2$, and dc gain = 1. At what frequency does $|T|$ peak? What is the peak transmission?

D *13.32 Use the information in Fig. 13.16(a) to obtain the transfer function of a second-order low-pass filter that just meets the specifications defined in Fig. 13.3 with $\omega_p = 1$ rad/s and $A_{max} = 3$ dB. Note that there are two optimal solutions. For each, find ω_0 and Q. Also, if $\omega_s = 2$ rad/s, find the value of A_{min} obtained in each case.

13.33 Find the transfer function of a second-order high-pass filter with a maximally flat passband response, a 3-dB frequency at $\omega = 1$ rad/s, and a high-frequency gain of unity. Give the location of the poles and zeros.

13.34 Find the transfer function of a second-order bandpass filter for which the center frequency $f_0 = 10$ kHz, the 3-dB bandwidth is 500 Hz, and the center-frequency gain is 10. Also, give the locations of the poles and zeros.

D **13.35 (a) Show that $|T|$ of a second-order bandpass function is geometrically symmetrical around the center frequency ω_0. That is, the members of each pair of frequencies ω_1 and ω_2 for which $|T(j\omega_1)| = |T(j\omega_2)|$ are related by $\omega_1\omega_2 = \omega_0^2$.

(b) Find the transfer function of the second-order bandpass filter that meets specifications of the form in Fig. 13.4 where $\omega_{p1} = 8100$ rad/s, $\omega_{p2} = 10{,}000$ rad/s, and $A_{max} = 3$ dB. If $\omega_{s1} = 3000$ rad/s find A_{min} and ω_{s2}.

13.36 Consider a second-order all-pass filter in which errors in the component values result in the Q factor of the zeros being greater than the Q factor of the poles. Roughly sketch the expected $|T|$. Repeat for the case of the Q factor of the zeros lower than the Q factor of the poles.

13.37 Consider a second-order all-pass circuit in which errors in the component values result in the frequency of the zeros being slightly lower than that of the poles. Roughly sketch the expected $|T|$. Repeat for the case of the frequency of the zeros slightly higher than the frequency of the poles.

Section 13.5: The Second-Order LCR Resonator

13.38 Analyze the circuit in Fig. 13.17(c) to determine its transfer function $T(s) \equiv V_o(s)/V_i(s)$, and hence show that its poles are characterized by ω_0 and Q of Eqs. (13.34) and (13.35), respectively.

D 13.39 Design the LCR resonator of Fig. 13.17(a) to obtain natural modes with $\omega_0 = 10^5$ rad/s and $Q = 5$. Use $R = 10$ kΩ.

13.40 For the LCR resonator of Fig. 13.17(a), find the change in ω_0 that results from

(a) increasing L by 1%
(b) increasing C by 1%
(c) decreasing R by 1%

13.41 For each of the circuits in Fig. P13.41, find the transmission as ω approaches zero and as ω approaches ∞, and hence find the transmission zeros.

