Signal Conditioning Problems

Conceptual

1. T/F Circuit on left: \( R_f = 10\, \Omega \), \( R_{in} = 5\, \Omega \), \( C = 0.01\, \mu F \). The circuit is a high-pass filter with a high-frequency gain of 2 and a break frequency of \( 2 \times 10^4 \) Hz.

2. T/F Circuit in middle: \( R_f = 20\, \Omega \), \( R_{in} = 4\, K\sigma \), \( C_{in} = 0.1\, \mu F \), \( C_f = 10\, pF \). For \( V_{in} = 20 \cos(10^5 t) \) mV, \(|V_o|\) is approximately 100 mV.

3. T/F Circuit on right: \( R_f = 10\, \Omega \), \( R_{in} = 5\, K\sigma \), \( C = 0.1\, \mu F \). The circuit is a low-pass filter with a lowpass gain of 2 and a break frequency of 1000 r/s.

4. T/F Time and frequency domain. Lowering the time constant of a 1\textsuperscript{st}-order low-pass filter will result in a lower break frequency.

5. T/F Time and frequency domain. Lowering the break frequency of a low-pass filter will allow it, in its time-domain response to a step function input, to reach its steady-state value more quickly.

6. T/F A low-pass filter with \( \omega_b = 1000 \) r/s and a DC gain of 10 has a transfer function of \( 10/(s+1000) \) and its time-domain response to an input of \( 1u(t) \) V is \( 10 \left( 1 - e^{-1000t} \right) \) V. Why or why not?

7. An ideal op-amp is used to measure strain as shown above. Given a nominal 1k\sigma resistance for the strain gage, and a strain gage factor of 2, \( v_{out} = 4.004V \) if the strain, \( \varepsilon = 0.001 \).

8. Given the same strain gage, \( v_{out} = 4 \cos 10t \) mV if the strain, \( \varepsilon = 0.001 \cos(10t) \).
9. **T/F** Time-domain response. Increasing C will lower the magnitude of the static gain coefficient.

10. **T/F** Time-domain response. Increasing $R_i$ will increase the time constant.

11. **T/F** Frequency-domain response. Lowering $R_{in}$ will lower the break frequency.

12. **T/F** Frequency-domain response. Increasing $R_i$ will increase magnitude of the DC gain.

For the next two questions, $TF(s) = \frac{V_{o}(s)}{V_{i}(s)} = \frac{1000}{s + 20}$

13. **T/F** If $v_{i-1} = 5 \cos (10t) \text{V}$ and $v_{i-2} = 50 \cos (100t) \text{V}$, the steady-state amplitude of $v_{o-1}$ will be greater than $v_{o-2}$. **Why or why not?**

14. **T/F** If $v_{i-1} = 1000 \cos(10^4 t) \text{V}$ and $v_{i-2} = 10 \cos(500t) \text{V}$, the steady-state amplitude of $v_{o-2}$ is greater than $v_{o-1}$. **Why or why not?**

15. **T/F** Increasing C in the high-pass filter will lower its break frequency.

16. **T/F** Increasing $R_{in}$ in the bandpass filter has no effect on its lower break frequency.

17. **T/F** Increasing C in the high-pass filter has no effect on its high-frequency gain.

18. **T/F** Increasing $C_{in}$ in the bandpass filter has no effect on its passband gain.

19. **T/F** The gain of an op-amp amplifier is independent of frequency.
20. **T/F** An amplifier have a gain of G is needed. Using identical op-amps, a two-stage amplifier (each stage having a gain of \sqrt{G}) will maintain its gain at higher frequencies than a single-stage amplifier.

21. **T/F** A 1st-order low-pass filter has a high-frequency slope of -20 dB/dec, and a 2nd-order filter would have a high-frequency slope of -40 dB/dec.

22. **T/F** The voltage at which an op-amp circuit saturates increases as the power supply voltage, $V_{cc}$, increases.

23. **T/F** An op-amp buffer circuit is useful when a signal source has a very high Thevenin impedance. *Why or why not?*

24. **T/F** An instrumentation amplifier can be described as a differential amplifier with buffered inputs.

25. **T/F** The gain, $|V_o/V_s|$, for the circuit on the left varies with $R_s$.

26. **T/F** The gain, $|V_o/V_s|$, for the circuit on the right is not a function of $R_s$.

