Bandwidth – 1
TIPL 1211
TI Precision Labs – Op Amps

Presented by Pete Semig

Prepared by Art Kay, Pete Semig, and Tim Green
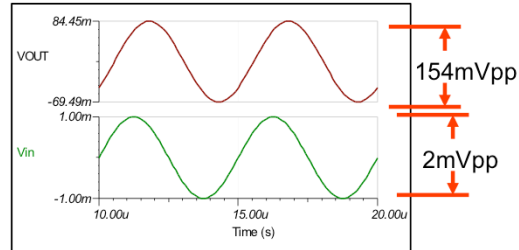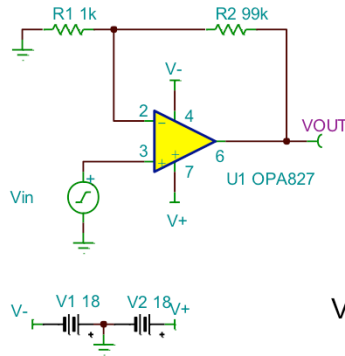
TEXAS INSTRUMENTS

Hello, and welcome to the TI Precision Lab discussing op amp bandwidth, part 1.

In this video we'll discuss gain and how it's represented linearly and in decibels. Poles, zeros, bode plots, cutoff frequency, and the definition of bandwidth will also be discussed. Finally, TINA-TI will be used to correlate bandwidth simulation results with our theoretical calculations.

What is the Problem?

R1 1k R2 99k

V−

2
4

3
6

7

VOUT

U1 OPA827

Vin

V+

V− V1 18 V2 18 V+

VOUT
84.45m
−69.49m

Vin
1.00m
−1.00m

10.00u 15.00u 20.00u
Time (s)

154mVpp

2mVpp

$$V_{in} = 2mV_{pp} \qquad G_{CL} = 1 + \frac{R_2}{R_1} = 1 + \frac{99k\Omega}{1k\Omega} = 100\frac{V}{V}$$

$$V_{out-calc} = V_{in} \times G_{CL} = 2mV_{pp} \times 100\frac{V}{V} = \boxed{200mV_{pp}}$$

$$V_{out-sim} = \boxed{154mV_{pp}}$$

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In this transient simulation, the OPA827 is set up in a non-inverting configuration with a closed loop gain of 100V/V. The input signal, Vin, is 2mVpp. The product of the input signal and closed loop gain is 200mVpp.

When simulated, however, the output voltage is only 154mVpp. Why?

In order to answer this question, we need to fully understand the concept of bandwidth. First, let's review a few topics.

Review: Gain, Linear vs. Decibel

- Linear (V/V) to Decibels (dB)

$$G_{dB} = 20 \times \log(G_{V/V})$$

- Example: Convert the closed-loop gain (G_{CL}) of an op amp circuit from 100V/V to decibels

- Solution:

$$G_{CL(dB)} = 20 \times \log\left(100\,\frac{V}{V}\right) = 40dB$$

- Decibels (dB) to Linear (V/V)

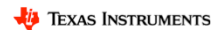$$G_{V/V} = 10^{\left(\frac{G_{dB}}{20}\right)}$$

- Example: Convert the open-loop gain (A_{OL}) range of the OPA188 to V/V

- Solution:

$$G_{A_{OL}\,@1Hz} = 10^{\left(\frac{130dB}{20}\right)} = 3,162,277\,\frac{V}{V}$$

$$G_{A_{OL}\,@2MHz} = 10^{\left(\frac{0dB}{20}\right)} = 1\,\frac{V}{V}$$

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When working with electronics we often need to express quantities such as op amp gain, signal-to-noise ratio, common-mode-rejection ratio, and power supply rejection ratio whose values have very large spans.

Therefore it is important to have a mechanism upon which we can represent a large range of values while using small numbers. This mechanism is called the 'decibel', or 'dB' for short. Note that decibels have no units.

This slide shows how to convert linear gain values to dB and vice versa.

This equation shows how to convert from a linear gain in volts per volt to decibels. For example, let's convert the closed loop gain of an op amp circuit from 100V/V to decibels.

Substituting 100V/V for the linear gain in the given equation yields 40dB.

Similarly, given a gain in decibels we can convert it to a linear representation using this equation.

While the previous example may not seem like a significant improvement in representing large numbers, let's look at the open loop gain, or Aol, of the OPA188.
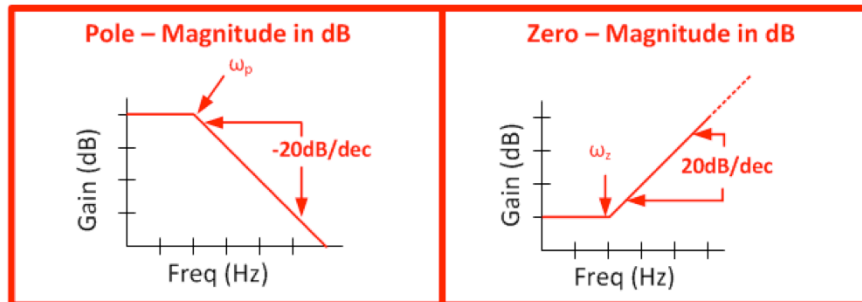
Poles & Zeros, Standard Form

$$H(s) = G \frac{\left(\dfrac{s}{\omega_{z1}} + 1\right) \cdot \left(\dfrac{s}{\omega_{z2}} + 1\right)}{\left(\dfrac{s}{\omega_{p1}} + 1\right) \cdot \left(\dfrac{s}{\omega_{p2}} + 1\right)}$$

Zeros: ω_{z1}, ω_{z2}
Roots in the numerator

Poles: ω_{p1}, ω_{p2}
Roots in the denominat

Where
$s = j \times \omega = 2 \times \pi \times f$

Pole – Magnitude in dB — Gain (dB) vs Freq (Hz), ω_p, -20dB/dec

Zero – Magnitude in dB — Gain (dB) vs Freq (Hz), ω_z, 20dB/dec

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Now let's take a look at 'poles' and 'zeros'.

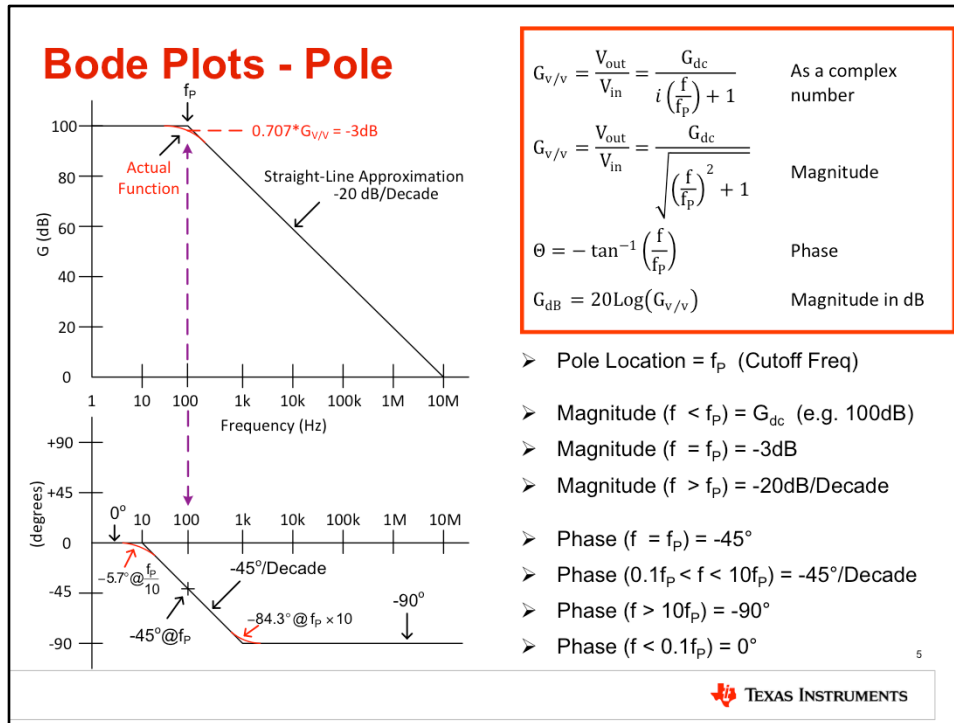H(s) represents a transfer function with two poles and two zeros.

The 's' represents jΩ (j-omega) where omega is 2*pi*f.

The frequencies at which each term in the numerator equal zero are called zeros.

The frequencies at which each term in the denominator equal zero are called poles.