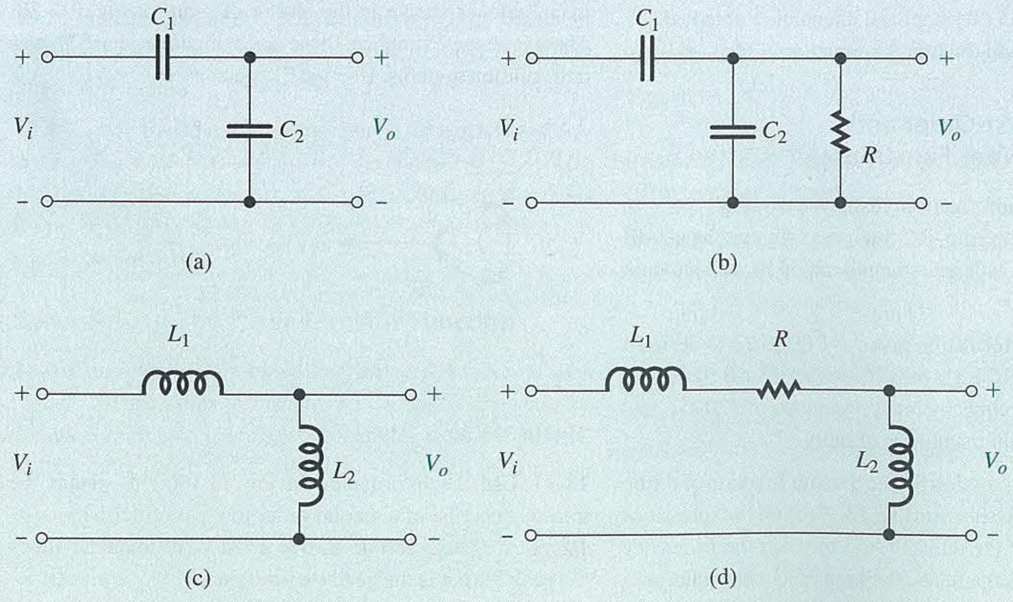

Figure P13.41

D 13.42 Use the circuit of Fig. 13.18(b) to design a low-pass filter with $\omega_0 = 10^6$ rad/s and $Q = 1/\sqrt{2}$. Utilize a 1-nF capacitor.

13.43 Derive an expression for $V_o(s)/V_i(s)$ of the high-pass circuit in Fig. 13.18(c).

13.44 Consider the LCR resonator of Fig. 13.17(a) with node x disconnected from ground and connected to an input signal source V_x, node y disconnected from ground and connected to another input signal source V_y, and node z disconnected from ground and connected to a third input signal source V_z. Use superposition to find the voltage that develops across the resonator, V_o, in terms of V_x, V_y, and V_z.

Section 13.6: Second-Order Active Filters Based on Inductor Replacement

D 13.45 Design the circuit of Fig. 13.20 (utilizing suitable component values) to realize an inductance of (a) 15 H, (b) 1.5 H, and (c) 0.15 H.

13.46 Figure P13.46 shows a generalized form of the Antoniou circuit of Fig. 13.20(a). Here, R_5 is eliminated and the other four components are replaced by general impedances Z_1, Z_2, Z_3, and Z_4.

(a) With an impedance Z_5 connected between node 2 and ground, show that the input impedance looking into port 1 (i.e., between node 1 and ground) is

$$Z_{11} = \left(\frac{Z_1Z_3}{Z_2Z_4}\right)Z_5$$

(b) From the symmetry of the circuit, show that if an impedance Z_6 is connected between terminal 1 and ground, the input impedance looking into port 2, which is between terminal 2 and ground, is given by

$$Z_{22} = \left(\frac{Z_2Z_4}{Z_1Z_3}\right)Z_6$$

(c) From the expressions above, observe that the two-port network in Fig. P13.46 acts as an "impedance transformer." Since by the appropriate choice of Z_1, Z_2, Z_3, and Z_4, the transformation ratio can be a general function of the complex frequency variable s, the circuit is known as a generalized impedance converter, or GIC.

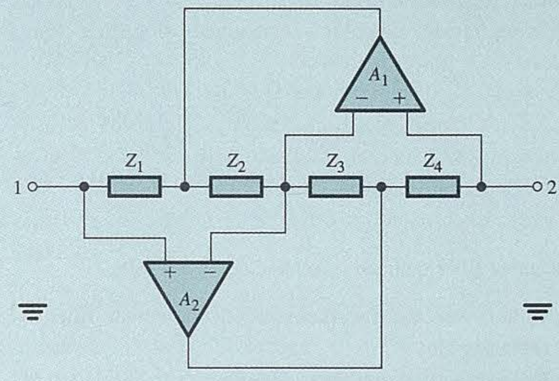

Figure P13.46

13.47 Consider the Antoniou circuit of Fig. 13.20(a) with R_5 eliminated, a capacitor C_6 connected between node 1 and ground, and a voltage source V_2 connected to node 2. Show that the input impedance seen by V_2 is $R_2/s^2C_4C_6R_1R_3$. How does this impedance behave for physical frequencies $(s = j\omega)$? (This impedance is known as a **frequency-dependent negative resistance**, or FDNR.)