27. **T/F** The gain, $|V_o/V_s|$, for the circuit on the left cannot be less than one, whereas the gain for the circuit on the right can be less than one.

**Workout**

1. i) Classify the amplifier model shown below.
   
   ii) Express $V_o$ as a function of $V_s$.
   
   iii) Given $V_s$, what is the maximum possible amplification?
   
   iv) To obtain the amplification given in iii), what must $R_i$ be related to $R_s$? How must $R_o$ be related to $R_L$?
2. i) Classify the amplifier model shown below.
   ii) Express $V_o$ as a function of $V_s$.
   iii) Given $V_s$, what is the maximum possible amplification?
   iv) To obtain the amplification given in iii), what must $R_i$ be related to $R_s$? How must $R_o$ be related to $R_L$?

![Fig. P9.7](image)

3. i) Classify the amplifier model shown below.
   ii) Express $V_o$ as a function of $V_s$.
   iii) Given $V_s$, what is the maximum possible amplification?
   iv) To obtain the amplification given in iii), what must $R_i$ be related to $R_s$? How must $R_o$ be related to $R_L$?

![Fig. P9.8](image)

4. i) Classify the amplifier model shown below.
   ii) Express $V_o$ as a function of $V_s$.
   iii) Given $V_s$, what is the maximum possible amplification?
   iv) To obtain the amplification given in iii), what must $R_i$ be related to $R_s$? How must $R_o$ be related to $R_L$?

![Fig. P9.9](image)
5. The example below uses a photoconductor as part of an optical detector. Assume the photoconductor’s resistance, \( R_{\text{pc}} \), varies as shown. A current source is intended to convert changes of resistance into changes of voltage.

i) Design an amplifier circuit which amplifies \( V_{\text{pc}} \) so that, when the light power is 100 mW, the output voltage is 10 V.

ii) Design the amplifier to have a very high input resistance (\( i_{\text{in}} \) very small). Explain why this is desirable.

iii) Give the overall sensitivity of the detector (photoconductor circuit + amplifier in V/mW).

![Diagram of photoconductor circuit](Fig.P9.10)

6. Choose \( R_1 \), \( R_2 \), \( R_3 \), and \( R_4 \) so that:

i) \( V_{\text{o-1st stage}} \) = 0.4 V when the temperature is 1250 °C.

ii) \( V_{\text{o-2nd stage}} \) = -8 V when the temperature is 1250 °C.

iii) Plot \( V_{\text{o-2nd stage}} \) as a function of temperature for 500 °C < temp < 1250 °C.

Use resistance value between 1 k\( \Omega \) and 100 K\( \Omega \).

![Diagram of circuit](Fig.P9.11)
7. A system for monitoring the effectiveness of a process in removing a compound from a product stream. Design for $V_0$ to vary from -5 V to 5 V as the concentration difference $C_1 - C_2$ varies between -200 and 200 ppm.

Find:

i) The sensitivity of the sensor probes (in mV/ppm).

ii) The values for the resistances (choose between 2 kΩ and 200 kΩ).

iii) The sensitivity of the resulting detector (in mV/ppm).

8. In the circuit below, $R = R_o + \Delta R$ is the resistance of a resistive sensor.

i) Show that $V_o$ may be expressed as $V_o(-\Delta R)/(R_1 + R_o)$.

ii) Find the sensitivity of $V_o$ with respect to $\Delta R$. That is, find $dV_o/d\Delta R$.

iii) In a practical op-amp circuit, could $R$ be a 120 Ω strain gage? Why or why not?
9. Using the ideal op-amp model, find $i_o$.

![Fig. P9.14]

10. Find $V_o$.

![Fig. P9.15]

11. Using an op-amp in the inverting configuration, design a low-pass filter with a break frequency of 1000 rad/sec and a low-pass gain magnitude of 10. Use $R_{in} = 10$ kΩ.
   
   i) Sketch the circuit showing the calculated values of $R_f$ and $C$.
   
   ii) Given the transfer function.
   
   iii) Using semilog paper, give the straight-line Bode magnitude plot

12. When a given load is placed on a **four-active arm** cantilever load cell, $\varepsilon=0.0004$.
   
   i) What is $V_o$?
   
   ii) Specify $R_b$ in the amplifier below to give an output of $V_o=60$ mV. Use $R_a=2$ kΩ and
assume \( S = 2 \), \( V_s = 15 \text{V} \), and \( R_1, R_2, R_3, \) and \( R_4 \) to all be 350\( \Omega \) strain gages.