Each pole and zero is factored to be (s/omega +1). This is called the standard form because it allows you to *easily* determine the pole and zero by inspection. Furthermore, notice that the dc gain is factored out of the transfer function. This makes it easy to determine the low frequency gain.
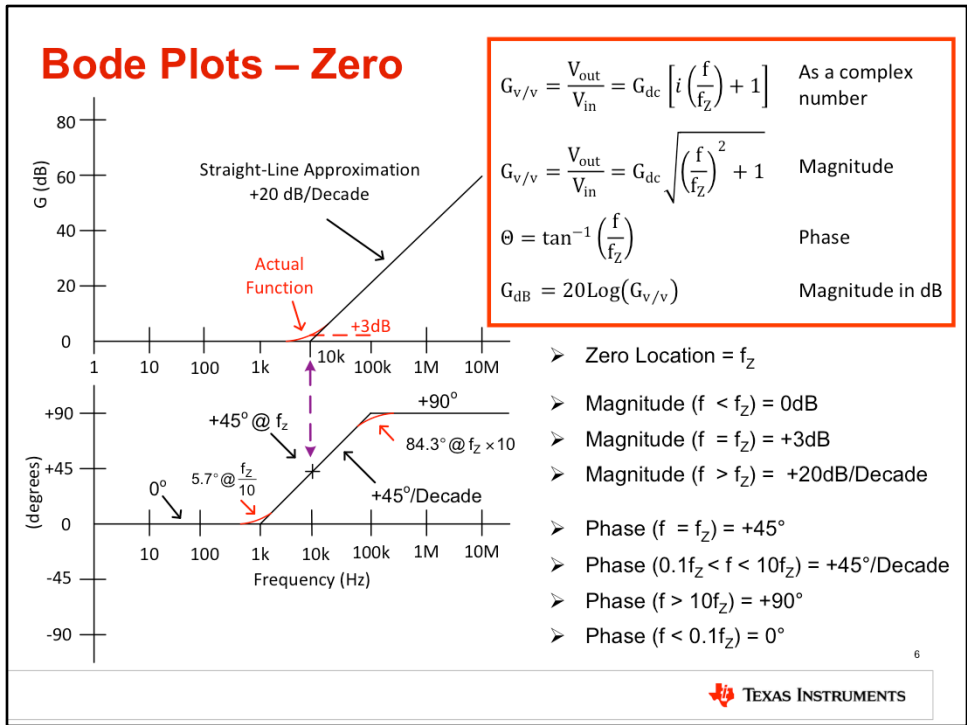
A plot of gain vs. frequency for a pole is shown in the lower left. Notice that the gain is given as a magnitude in dB. Note that the gain of a pole decreases, or rolls off, at a rate of *-20dB/decade* in frequency. This makes sense because for higher frequencies the denominator will become large causing the magnitude to decrease. In the next slide we will see more detail on this.

Bode Plots - Pole

G (dB): 100, 80, 60, 40, 20, 0 vs Frequency (Hz): 1, 10, 100, 1k, 10k, 100k, 1M, 10M

f_P

$0.707 * G_{v/v} = -3dB$

Actual Function

Straight-Line Approximation -20 dB/Decade

(degrees): +90, +45, 0, -45, -90 vs 10, 100, 1k, 10k, 100k, 1M, 10M

$0°$

$-5.7° @ \frac{f_P}{10}$

$-45°/Decade$

$-45° @ f_P$

$-84.3° @ f_P \times 10$

$-90°$

$$G_{v/v} = \frac{V_{out}}{V_{in}} = \frac{G_{dc}}{i\left(\frac{f}{f_P}\right) + 1}$$ As a complex number

$$G_{v/v} = \frac{V_{out}}{V_{in}} = \frac{G_{dc}}{\sqrt{\left(\frac{f}{f_P}\right)^2 + 1}}$$ Magnitude

$$\Theta = -\tan^{-1}\left(\frac{f}{f_P}\right)$$ Phase

$$G_{dB} = 20\text{Log}\left(G_{v/v}\right)$$ Magnitude in dB

➤ Pole Location = f_P (Cutoff Freq)

➤ Magnitude (f < f_P) = G_{dc} (e.g. 100dB)

➤ Magnitude (f = f_P) = -3dB

➤ Magnitude (f > f_P) = -20dB/Decade

➤ Phase (f = f_P) = -45°

➤ Phase (0.1f_P < f < 10f_P) = -45°/Decade

➤ Phase (f > 10f_P) = -90°

➤ Phase (f < 0.1f_P) = 0°

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This slide illustrates the equations for a pole and its associated response. Later we will provide a real world circuit example for a pole. Looking at the equations, you can see that the first equation represents a pole as a complex number. Complex numbers have a real and imaginary part. For practical circuits the complex function is converted to a magnitude and phase. The second equation shows the magnitude and the third equation shows the phase. As discussed earlier 20*log base 10 of the linear gain yields the gain in decibels.

The graphs show the magnitude in dB as well as the phase in degrees. This type of plot is called a Bode plot. Notice that both the horizontal axis and vertical axis are logarithmic. Let's look at some key points on the bode plot. First, the pole frequency as denoted by f_P. For frequencies below f_P the gain is constant and is denoted G_{DC}. In other words, the gain at dc or zero frequency would be G_{DC}. In this example G_{DC} = 100dB. Also notice that the gain at f_P is attenuated by 3db, or is 0.707 times the dc gain. Finally, for frequencies greater than f_P, the magnitude plot rolls off at a rate of -20dB/decade.

Now let's consider the graph of phase shift vs. frequency. The phase shift at the pole frequency is -45 degrees. Phase begins to change one decade before the pole and stops changing one decade after the pole. In this region
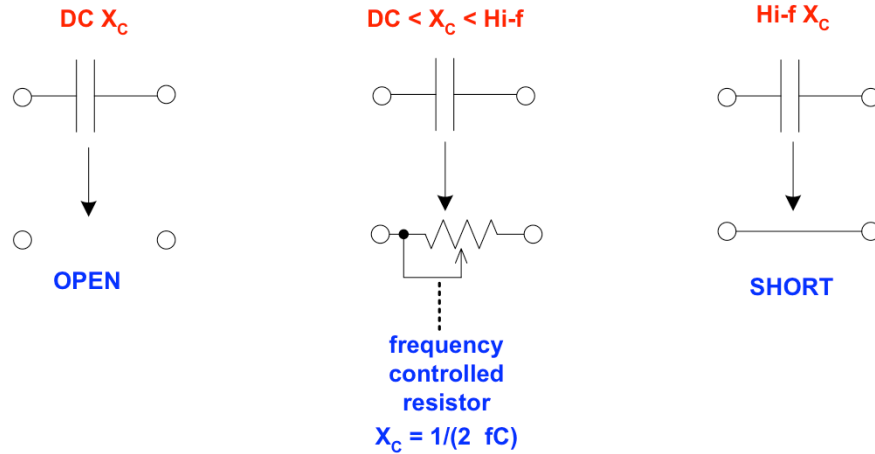
Bode Plots – Zero

$$G_{v/v} = \frac{V_{out}}{V_{in}} = G_{dc}\left[i\left(\frac{f}{f_Z}\right) + 1\right]$$ — As a complex number

$$G_{v/v} = \frac{V_{out}}{V_{in}} = G_{dc}\sqrt{\left(\frac{f}{f_Z}\right)^2 + 1}$$ — Magnitude

$$\Theta = \tan^{-1}\left(\frac{f}{f_Z}\right)$$ — Phase

$$G_{dB} = 20\,Log(G_{v/v})$$ — Magnitude in dB

Straight-Line Approximation +20 dB/Decade

Actual Function

+3dB

+45° @ f_Z

84.3° @ $f_Z \times 10$

5.7° @ $\frac{f_Z}{10}$

0°

+45°/Decade

+90°

G (dB): 80, 60, 40, 20, 0

Frequency (Hz): 1, 10, 100, 1k, 10k, 100k, 1M, 10M

(degrees): +90, +45, 0, -45, -90

- Zero Location = f_Z
- Magnitude (f < f_Z) = 0dB
- Magnitude (f = f_Z) = +3dB
- Magnitude (f > f_Z) = +20dB/Decade
- Phase (f = f_Z) = +45°
- Phase (0.1f_Z < f < 10f_Z) = +45°/Decade
- Phase (f > 10f_Z) = +90°
- Phase (f < 0.1f_Z) = 0°

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This slide illustrates the equations for a zero and its associated response. Looking at the equations, you can see that the first equation represents a zero as a complex number. Complex numbers have a real and imaginary part. For practical circuits the complex function is converted to a magnitude and phase. The second equation shows the magnitude and the third equation shows the phase. Taking 20 Log10 of the magnitude function gives the magnitude in dB.

The equations were used to generate the bode plot and phase plot. Let's look at some key points on the bode plot. First, the zero frequency is denoted f_Z. For frequencies below f_Z the gain is constant and is denoted G_{DC}. In this example G_{DC} = 0dB. Also notice that the gain at f_Z is at **+3db**, or is 1.414 times the dc gain. Finally, for frequencies greater than f_Z, the magnitude plot increases at a rate of +20dB/decade.

Now let's consider the graph of phase shift vs. frequency. The phase shift at the zero frequency is +45 degrees. Phase begins to change one decade before the zero and stops changing one decade after the zero. In this region the slope is +45 degrees per decade. Considering frequencies that are lower than one decade below the zero, the phase shift is 0 degrees. For frequencies greater than one decade beyond the zero the phase shift is +90 degrees.

Capacitor – Intuitive Model

DC X_C

DC < X_C < Hi-f

Hi-f X_C

OPEN

SHORT

frequency controlled resistor

$X_C = 1/(2\pi fC)$

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First let's consider the operation of a capacitor over frequency. It often helps to think of three different regions of operation.   At "DC" or very ***"Low Frequency"*** the capacitor will be viewed as an open circuit. At "High Frequency" the capacitor will be viewed as a short circuit. In between the capacitor will be viewed as a frequency controlled resistor with a $1/2\pi fC$ decrease in impedance as frequency increases. Knowing these basic relationships helps when drawing and analyzing bode plots.

Real-World Pole Example
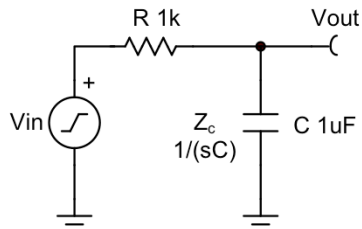
$$V_{out} = \frac{Z_C}{R + Z_C} \times V_{in} = \frac{\frac{1}{sC}}{R + \frac{1}{sC}} \times V_{in}$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{sRC + 1} = \frac{1}{\frac{s}{\left(\frac{1}{RC}\right)} + 1} = \frac{1}{\frac{s}{\omega_p} + 1}$$

$$Z_c = \frac{1}{sC} = \frac{1}{j2\pi fC}$$

$$X_c = \frac{1}{2\pi fC}$$

Since $\omega_p = \frac{1}{RC}$ and $\omega_p = 2\pi f_p$

$$f_p = \frac{1}{2\pi RC} = \frac{1}{2\pi(1k\Omega)(1\mu F)} = 159Hz$$

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Now let's look at a real world circuit that generates a pole.