D 13.48 Design the circuit of Fig. 13.22(e) to realize an LPN function with $f_0 = 10$ kHz, $f_n = 12$ kHz, $Q = 10$, and a unity dc gain. Select $C_4 = 10$ nF.

D *13.49 It is required to design a fifth-order Butterworth filter having a 3-dB bandwidth of 10^5 rad/s and a unity dc gain. Use a cascade of two circuits of the type shown in Fig. 13.22(a) and a first-order op amp–RC circuit of the type shown in Fig. 13.13(a). Select appropriate component values.

D 13.50 Design the all-pass circuit of Fig. 13.22(g) to provide a phase shift of 180° at $f = 2$ kHz and to have $Q = 2$. Use 1-nF capacitors.

D 13.51 Using the transfer function of the HPN filter, given in Table 13.1, derive the design equations also given.

D13.52** It is required to design a third-order low-pass filter whose $|T|$ is equiripple in both the passband and the stopband (in the manner shown in Fig. 13.3, except that the response shown is for $N = 5$). The filter passband extends from $\omega = 0$ to $\omega = 1$ rad/s, and the passband transmission varies between 1 and 0.9. The stopband edge is at $\omega = 1.2$ rad/s. The following transfer function was obtained using filter-design tables:

$$T(s) = \frac{0.4508\left(s^2 + 1.6996\right)}{(s + 0.7294)(s^2 + s0.2786 + 1.0504)}$$

The actual filter realized is to have $\omega_p = 10^5$ rad/s.

(a) Obtain the transfer function of the actual filter by replacing s by $s/10^5$.

(b) Realize this filter as the cascade connection of a first-order LP op amp–RC circuit of the type shown in Fig. 13.13(a) and a second-order LPN circuit of the type shown in Fig. 13.22(e). Each section is to have a dc gain of unity. Select appropriate component values. (*Note:* A filter with an equiripple response in both the passband and the stopband is known as an **elliptic filter**.)

Section 13.7: Second-Order Active Filters Based on the Two-Integrator-Loop Topology

D 13.53 Design the KHN circuit of Fig. 13.24(a) to realize a bandpass filter with a center frequency of 2 kHz and a 3-dB bandwidth of 50 Hz. Use 10-nF capacitors. Give the complete circuit and specify all component values. What value of center-frequency gain is obtained?

D 13.54 (a) Using the KHN biquad with the output summing amplifier of Fig. 13.24(b), show that an all-pass function is realized by selecting $R_L = R_H = R_B/Q$. Also show that the flat gain obtained is KR_F/R_H.
(b) Design the all-pass circuit to obtain $\omega_0 = 10^5$ rad/s, $Q = 4$, and flat gain $= 10$. Select appropriate component values.

13.55 Consider the case of the KHN circuit used together with the summing amplifier in Fig. 13.24(b) to realize a notch filter with a notch frequency ω_n and a high-frequency gain of G. Find expressions for the values required of the resistances associated with the summing amplifier.

D 13.56 Design the circuit of Fig. 13.26 to realize a low-pass notch filter with $\omega_0 = 10^5$ rad/s, $Q = 10$, dc gain $= 1$, and $\omega_n = 1.3 \times 10^5$ rad/s. Use $C = 10$ nF and $r = 20$ kΩ.

D 13.57 In the all-pass realization using the circuit of Fig. 13.26, which component(s) does one need to trim to adjust (a) only ω_z and (b) only Q_z?

D13.58** Repeat Problem 13.52 using the Tow–Thomas biquad of Fig. 13.26 to realize the second-order section in the cascade.

Section 13.8: Single-Amplifier Biquadratic Active Filters

D 13.59 Design the circuit of Fig. 13.29 to realize a pair of poles with $\omega_0 = 10^5$ rad/s and $Q = 1/\sqrt{2}$. Use $C_1 = C_2 = 1$ nF.