![Fig. P9.16](image)

iii) A filtering stage is needed. Design an active \textbf{bandpass} filtering stage to filter \( V_b \) with \( \omega_L = 100 \text{ r/s}, \) \( \omega_U = 5000 \text{ r/s} \) and a gain at resonance of 10. Use \( R_{in} = 10\text{k}\Omega \).

*Neatly add this stage to the above schematic.*

iii) Using semilog paper, neatly sketch the straight line Bode magnitude plot for \( |V_{out-bp filter}/V_b| \)

![Fig. P9.17](image)

13. i) Design a low-pass filtering stage to the amplifier below so that the \textbf{overall system}
transfer function has a DC gain of 100 and a break frequency of 10000 r/s.

ii) Neatly sketch the LP filtering stage in the space provided below. \textit{For the filter use} \( R_i = 100 \text{k}\Omega \).
iii) Give the overall transfer function in Bode form.
iv) Using semilog paper, plot the straight-line Bode magnitude plot for the overall system.

14. A force measurement transducer has a voltage output and has an underdamped 2nd-order response \( (K_s = 4 \text{ mV/N, } \zeta = 0.2, \omega_n = 100 \text{ r/s}). \)

\[
\frac{1}{\omega_n^2} \frac{d^2v}{dt^2} + \frac{2\zeta}{\omega_n} \frac{dv}{dt} + v = K_s
\]

Use phasor analysis to determine the actual steady-state force, \( f(t) \), when the measured steady-state voltage is \( v(t) = [20 + 50 \cos (150t)] \text{ mV}. \)

*Hint: Review system dynamics.*
15. The TC voltage plot below results when a thermocouple sensing junction, at \( t=4 \) seconds, is transferred from a temperature of 20°C to 100°C. (For a temperature of 0°C, the steady-state voltage is 0V)

Given that the TC behaves as a 1\(^{st}\)-order system, extract the system parameters and give the differential equation that relates the input TC temperature and output TC voltage.

\[
\tau \frac{dv}{dt} + v = K_s T
\]

*Hint: Review system dynamics.*

16. A thermocouple is used to measure temperature. The output voltage for \( T=0°C \) is 0V. The plot below is taken as the thermocouple is taken from 400°C to 0°C at \( t=2s \). Assume the TC behaves as a 1\(^{st}\)-order system.

\[
\tau \frac{dv}{dt} + v = K_s T
\]

i) Find the approximate differential equation relating input temperature to thermocouple voltage. Identify the time constant, \( \tau \), and the static gain coefficient, \( K \).

*Don’t forget units.*

ii) For the same thermocouple, give the thermocouple voltage, in steady-state, if its surrounding temperature, in °C, is \( T = 400 + 20 \cos t \).
17. i) Find the transfer function, $V_o/V_s$, of the circuit shown below.
   ii) Sketch the Bode magnitude plot for the circuit shown below given $R_1 = 1\, k\Omega$, $R_2 = 100\, \Omega$, $C = 0.1\, \mu F$, and $L = 10\, \mu H$.
   iii) What is $v_o(t)$, in steady-state, given $v_s(t) = 10\cos 10^4t\, V$.
   iv) What is $v_o(t)$, in steady-state, given $v_s(t) = 10\cos 10^6t\, V$.
   v) What is $v_o(t)$, in steady-state, given $v_s(t) = 10\cos 10^8t\, V$.

![Fig. P9.22](image)

17. Let $V_s$ be a sinusoidal signal (2 V amplitude, with a frequency of 4000 r/s) corrupted by high frequency noise (1 V amplitude, frequency 32 kr/s).
   i) What is the signal-to-noise ratio of $V_s$.
   ii) Design an active first-order low-pass filter using an op-amp in the inverting configuration. Let the low-frequency gain be 1 and the break frequency be 8000 r/s. Use $R_{in} = 10\, k\Omega$.
   iii) If $V_s$ is input to the op-amp circuit design in ii), what is the signal-to-noise ratio at the output?
   iv) Design an active second-order Sallen-Key low-pass filter. Let the low-frequency gain be 1 and the break frequency be 8000 r/s. Choose $\zeta = 0.7$.
   v) If $V_s$ is input to the op-amp circuit in iv), what is the signal-to-noise ratio at the output?
   vi) Compare the filtering effectiveness of the 1st-order filter to the 2nd-order filter.