This is a simple RC circuit where the output signal is measured across the capacitor. Think of it as a voltage divider. The impedance of the capacitor is given as Zc = 1/(sC). The output of this circuit is given by the standard voltage divider equation Zc / (R + Zc). Substituting 1/(sC) for Zc and simplifying yields the standard equation for a pole. By inspection you can see that the pole frequency omega-p is 1/(RC). Omega-p is an angular frequency, and it can be converted to Hertz using the relationship Omega-p = 2 pi fp.

The final equation for frequency is given as fp = 1/(2 pi R C). Plugging in the values for this example gives a pole frequency of 159Hz. Let's graph this function.

Real-World Pole Example
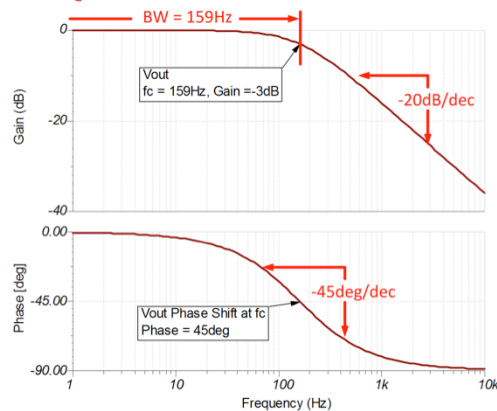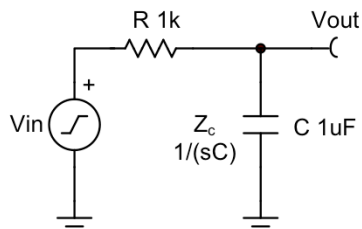
Cutoff Frequency:
Passband Gain is down -3dB at the cutoff frequency
Phase is shifted by -45deg at the cutoff
Bandwidth:
The frequency range of the passband (equal to the cutoff frequency in this case).

This figure shows the bode plot and the phase shift plot for the RC circuit. Recall that at dc or low frequencies a capacitor acts like an open. In this case the entire input signal is seen across the capacitor, so the gain is 1V/V or 0dB. Notice that the magnitude of the gain at the pole frequency is -3dB. Also notice that the phase at the pole frequency is -45 degrees. Furthermore, the phase shift begins about one decade before the pole and ends about one decade after the pole. Furthermore, the phase shift at very low frequencies is near zero degrees and at high frequencies the shift is nearly 90 degrees. Finally, notice that the gain decreases at a rate of -20dB/decade for frequencies above the pole frequency.

This circuit is a common building block and is called a low pass filter. The objective of this circuit is to pass low frequency signals and stop high frequency signals. For this reason, the pole frequency is often called the cutoff frequency, and denoted by fc. The idea is that all signals with frequency greater then the cutoff frequency are "cut off" or eliminated. In fact the high frequency signals are only attenuated and not fully eliminated. Another term associated with low pass filters is "bandwidth". Bandwidth is simply the *width* of the pass-band, and in this case is synonymous with the cutoff frequency. In later videos we will discuss different types of filters. For some filters, such as a band pass filter, the bandwidth definition *will* include both a lower and upper cutoff frequency.

Real-World Pole & Zero Example
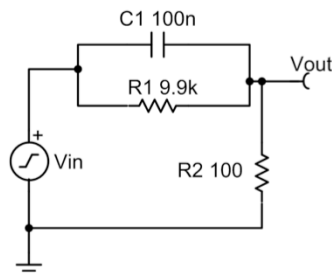
Derivation of Gain Equation

$$Z_{R1||C1} = \frac{R_1\left(\frac{1}{sC_1}\right)}{R_1 + \frac{1}{sC_1}}$$ R1 & C1 in Parallel

$$G_{v/v} = \frac{V_{out}}{V_{in}} = \frac{R_2}{R_2 + Z_{R1||C1}}$$ Gain

$$G_{v/v} = \frac{V_{out}}{V_{in}} = \left(\frac{R_2}{R_2 + R_1}\right)\left(\frac{[C_1 R_1]s + 1}{\left[\frac{C_1 R_1 R_2}{R_2 + R_1}\right]s + 1}\right)$$ Standard form

$$G_{dc} = \frac{R_2}{R_2 + R_1}$$ DC gain

$$f_P = \frac{1}{2\pi C_1 R_1}$$ Pole

$$f_Z = \frac{1}{2\pi\left[\frac{C_1 R_1 R_2}{R_2 + R_1}\right]}$$ Zero

C1 100n

R1 9.9k

Vout

Vin

R2 100

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Ideally we would present a simple circuit that would demonstrate a zero. However, there is no simple real-world circuit that generates a zero. The circuit presented here contains both a pole and a zero. The mathematics for deriving the transfer function and solving for the pole and zero is shown to the right. First we start by finding the impedance of the parallel combination of R1 and C1. Next the resistor divider relationship is used to determine the input output relationship. Substituting the parallel impedance from above and simplifying we get the standard form of a transfer function with poles and zeros. In this form you can determine the dc gain, pole frequency, and zero frequency by inspection.   If we plug *in* the values for R1, C1, and R2 into the equations we can determine the dc gain and pole and zero frequencies for this example.   Next we will use these results to help graph this function.

Real-World Pole & Zero Example
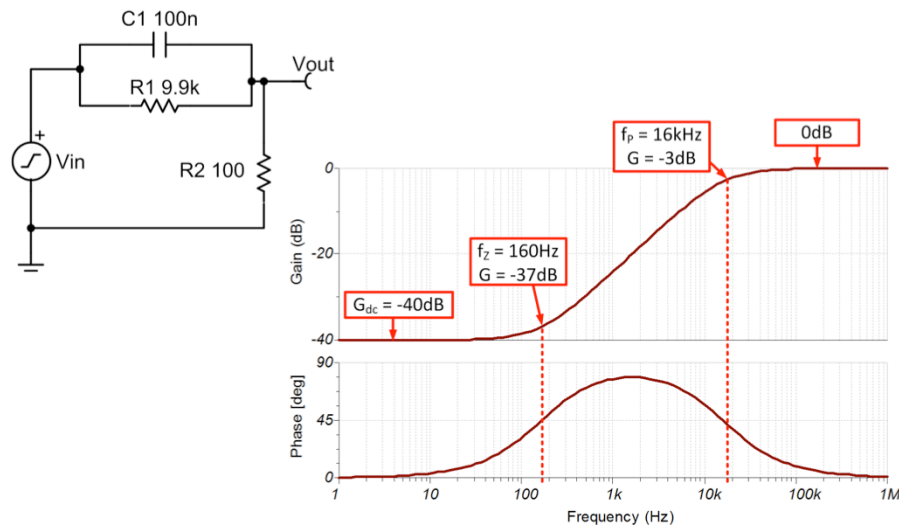
This slide shows the bode plot for the example circuit. First let's consider the gain at high frequencies and low frequencies. At low frequencies the capacitor C1 acts like an open, so you can consider this to be a simple series circuit of R1 and R2. In this case the dc gain can be determined using the voltage divider equation. In this example the dc gain is -40dB or 0.01V/V. At high frequencies the capacitor C1 acts like a short. In this case all of the signal is directed to the output and the gain is 0dB or 1V/V. At this point you can finish the graph by solving for the pole and zero frequency using the equations from the previous slide. The zero frequency occurs at 160Hz. For frequencies higher than the zero the bode plot will rise at +20dB/decade. The pole frequency occurs at 16kHz. ***The pole effectively cancels the zero at frequencies above 16kHz***. Remember that the slop of the zero is +20dB/decade and the pole is -20dB/decade.

Let's also consider the phase shift response. Notice that the phase is at +45 degrees at the zero frequency. This is as expected based on our previous discussion of zeros. You will also notice that the phase approaches ***+90*** degrees as expected. At this point the phase begins to decrease at -45 degrees per decade because of the zero. The phase shift at the pole frequency is ***+45*** degrees, which makes sense because we shifted down ***-45*** degrees from ***+90***. Finally, at high frequencies the phase shifts back to zero degrees because the pole and zero fully cancel each other.

Relating the Bode Plot to Time Domain

(400Hz, -8.64dB)

(400Hz, -68.3 deg)

Vin

Vout

Vpk = 368mVpk
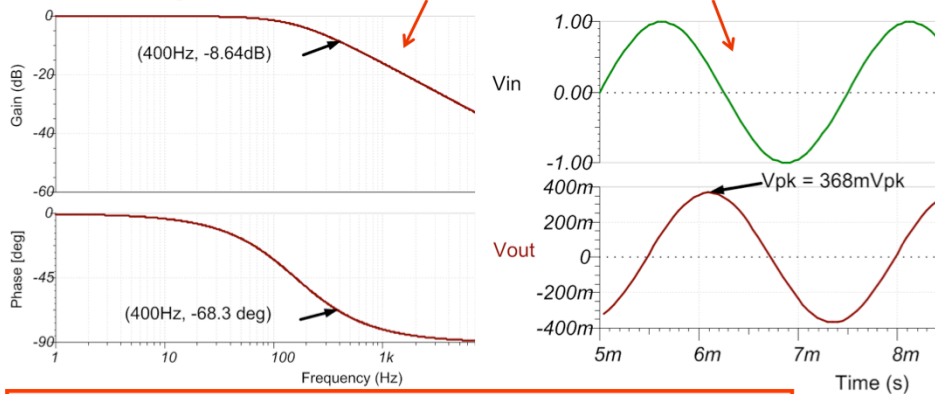
$$G_{v/v} = 10^{\left(\frac{-8.64dB}{20}\right)} = 0.370$$ Gain from Log to Linear

$$V_{out} = V_{in} \cdot G_{v/v} = (1Vpk)(0.370) = 370mVpk$$ Output Voltage

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The bode gives information on the gain as well as the phase shift for a circuit. In this example we're going to calculate the peak output voltage of a 1Vp sinusoid at 400Hz. Given the amplitude and frequency of the input signal we can use the bode plot *magnitude (Gain (dB))* to determine the output signal amplitude. First, find the gain at 400Hz. In this example the gain is -8.64dB. Convert the gain from dB to a linear representation and multiply the input signal by the linear gain. In this example -3.64dB translates to 0.370V/V. Since the input is 1Vpk the output is 370mVpk. Notice that the time domain simulation peak output is very close to the expected value from the bode plot.