13.60 Consider the bridged-T network of Fig. 13.28(a) with $R_3 = R_4 = R$ and $C_1 = C_2 = C$, and denote $CR = \tau$. Find the zeros and poles of the bridged-T network. If the network is placed in the negative-feedback path of an ideal infinite-gain op amp, as in Fig. 13.29, find the poles of the closed-loop amplifier.

13.61 Consider the bridged-T network of Fig. 13.28(b) with $R_1 = R_2 = R$, $C_4 = C$, and $C_3 = C/36$. Let the network be placed in the negative-feedback path of an infinite-gain op amp and let C_4 be disconnected from ground and connected to the input signal source V_i. Analyze the resulting circuit to determine its transfer function $V_o(s)/V_i(s)$, where $V_o(s)$ is the voltage at the op-amp output. Show that the circuit obtained is a bandpass filter and find its ω_0, Q, and the center-frequency gain.

D 13.62 Use the circuit in Fig. 13.30(b) with $\alpha = 1$ to realize a bandpass filter with a center frequency of 10 kHz and a 3-dB bandwidth of 2 kHz. Give the values of all components and specify the center-frequency gain obtained.

D13.63** Consider the bandpass circuit shown in Fig. 13.30(a). Let $C_1 = C_2 = C$, $R_3 = R$, $R_4 = R/4Q^2$, $CR = 2Q/\omega_0$, and $\alpha = 1$. Disconnect the positive input terminal of the op amp from ground and apply V_i through a voltage divider R_1, R_2 to the positive input terminal as well as through R_4/α as before. Analyze the circuit to find its transfer function V_o/V_i. Find the ratio R_2/R_1 so that the circuit realizes (a) an all-pass function and (b) a notch function. Assume the op amp to be ideal.

D*13.64 Derive the transfer function of the circuit in Fig. 13.33(b) assuming the op amp to be ideal. Thus show that the circuit realizes a high-pass function. What is the high-frequency gain of the circuit? Design the circuit for a maximally flat response with a 3-dB frequency of 10^4 rad/s. Use $C_1 = C_2 = 10$ nF. (*Hint:* For a maximally flat response, $Q = 1/\sqrt{2}$ and $\omega_{3dB} = \omega_0$.)

D*13.65 Design a fifth-order Butterworth low-pass filter that has a 3-dB bandwidth of 10 kHz and a dc gain of unity. Use the cascade connection of two Sallen-and-Key circuits [Fig. 13.34(c)] and a first-order section [Fig. 13.13(a)]. Use a 10-kΩ value for all resistors.

D 13.66 The process of obtaining the complement of a transfer function by interchanging input and ground, as illustrated in Fig. 13.31, applies to any general network (not just RC networks as shown). Show that if the network n is a bandpass with a center-frequency gain of unity, then the complement obtained is a notch. Verify this by using the RLC circuits of Fig. 13.18(d) and (e).

Section 13.9: Sensitivity

13.67 Evaluate the sensitivities of ω_0 and Q relative to R, L, and C of the low-pass circuit in Fig. 13.18(b).

***13.68** Verify the following sensitivity identities:

(a) If $y = uv$, then $S_x^y = S_x^u + S_x^v$.
(b) If $y = u/v$, then $S_x^y = S_x^u - S_x^v$.
(c) If $y = ku$, where k is a constant, then $S_x^y = S_x^u$.
(d) If $y = u^n$, where n is a constant, then $S_x^y = nS_x^u$.
(e) If $y = f_1(u)$ and $u = f_2(x)$, then $S_x^y = S_u^y \cdot S_x^u$.

13.69 For the op amp–RC resonator of Fig. 13.21(b), use the expressions for ω_0 and Q given in the top row of Table 13.1 to determine the sensitivities of ω_0 and Q to all resistors and capacitors.

***13.70** For the feedback loop of Fig. 13.34(a), use the expressions in Eqs. (13.77) and (13.78) to determine the sensitivities of ω_0 and Q relative to all passive components for the design in which $R_1 = R_2$.