18. Let $V_s$ be a sinusoidal signal (2 V amplitude, with a frequency of 5 kHz) corrupted by low frequency noise (1 V amplitude, frequency 60 Hz) and by high frequency noise (5 V amplitude, frequency 40 kHz).
   i) Design an active Sallen-Key band-pass filter. Let the center frequency be 5 kHz and let the quality factor be 10. Choose $R = 10\, k\Omega$.
   ii) Let $V_s$ be input to the circuit designed in i). Compare the signal-to-noise ratios at the input to those at the output.
19. Let $V_s$ be a sinusoidal signal (2 V amplitude, with a frequency of 5 kHz) corrupted by low frequency noise (1 V amplitude, frequency 60 Hz) and by high frequency noise (5 V amplitude, frequency 40 kHz).

i) Design an active Sallen-Key band-pass filter. Let the center frequency be 5 kHz and let the quality factor be 10. Choose $R = 10 \, k\Omega$.

ii) Let $V_s$ be input to the circuit designed in i). Compare the signal-to-noise ratios at the input to those at the output.

20. Let $V_s$ be a sinusoidal signal (2 V amplitude, with a frequency of 6 kHz) corrupted by low frequency noise (1 V amplitude, frequency 60 Hz) and by high frequency noise (5 V amplitude, frequency 40 kHz).

i) Design an active band-pass filter as described in Design Example 6.7.1. Let $f_b = 1.5 \, kHz$, $f_u = 12 \, kHz$, and the passband gain = 2. Choose $R_{in} = 100 \, k\Omega$.

ii) Let $V_s$ be input to the circuit designed in i). Compare the signal-to-noise ratios at the input to those at the output.

21. For each of the areas below, discuss the associated limitations of op-amps.

i) Current limitations of op-amps. What limits does this place on the resistances connected at the output of op-amps?

ii) Limits for op-amp output voltages.

iii) Limits associated with finite op-amp gain-bandwidth products.

22. i) Design an inverting amplifier, shown in Fig. with a $|\text{gain}|$ of 10. Use $R_{in} = 7.5 \, k\Omega$.

ii) Given $V_{cc} = 9 \, V$, sketch $V_o$ given the input is a 1 kHz triangle wave with a peak-to-peak amplitude of $\frac{1}{2} \, V$.

iii) Given $V_{cc} = 9 \, V$, sketch $V_o$ given the input is a 1 kHz triangle wave with a peak-to-peak amplitude of 2 V.

iv) Given $V_{cc} = 15 \, V$, sketch $V_o$ given the input is a 1 kHz sinusoid with an RMS voltage of 5 V.
23. Using the amplifier shown in Fig. , which shows the model accounting for finite gain-bandwidth product and non-ideal input-output op-amp resistances, determine \( v_o(t) \) and the \(|\text{gain}|\) for the following frequencies.

i) DC (\( f = 0 \))
ii) \( f = 1000 \) Hz
iii) \( f = 10 \) kHz
iv) \( f = 100 \) kHz
v) \( f = 1 \) MHz

24. Find \( v_o(t) \) and the signal-to-noise ratio (the noise is the high frequency component) at the output. Design a first-order low-pass filter having a DC gain of 25 and a break frequency of \( 2 \omega \). Use the ideal op-amp model and choose \( R_{in} = 10 \) k\( \Omega \).
i) DC \( (\omega = 0) \)
ii) \( \omega = 1000 \text{ r/s} \)
iii) \( \omega = 10 \text{ kr/s} \)
iv) \( \omega = 100 \text{ kr/s} \)
v) \( \omega = 1 \text{ Mr/s} \)
vi) \( \omega = 10 \text{ Mr/s} \)

Now, using the component values determined in i) – iv), and using the amplifier model shown in Fig. , which accounts for finite gain-bandwidth product and non-ideal input-output op-amp resistances, determine \( v_0(t) \) and the signal-to-noise ratio at the output for the same values of \( \omega \).