Relating the Bode Plot to Time Domain
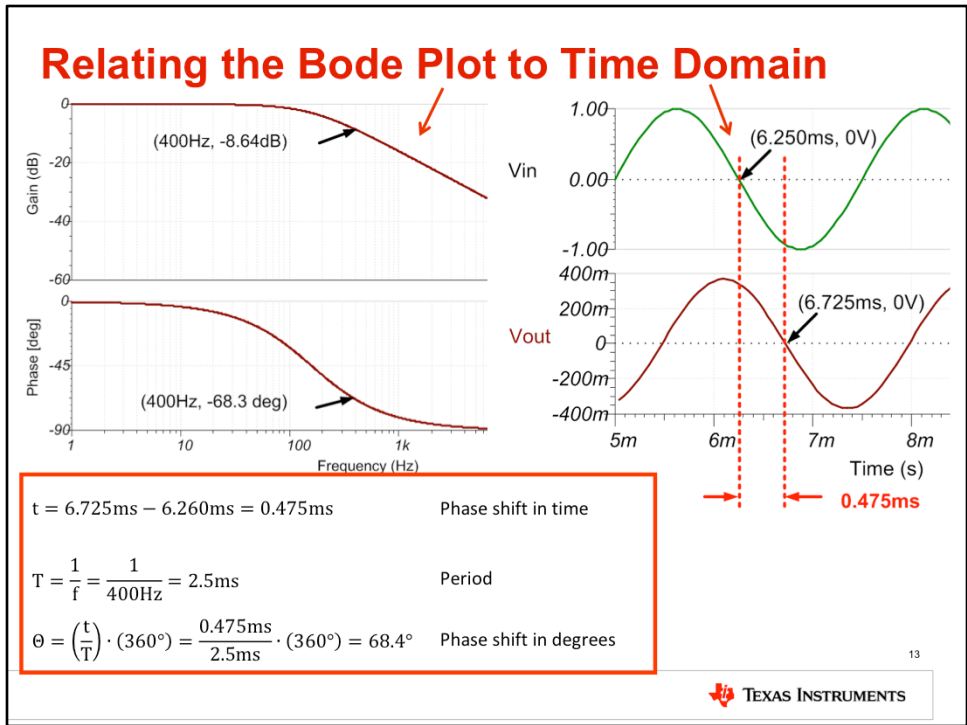
Here we will continue the example considering the phase shift in the time domain. Notice on the **bode phase (Phase (deg))** that the phase shift is -68.3deg at 400Hz. On the time domain plot, you can see that the output signal is shifted to the right in time. This is called a phase shift or time delay. The calculation at the bottom of the page illustrates how you can convert the time delay to a phase shift in degrees. In this case the time delay is about 0.475ms and the period of the 400Hz input is 2.5ms. The delay in degrees is calculated by taking the **ratio** of the time delay to the period and multiplying by 360 degrees. As with the previous example the time domain **results** compare well to the bode plot results. Next we will cover a step-by-step example of a SPICE ac analysis.
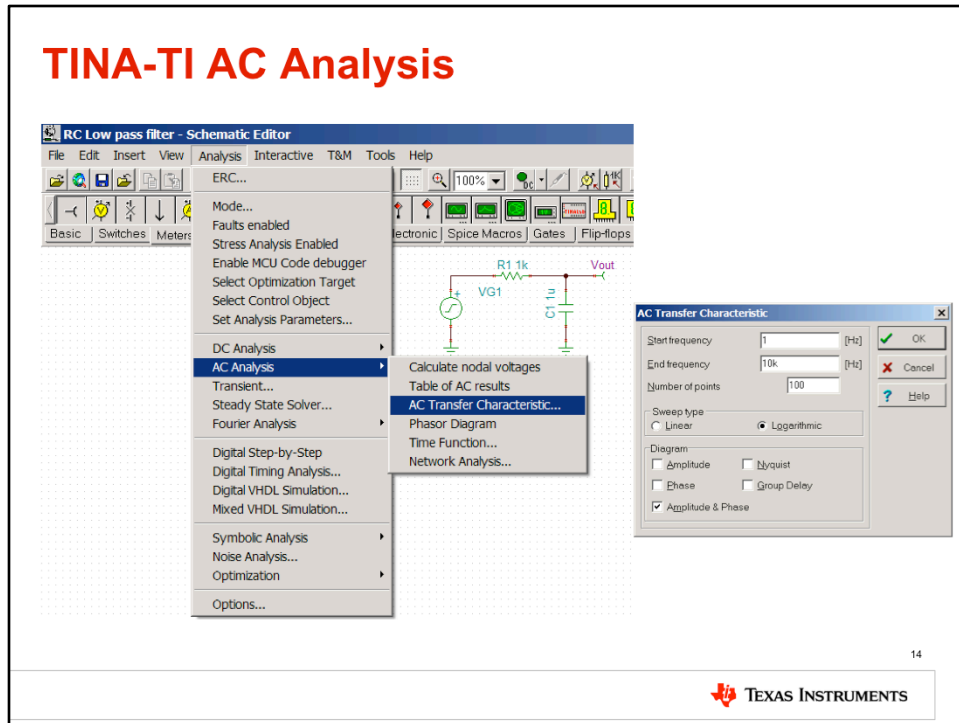
Texas Instrument's SPICE simulator, TINA-TI, can be used to simulate the ac response, or transfer characteristic, of the circuits we have discussed. It can be downloaded from www.ti.com/tina-ti.

Once the circuit is implemented, you can run the transfer characteristic by selecting Analysis->AC Analysis->AC Transfer Characteristic.

In the AC Transfer Characteristic window, set the beginning and ending frequency. Since the frequency range is generally very large, select 'logarithmic' for the sweep type. In the Diagram section, select Amplitude & Phase.
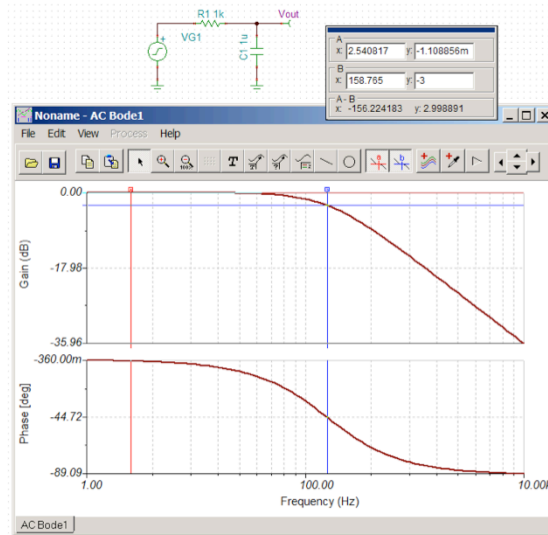
The cursors in the diagram window allow us to easily find the gain, in dB, at a particular frequency. In order to enable the cursors, simply click these buttons. Now you can either drag the cursors left and right, or you can type a particular value for x or y. For example, typing '-3' in the 'y' box for cursor B and pressing 'Enter' will yield the exact cutoff frequency for this circuit.

Original Problem Revisited
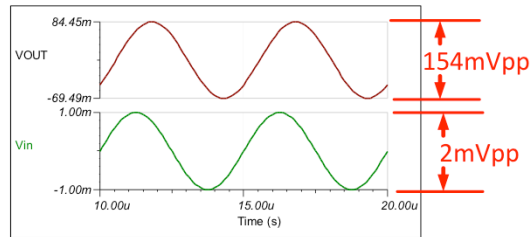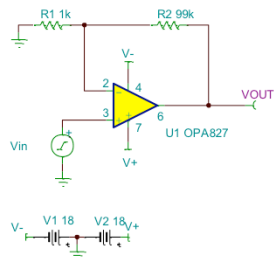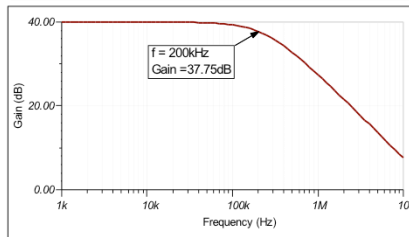
At the beginning of this presentation we were given an OPA827 set up in a non-inverting configuration with gain=100V/V, or 40dB. The input signal (Vin) was 2mVpp. We expected an output signal of 200mVpp, but observed only 154mVpp. Why?

Looking at the transient simulation we see that the input signal, Vin, has a period of 5us. The corresponding frequency is 1/5us, or 200kHz.

An ac analysis of the circuit shows that the gain is only 37.75dB at 200kHz. We originally expected it to be 40dB.

Converting the gain to a linear representation we find it is only 77.179V/V…not 100V/V.