Section 13.10: Transconductance-C Filters

13.71 For the fully differential transconductor of Fig. 13.35(f), find an expression for G_m in terms of I and the MOSFET's transconductance parameter k_n. For $k_n = 0.5$ mA/V^2, find the bias current I that results in $G_m = 0.25$ mA/V. If for tuning purposes it is required to adjust G_m in a ±5% range, what is the required range for adjusting I?

D 13.72 Using the circuit of Fig. 13.36(a) to realize a 1-kΩ resistance, what G_m is needed? If the output resistance of the transconductor is 100 kΩ, what is the resistance actually realized?

D 13.73 Using four transconductors, give the circuit for obtaining an output voltage V_o related to three input voltages V_1, V_2, and V_3 by $V_o = V_1 - 2V_2 + 3V_3$. Give the values of the four transconductances as ratios of G_m of the transconductor that delivers the output voltage.

D 13.74 For the integrator in Fig. 13.36(b), what value of G_m is needed to obtain an integrator with a unity-gain frequency of 10 MHz utilizing a 5-pF capacitor?

D 13.75 If the transconductor in the integrator of Fig. 13.36(b) has an output resistance R_o and an output capacitance C_o, what is the transfer function realized? If the error in the integrator time constant must be less than 1%, what is the smallest value of C that can be used? If the low-frequency pole introduced by R_o is to be at least two decades lower than the unity-gain frequency of the integrator, what is the smallest G_m that this transconductor must have?

D 13.76 Design the first-order low-pass filter in Fig. 13.36(c) to have a pole frequency of 20 MHz and a dc gain of 10. Use $C = 2$ pF.

D 13.77 If a capacitor C_1 is connected between the input node and node X in the circuit of Fig. 13.36(c), what transfer function V_o/V_i is realized?

D *13.78 For the circuit in Fig. P13.78:

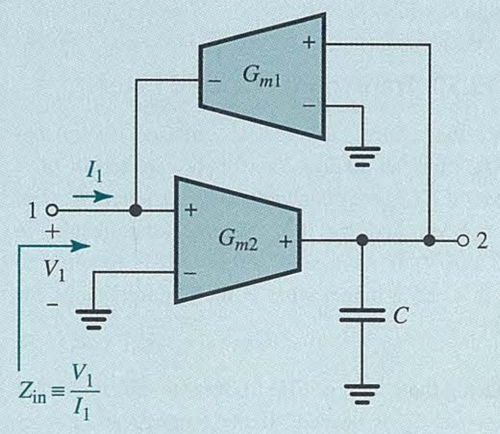

Figure P13.78

(a) Show that the input impedance Z_{in} is that of an inductance L and find an expression for L.
(b) Use the inductance generated at the input to form an LCR resonator. To realize the resistance R, use a third transconductor G_{m3}.
(c) Use a fourth inverting transconductor G_{m4} with its input connected to an input voltage V_i and its output connected to node 1. Compare the circuit thus created to the two-integrator-loop G_m–C filter of Fig. 13.37(b).
(d) What filter function is (i) V_1/V_i, (ii) V_2/V_i?

D 13.79 Consider the G_m–C second-order bandpass filter of Fig. 13.37(b) and its associated expressions in Eqs. (13.95) and (13.96). Generate an alternative design based on selecting $G_{m1} = G_{m2} = G_{m3} = G_m$ and $C_2 = C$. Find expressions for C_1 and G_m in terms of ω_0, Q, and C.

D 13.80 Design the circuit of Fig. 13.37(c) to realize a bandpass function having a center frequency of 25 MHz, $Q = 5$, and a center-frequency gain of 5. Select $G_{m1} = G_{m2}$ and $C_1 = C_2 = 5$ pF.

D 13.81 To enable the second-order G_m–C circuit in Fig. 13.37(b) to realize filter functions other than bandpass and lowpass, implement the following modifications:

(a) Connect a capacitor C_3 between the positive input terminal and the output terminal of transconductor G_{m4} and
(b) Add a fifth negative transconductor G_{m5} with V_i applied to its input, and its output connected to the node at which V_2 is taken.