Multiplying the 2mVpp input signal by 77.179V/V yields 154mVpp, which is consistent with our simulation.
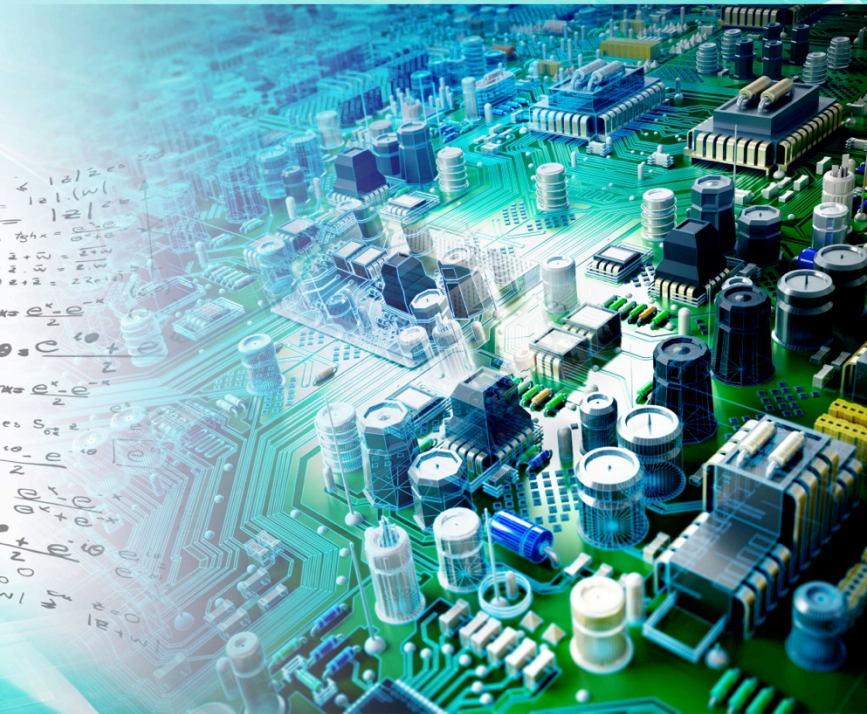
Thanks for your time! Please try the quiz.

In summary, this video discussed gain and how it's represented linearly and in decibels. Poles, zeros, bode plots, cutoff frequency, and the definition of bandwidth were also discussed. Finally, TINA-TI was used to correlate simulation results with our theoretical calculations.

Thank you for time! Please try the quiz to check your understanding of this video's content.

Bandwidth 1

Multiple Choice Quiz

TI Precision Labs – Op Amps

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Quiz: Bandwidth 1

1. Select the best description for a pole.
a. The root of the numerator causes the gain to decrease by 20 dB/decade
b. The root of the denominator causes the gain to increase by 20 dB/decade
c. The root of the numerator causes the gain to increase by 20 dB/decade
d. The root of the denominator causes the gain to decrease by 20 dB/decade

2. Select the best description for a zero.
a. The root of the numerator causes the gain to decrease by 20 dB/decade
b. The root of the denominator causes the gain to increase by 20 dB/decade
c. The root of the numerator causes the gain to increase b 20 dB/decade
d. The root of the denominator causes the gain to decrease by 20 dB/decade

3. How is the gain curve affected at the pole frequency?
a. The gain is attenuated by -20dB
b. The gain is attenuated by -3dB
c. The gain is increased by +20dB
d. The gain is increased by +3dB

Quiz: Bandwidth 1

4. How is the gain curve affected at the zero frequency?
a. The gain is attenuated by -20dB
b. The gain is attenuated by -3dB
c. The gain is increased by +20dB
d. The gain is increased by +3dB

5. How is the phase curve affected at the zero frequency?
a. The phase is at 0 deg
b. The phase is at -90 deg
c. The phase is at +45 deg
d. The phase is at -45 deg

6. How is the phase curve affected at the pole frequency?
a. The phase is at 0 deg
b. The phase is at -90 deg
c. The phase is at +45 deg
d. The phase is at -45 deg

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Quiz: Bandwidth 1

7. What is the rate of change of the phase curve at frequencies near a pole?

a. The phase is at +45 deg/decade
b. The phase is at -45 deg/decade
c. The phase is at +90 deg/decade
d. The phase is at -90 deg/decade

8. What is the rate of change of the phase curve at frequencies near a zero?

a. The phase is at +45 deg/decade
b. The phase is at -45 deg/decade
c. The phase is at +90 deg/decade
d. The phase is at -90 deg/decade

9. What is the maximum phase shift introduced by a pole?

a. +90 deg
b. +180 deg
c. -90 deg
d. -180 deg

Quiz: Bandwidth 1

10. What is the maximum phase shift introduced by a zero?

a. +90 deg

b. +180 deg

c. -90 deg

d. -180 deg

11. What is the behavior of a capacitor at low frequencies?

a. Open

b. Short

c. Variable impedance

12. What is the behavior of a capacitor at high frequencies?

a. Open
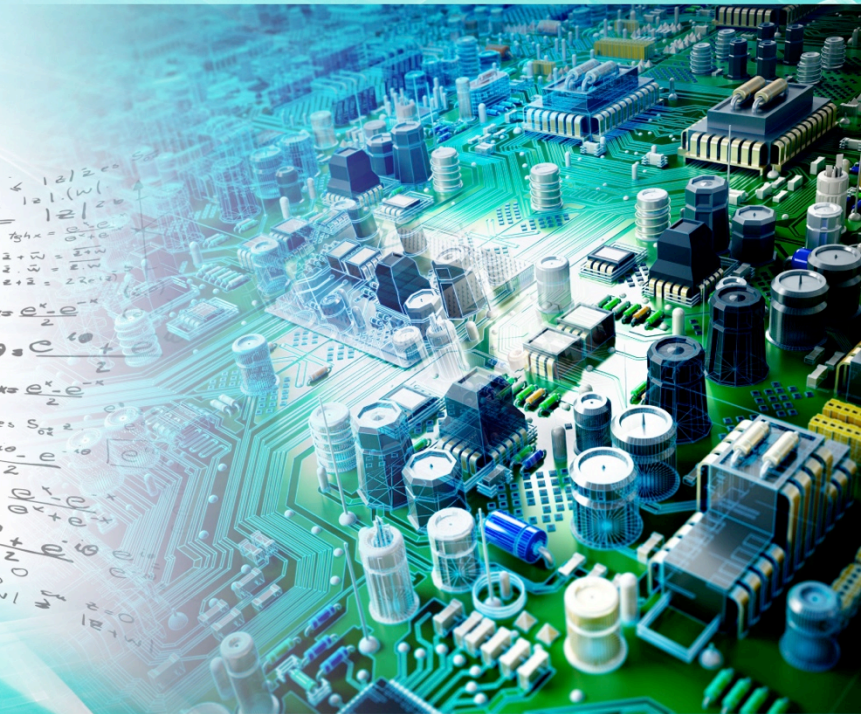
b. Short

c. Variable impedance

Quiz: Bandwidth 1

13. What effect does a phase shift have on a sinusoidal waveform?
a. It causes distortion
b. It reduces the amplitude
c. It increases the amplitude
d. It introduces a time delay

Bandwidth 1

Multiple Choice Quiz: Solutions

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Quiz: Bandwidth 1

1. Select the best description for a pole.
a. The root of the numerator causes the gain to decrease by 20 dB/decade
b. The root of the denominator causes the gain to increase by 20 dB/decade
c. The root of the numerator causes the gain to increase by 20 dB/decade
d. The root of the denominator causes the gain to decrease by 20 dB/decade

2. Select the best description for a zero.
a. The root of the numerator causes the gain to decrease by 20 dB/decade
b. The root of the denominator causes the gain to increase by 20 dB/decade
c. The root of the numerator causes the gain to increase b 20 dB/decade
d. The root of the denominator causes the gain to decrease by 20 dB/decade

3. How is the gain curve affected at the pole frequency?
a. The gain is attenuated by -20dB
b. The gain is attenuated by -3dB
c. The gain is increased by +20dB
d. The gain is increased by +3dB

Quiz: Bandwidth 1

4. How is the gain curve affected at the zero frequency?
a. The gain is attenuated by -20dB
b. The gain is attenuated by -3dB
c. The gain is increased by +20dB
d. The gain is increased by +3dB

5. How is the phase curve affected at the zero frequency?
a. The phase is at 0 deg
b. The phase is at -90 deg
c. The phase is at +45 deg
d. The phase is at -45 deg

6. How is the phase curve affected at the pole frequency?
a. The phase is at 0 deg
b. The phase is at -90 deg
c. The phase is at +45 deg
d. The phase is at -45 deg

Quiz: Bandwidth 1

7. What is the rate of change of the phase curve at frequencies near a pole?
a. The phase is at +45 deg/decade
b. The phase is at -45 deg/decade
c. The phase is at +90 deg/decade
d. The phase is at -90 deg/decade

8. What is the rate of change of the phase curve at frequencies near a zero?
a. The phase is at +45 deg/decade
b. The phase is at -45 deg/decade
c. The phase is at +90 deg/decade
d. The phase is at -90 deg/decade

9. What is the maximum phase shift introduced by a pole?
a. +90 deg
b. +180 deg
c. -90 deg
d. -180 deg

Quiz: Bandwidth 1

10. What is the maximum phase shift introduced by a zero?
a. +90 deg
b. +180 deg
c. -90 deg
d. -180 deg

11. What is the behavior of a capacitor at low frequencies?
a. Open
b. Short
c. Variable impedance

12. What is the behavior of a capacitor at high frequencies?
a. Open
b. Short
c. Variable impedance

Quiz: Bandwidth 1

13. What effect does a phase shift have on a sinusoidal waveform?
a. It causes distortion
b. It reduces the amplitude
c. It increases the amplitude
d. It introduces a time delay

Bandwidth 1
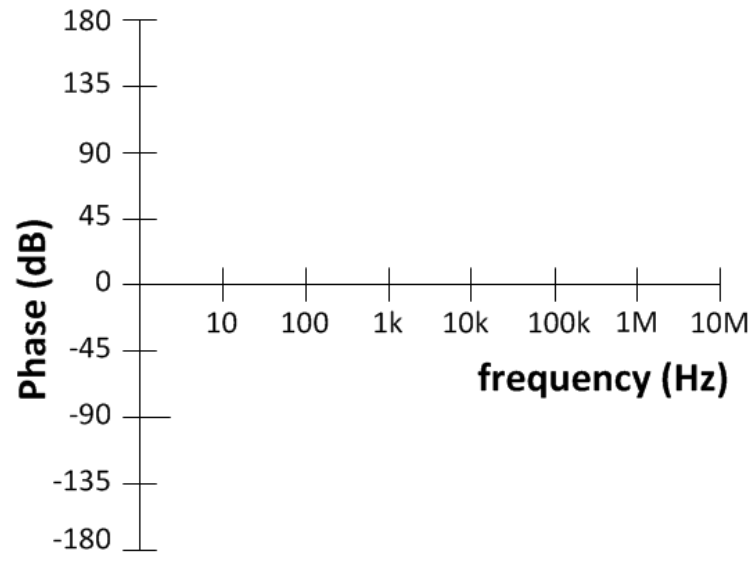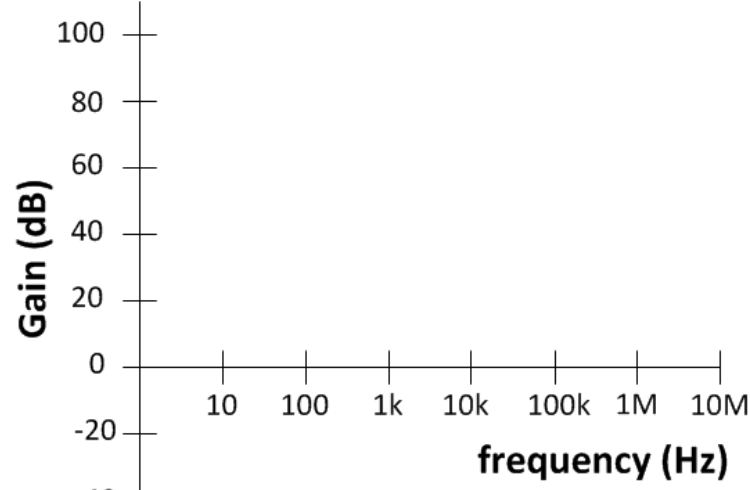
Exercises

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TEXAS INSTRUMENTS

1. Graph the gain and phase for the following circuit by hand (i.e. no simulation tools).

$$H(s) = 10000 \cdot \frac{\left(\dfrac{s}{2 \cdot \pi \cdot 10000} + 1\right)}{\left(\dfrac{s}{2 \cdot \pi \cdot 100} + 1\right)}$$

Gain (dB) vs frequency (Hz) plot — vertical axis from -60 to 100 dB, horizontal axis 10, 100, 1k, 10k, 100k, 1M, 10M.

Phase (dB) vs frequency (Hz) plot — vertical axis from -180 to 180, horizontal axis 10, 100, 1k, 10k, 100k, 1M, 10M.
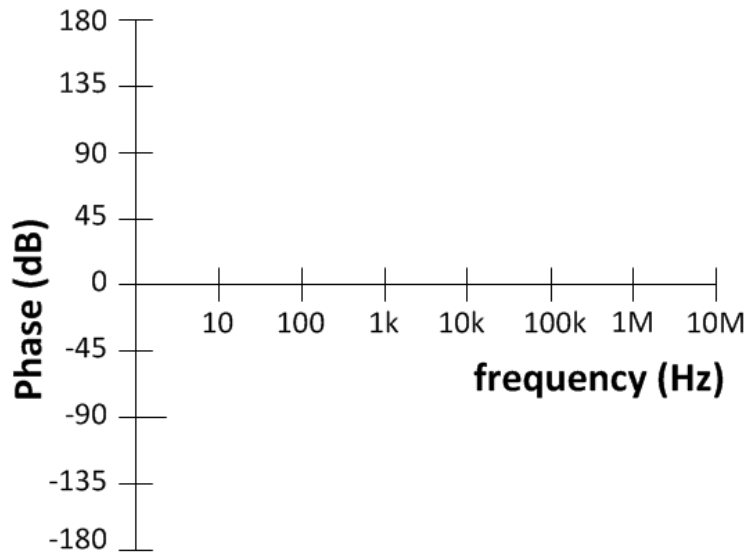
2. Graph the gain and phase for the following circuit by hand (i.e. no simulation tools).

$$H(s) = 100000 \frac{\left(\dfrac{s}{2 \cdot \pi \cdot 100000} + 1\right)}{\left(\dfrac{s}{2 \cdot \pi \cdot 100} + 1\right) \cdot \left(\dfrac{s}{2 \cdot \pi \cdot 1000} + 1\right)}$$
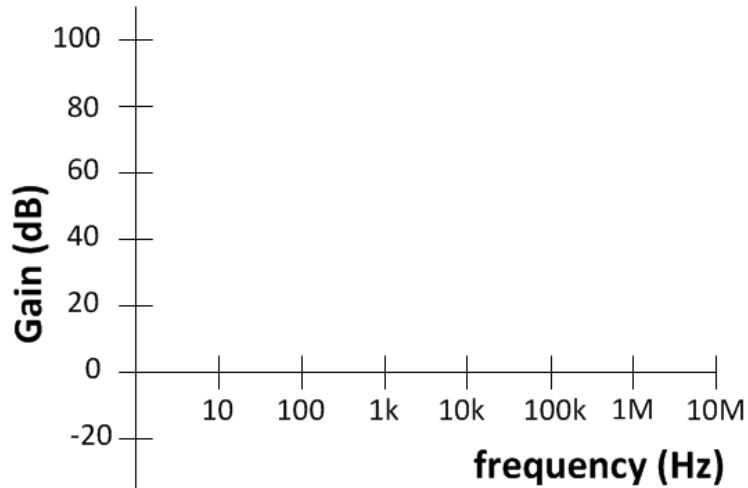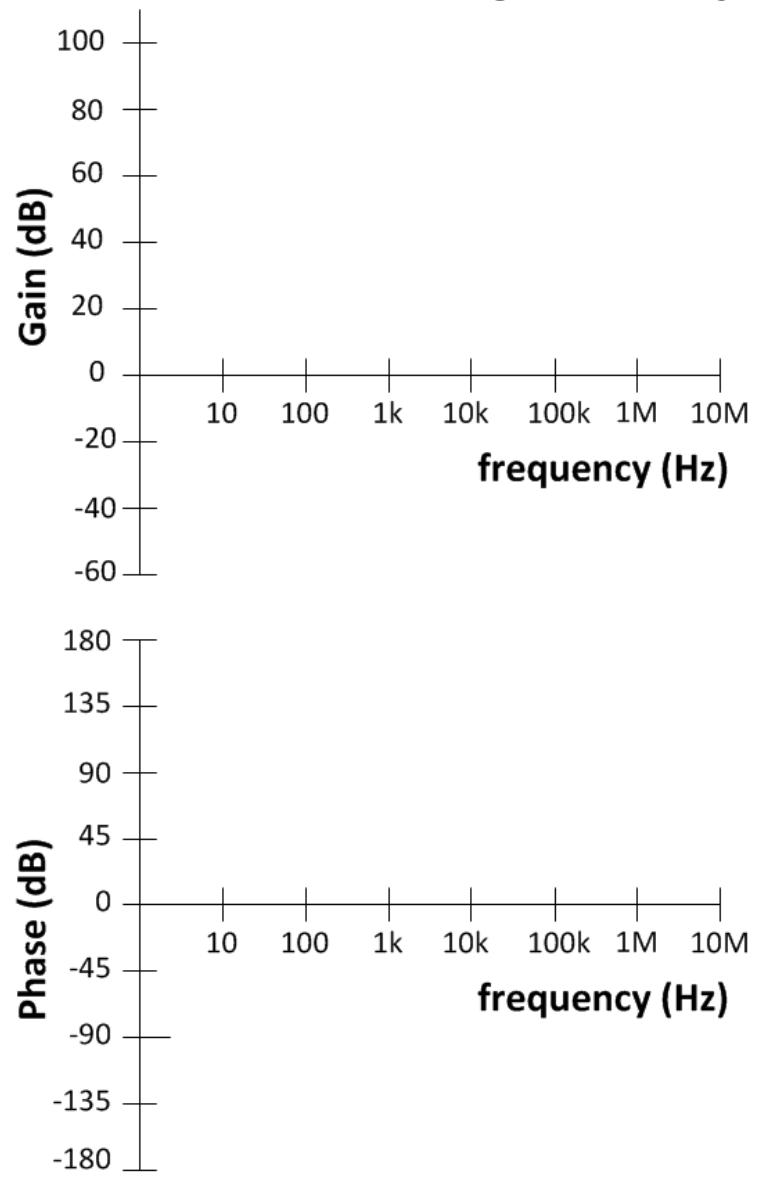
3. Graph the gain and phase for the following circuit by hand (i.e. no simulation tools).

$$H(s) = 1000 \frac{\left(\dfrac{s}{2\cdot\pi\cdot100000} + 1\right)}{\left(\dfrac{s}{2\cdot\pi\cdot100} + 1\right)\cdot\left(\dfrac{s}{2\cdot\pi\cdot10000} + 1\right)}$$

Gain (dB) vs **frequency (Hz)**

Gain axis: 100, 80, 60, 40, 20, 0, -20, -40, -60
Frequency axis: 10, 100, 1k, 10k, 100k, 1M, 10M

Phase (dB) vs **frequency (Hz)**

Phase axis: 180, 135, 90, 45, 0, -45, -90, -135, -180
Frequency axis: 10, 100, 1k, 10k, 100k, 1M, 10M

4. Simulate the circuit below. Calculate the poles in this circuit considering that R1 and C1 are not significantly loaded by R2 and C2. Check the agreement between simulation and calculation.