Derive an expression for the transfer function V_2/V_i.

Section 13.11: Switched-Capacitor Filters

13.82 For the switched-capacitor input circuit of Fig. 13.38(b), in which a clock frequency of 200 kHz is used, what input resistances correspond to capacitance C_1 values of 1 pF, 5 pF, and 10 pF?

13.83 For a dc voltage of 1 V applied to the input of the circuit of Fig. 13.38(b), in which C_1 is 1 pF, what charge is transferred for each cycle of the two-phase clock? For a 100-kHz clock, what is the average current drawn from the input source? For a feedback capacitance of 10 pF, what change would you expect in the output for each cycle of the clock? For an amplifier that saturates at ± 10 V and the feedback capacitor initially discharged, how many clock cycles would it take to saturate the amplifier? What is the average slope of the staircase output voltage produced?

D 13.84 Design the circuit of Fig. 13.40(b) to realize, at the output of the second (noninverting) integrator, a maximally flat low-pass function with $\omega_{3dB} = 10^3$ rad/s and unity dc gain. Use a clock frequency $f_c = 100$ kHz and select $C_1 = C_2 = 5$ pF. Give the values of C_3, C_4, C_5, and C_6. (*Hint:* For a maximally flat response, $Q = 1/\sqrt{2}$ and $\omega_{3dB} = \omega_0$.)

Section 13.12: Tuned Amplifiers

*13.85 A voltage signal source with a resistance $R_s = 10$ kΩ is connected to the input of a common-emitter BJT amplifier. Between base and emitter is connected a tuned circuit with $L = 0.5$ μH and $C = 200$ pF. The transistor is biased at 1 mA and has $\beta = 200$, $C_\pi = 10$ pF, and $C_\mu = 0.5$ pF. The transistor load is a resistance of 5 kΩ. Find ω_0, Q, the 3-dB bandwidth, and the center-frequency gain of this single-tuned amplifier.

13.86 A coil having an inductance of 10 μH is intended for applications around 1-MHz frequency. Its Q is specified to be 250. Find the equivalent parallel resistance R_p. What is the value of the capacitor required to produce resonance at 1 MHz? What additional parallel resistance is required to produce a 3-dB bandwidth of 12 kHz?

13.87 An inductance of 36 μH is resonated with a 1000-pF capacitor. If the inductor is tapped at one-third of its turns and

a 1-kΩ resistor is connected across the one-third part, find f_0 and Q of the resonator.

*13.88 Consider a common-emitter transistor amplifier loaded with an inductance L. Ignoring r_o, show that for $\omega C_\mu \ll 1/\omega L$, the amplifier input admittance is given by

$$Y_{in} \simeq \left(\frac{1}{r_\pi} - \omega^2 C_\mu L g_m\right) + j\omega(C_\pi + C_\mu)$$

(*Note:* The real part of the input admittance can be negative. This can lead to oscillations.)

*13.89 (a) Substituting $s = j\omega$ in the transfer function $T(s)$ of a second-order bandpass filter [see Fig. 13.16(c)], find $|T(j\omega)|$. For ω in the vicinity of ω_0 [i.e., $\omega = \omega_0 + \delta\omega = \omega_0(1 + \delta\omega/\omega_0)$, where $\delta\omega/\omega_0 \ll 1$ so that $\omega^2 \simeq \omega_0^2(1 + 2\delta\omega/\omega_0)$], show that, for $Q \gg 1$,

$$|T(j\omega)| \simeq \frac{|T(j\omega_0)|}{\sqrt{1 + 4Q^2(\delta\omega/\omega_0)^2}}$$

(b) Use the result obtained in (a) to show that the 3-dB bandwidth B, of N synchronously tuned sections connected in cascade, is

$$B = (\omega_0/Q)\sqrt{2^{1/N} - 1}$$