TEXAS INSTRUMENTS

Bandwidth 1
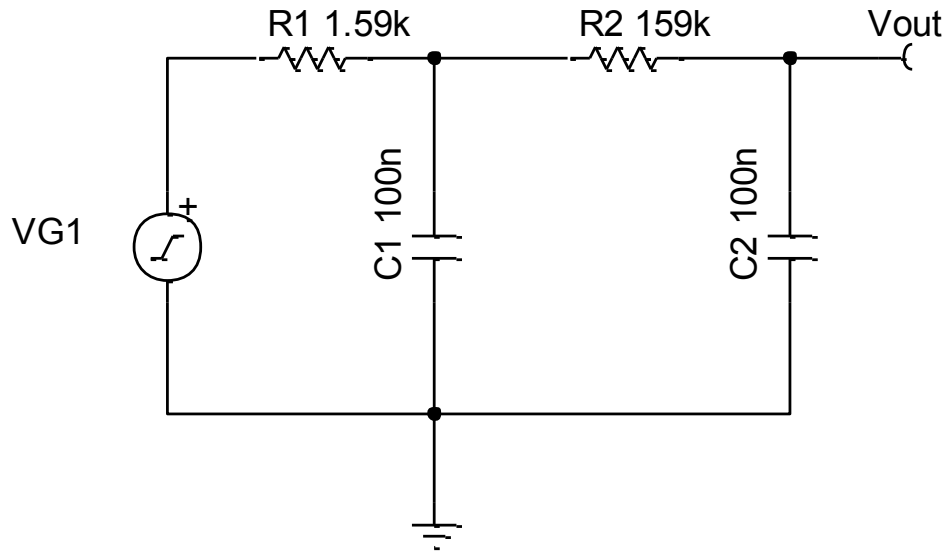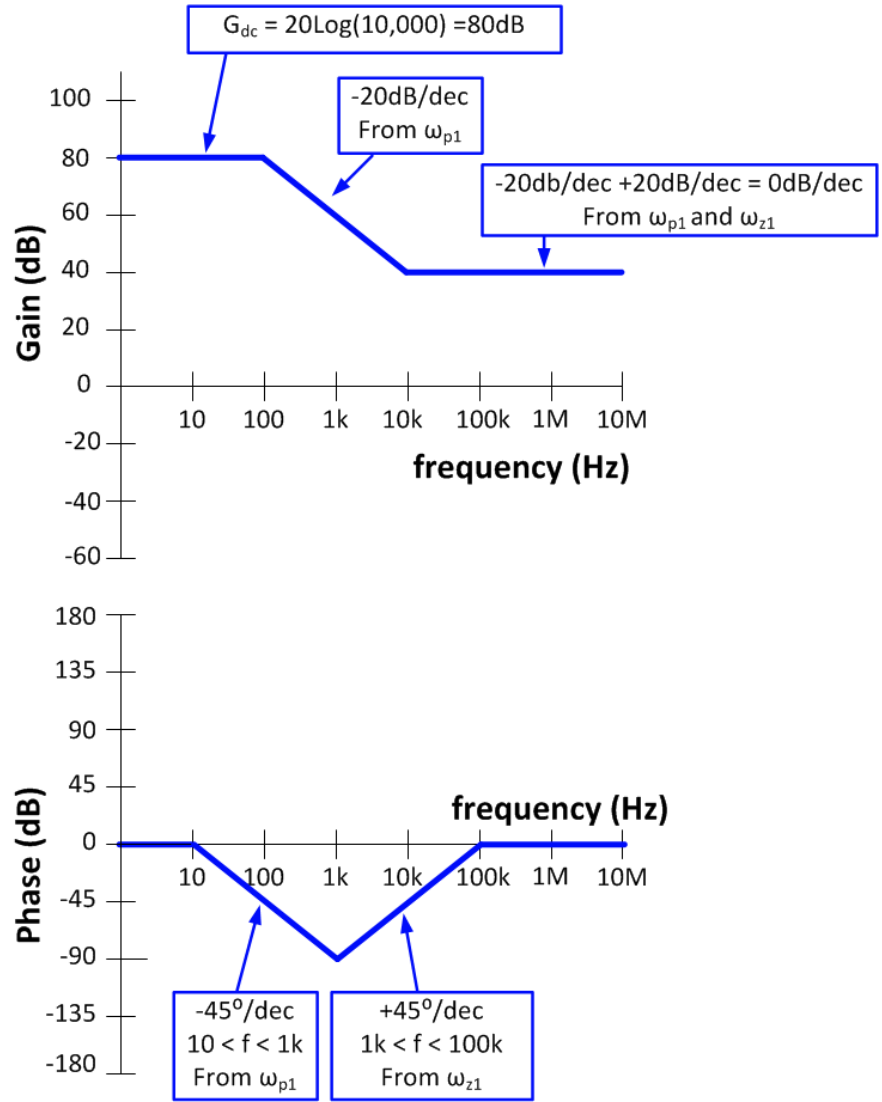
Solutions

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1. Graph the gain and phase for the following circuit by hand (i.e. no simulation tools).

$$H(s) = 10000 \frac{\left(\dfrac{s}{2 \cdot \pi \cdot 10000} + 1\right)}{\left(\dfrac{s}{2 \cdot \pi \cdot 100} + 1\right)} = G_{dc} \cdot \frac{\left(\dfrac{s}{\omega_{z1}} + 1\right)}{\left(\dfrac{s}{\omega_{p1}} + 1\right)}$$

G_{dc} = 20Log(10,000) =80dB

-20dB/dec
From ω_{p1}

-20db/dec +20dB/dec = 0dB/dec
From ω_{p1} and ω_{z1}

Gain (dB)

frequency (Hz)

Phase (dB)

frequency (Hz)

-45°/dec
10 < f < 1k
From ω_{p1}

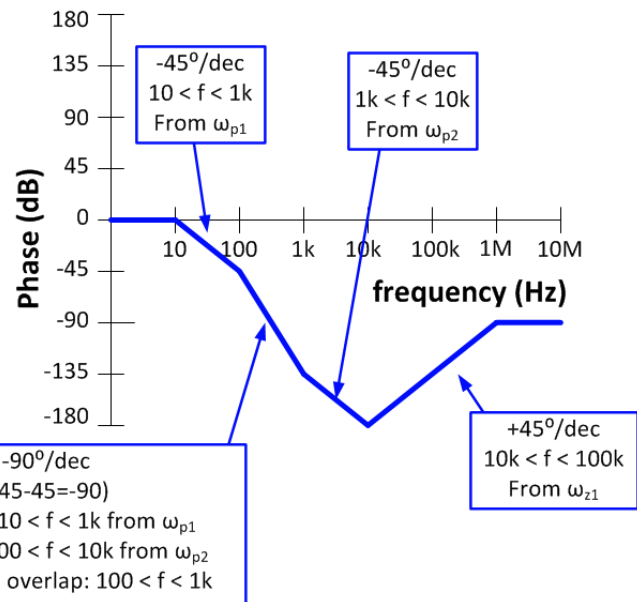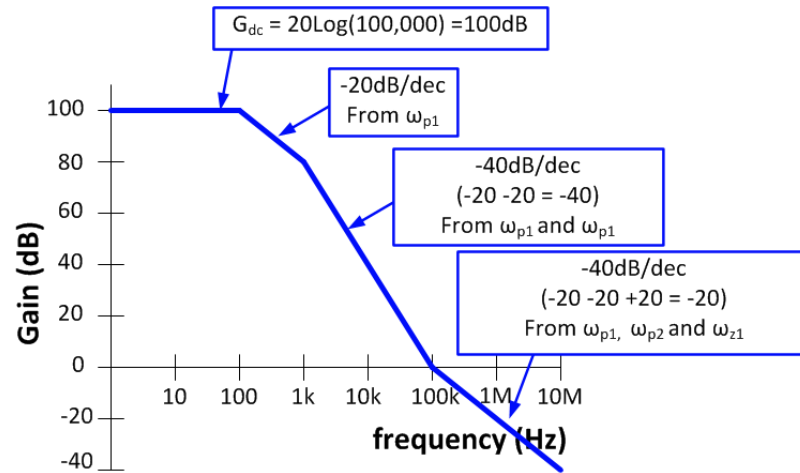+45°/dec
1k < f < 100k
From ω_{z1}

2. Graph the gain and phase for the following circuit by hand (i.e. no simulation tools).

$$H(s) = 100000 \frac{\left(\dfrac{s}{2 \cdot \pi \cdot 100000} + 1\right)}{\left(\dfrac{s}{2 \cdot \pi \cdot 100} + 1\right) \cdot \left(\dfrac{s}{2 \cdot \pi \cdot 1000} + 1\right)}$$

$G_{dc} = 20Log(100,000) = 100dB$

-20dB/dec
From ω_{p1}

-40dB/dec
(-20 -20 = -40)
From ω_{p1} and ω_{p1}

-40dB/dec
(-20 -20 +20 = -20)
From ω_{p1}, ω_{p2} and ω_{z1}

Gain (dB) axis: 100, 80, 60, 40, 20, 0, -20, -40
frequency (Hz): 10, 100, 1k, 10k, 100k, 1M, 10M

-45°/dec
10 < f < 1k
From ω_{p1}

-45°/dec
1k < f < 10k
From ω_{p2}

+45°/dec
10k < f < 100k
From ω_{z1}

Phase (dB) axis: 180, 135, 90, 45, 0, -45, -90, -135, -180
frequency (Hz): 10, 100, 1k, 10k, 100k, 1M, 10M

-90°/dec
(-45-45=-90)
-45°/dec, 10 < f < 1k from ω_{p1}
-45°/dec, 100 < f < 10k from ω_{p2}
ω_{p1} and ω_{p2} overlap: 100 < f < 1k

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TEXAS INSTRUMENTS

3. Graph the gain and phase for the following circuit by hand (i.e. no simula

$$H(s) = 1000 \frac{\left(\dfrac{s}{2 \cdot \pi \cdot 100000} + 1\right)}{\left(\dfrac{s}{2 \cdot \pi \cdot 100} + 1\right)\left(\dfrac{s}{2 \cdot \pi \cdot 10000} + 1\right)} = G_{dc} \cdot \frac{\left(\dfrac{s}{\omega_{z1}} + 1\right)}{\left(\dfrac{s}{\omega_{p1}} + 1\right)\left(\dfrac{s}{\omega_{p2}} + 1\right)}$$
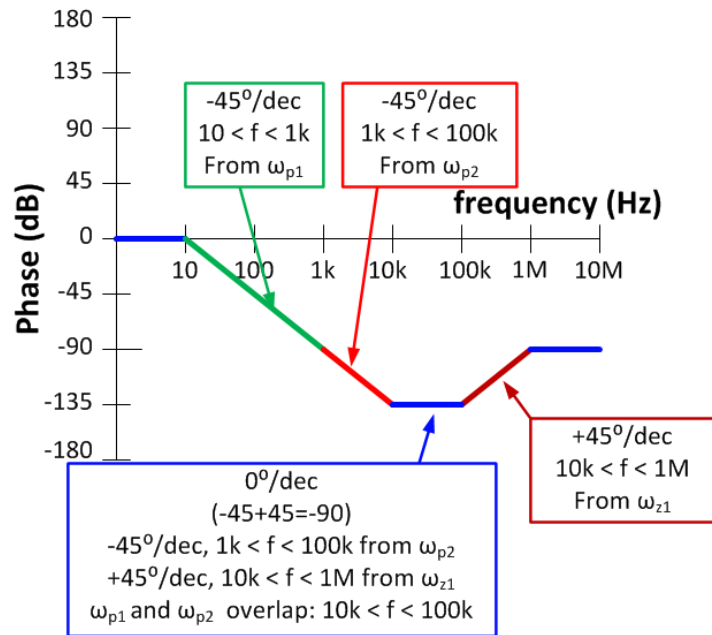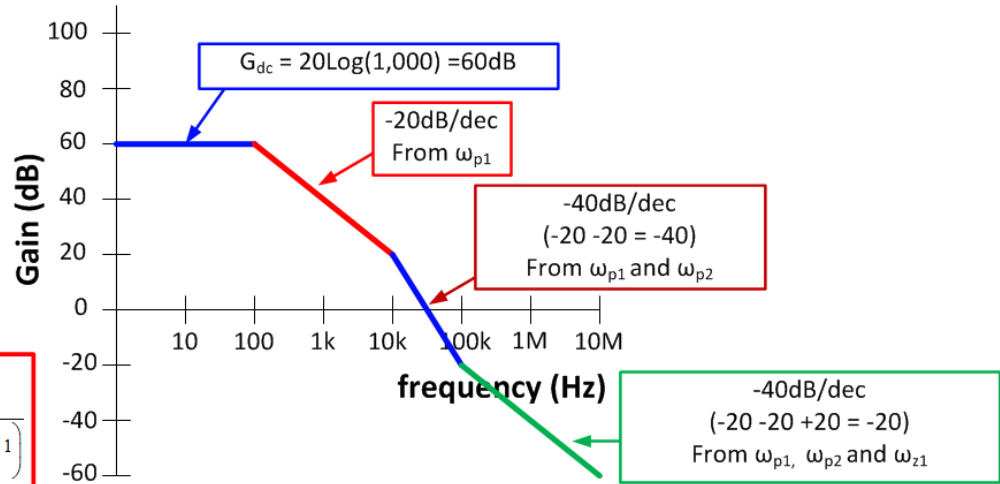

Gain plot annotations:
- $G_{dc} = 20\log(1{,}000) = 60\text{dB}$
- -20dB/dec From ω_{p1}
- -40dB/dec (-20 -20 = -40) From ω_{p1} and ω_{p2}
- -40dB/dec (-20 -20 +20 = -20) From $\omega_{p1,}$ ω_{p2} and ω_{z1}

Phase plot annotations:
- -45°/dec, 10 < f < 1k, From ω_{p1}
- -45°/dec, 1k < f < 100k, From ω_{p2}
- +45°/dec, 10k < f < 1M, From ω_{z1}
- 0°/dec (-45+45=-90), -45°/dec, 1k < f < 100k from ω_{p2}, +45°/dec, 10k < f < 1M from ω_{z1}, ω_{p1} and ω_{p2} overlap: 10k < f < 100k
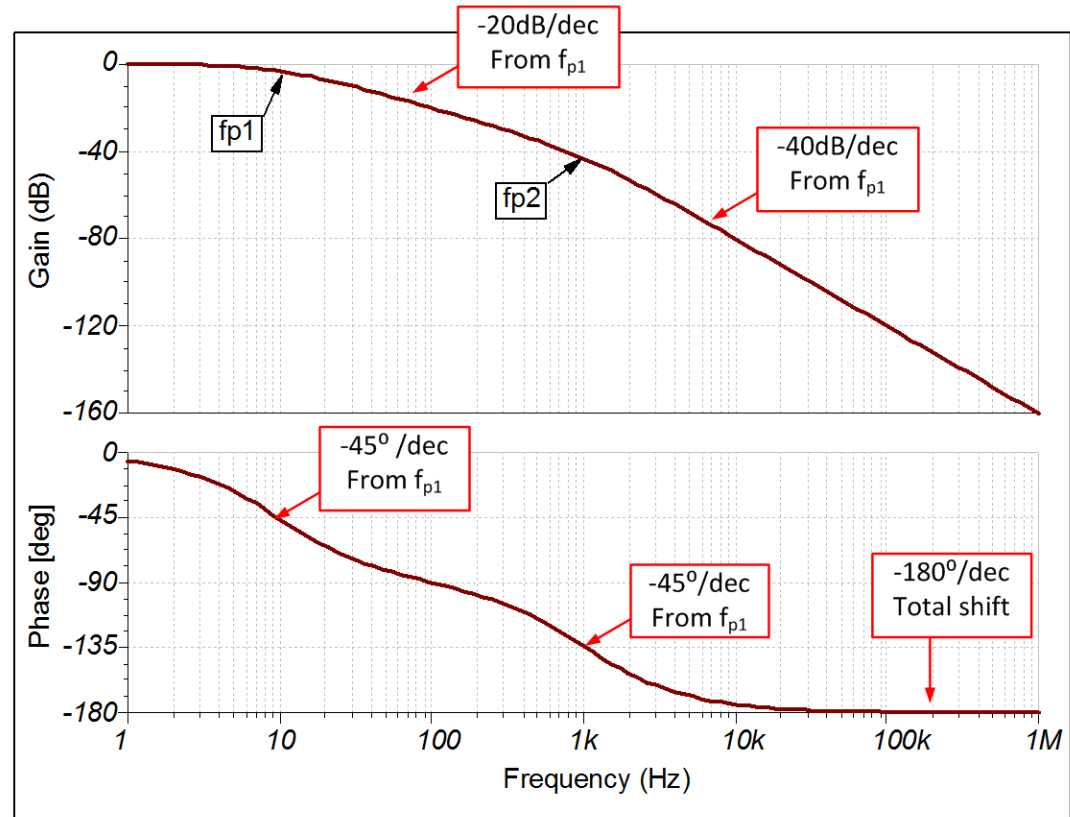
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TEXAS INSTRUMENTS

4. Simulate the circuit below. Calculate the poles in this circuit considering that R1 and C1 are not significantly loaded by R2 and C2. Check the agreement between simulation and calculation.
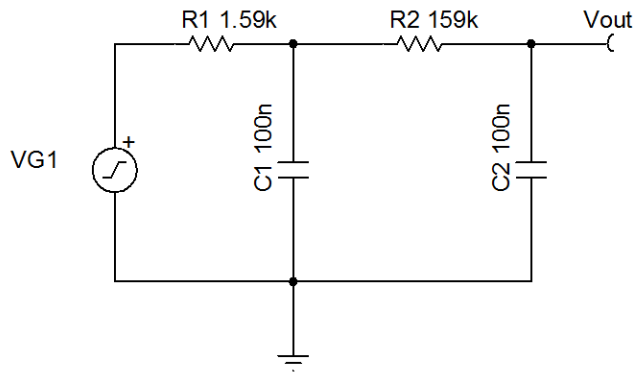
$$f_{p1} = \frac{1}{2 \cdot \pi \cdot 159k\Omega \cdot .1\mu F} = 10Hz$$

$$f_{p2} = \frac{1}{2 \cdot \pi \cdot 1.59k\Omega \cdot .1\mu F} = 1kHz$$

TEXAS INSTRUMENTS