Hello, and welcome to the TI Precision Lab discussing op amp bandwidth, part 4.

In this video we'll cover 5 bandwidth related topics:

First, a deeper look at how the slope of the Aol curve affects gain bandwidth

Second, How an op amps input capacitance can limit the bandwidth.

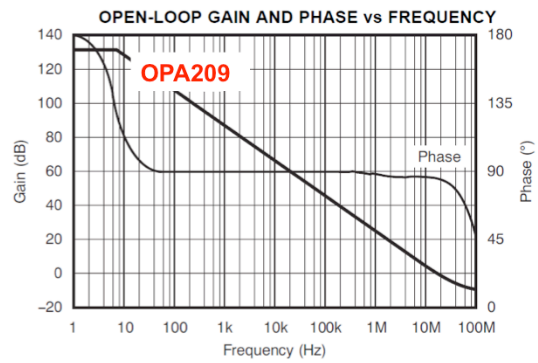
Third, How to calculate the practical gain verses frequency for amplifier circuits

Fourth, How to limit the bandwidth of a circuit on purpose using a feedback capacitor

And finally How slew rate can affect the response over frequency.

Gain Bandwidth Changes

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
Gain Bandwidth Product	GBW	Gain = +1		18		MHz



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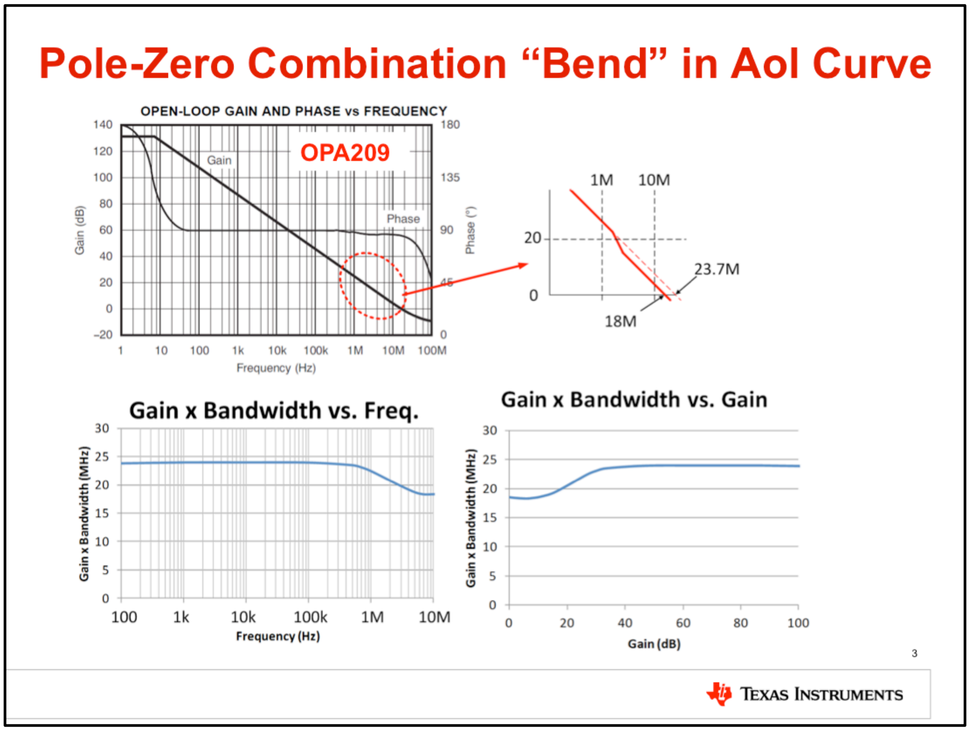
TEXAS INSTRUMENTS

At this point we have discussed the gain bandwidth product in great detail. We know that it is only valid where the slope of the Aol curve is -20dB/decade. Unfortunately, sometimes it is not obvious whether the gain bandwidth product is valid or not.

Here we have the gain bandwidth product specification from the OPA209 data sheet. The typical gain bandwidth product is listed as 18MHz given that the gain is 1V/V. But, what about other closed loop gains?

Here we have the open loop gain and phase curves versus frequency from the data sheet. The open loop gain curve appears to be linear and decreasing at a constant rate of -20dB/decade. Thus, one might assume that the gain bandwidth product is valid for all gain. However, simulation and real-world measurements will show that such an assumption is incorrect. Why?

Original:
Looking at the specifications table, you can see that the typical gain bandwidth product is 18MHz. Notice that the test condition is for a closed loop gain of +1. What about other closed loop gains? Looking at the open loop gain curve, the curve appears to be linear and decreasing at a rate of -20dB/decade. Thus, you might assume that the Gain Bandwidth Product is valid for all gains. However, simulation and real world measurement will show that this isn't true. Why is that?



Previously we assumed that the open loop gain curve had a constant slope of -20dB/decade. However, we find that there is a small bend in the Aol curve between 1MHz and 10MHz due to a pole-zero pair. A pole near 1MHz causes the open loop gain to decrease greater than -20dB/decade over a small range of frequency, but the pole is then quickly cancelled by a zero. Due to the logarithmic scale, it is not possible to see this small bend in the Aol curve. As a matter of fact, the bend is probably smaller than the thickness of the line in the curve. Zooming in on the bend in the curve you will notice that the gain bandwidth is 18MHz at the specified gain of 1V/V, but increases to 23.7MHz for closed-loop gains greater than 20dB.

While the bend in the Aol curve is difficult, if not impossible to see, the pole-zero pair is more apparent in the phase curve. Notice the dip in the phase curve near 1MHz. This is due to the pole-zero pair. Therefore it is recommended that one always inspect the phase curve in addition to the gain curve in an op amp data sheet.

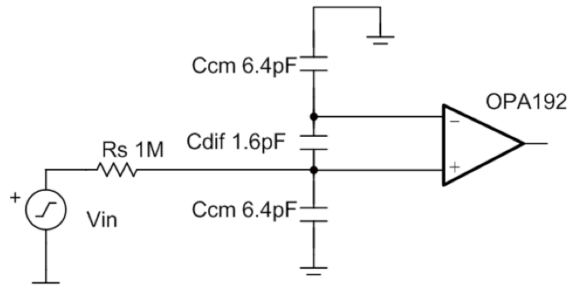
These two curves depict how the gain bandwidth product changes with frequency and closed-loop gain. Notice that at a closed-loop gain of 0dB, or 1V/V, the gain bandwidth product is 18MHz as stated in the data sheet. As the closed-loop gain increases, the bandwidth increases to 23.7MHz.

Ultimately there are three lessons to learn from this discussion:

First, it is not unusual to see some deviation in gain bandwidth for different closed loop gains and that the amount of deviation will vary depending on the amplifier.

Input Capacitance

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNIT
Z_{ID} Differential			100||1.6		MΩ||pF
Z_{IC} Common-mode			1||6.4		10^{13}Ω||pF



$$f_c = \frac{1}{2\cdot\pi\cdot R_{in}\cdot C_{cm}} = \frac{1}{2\cdot\pi\cdot(1M\Omega)\cdot(6.4pF)} = 24.87kHz$$

4

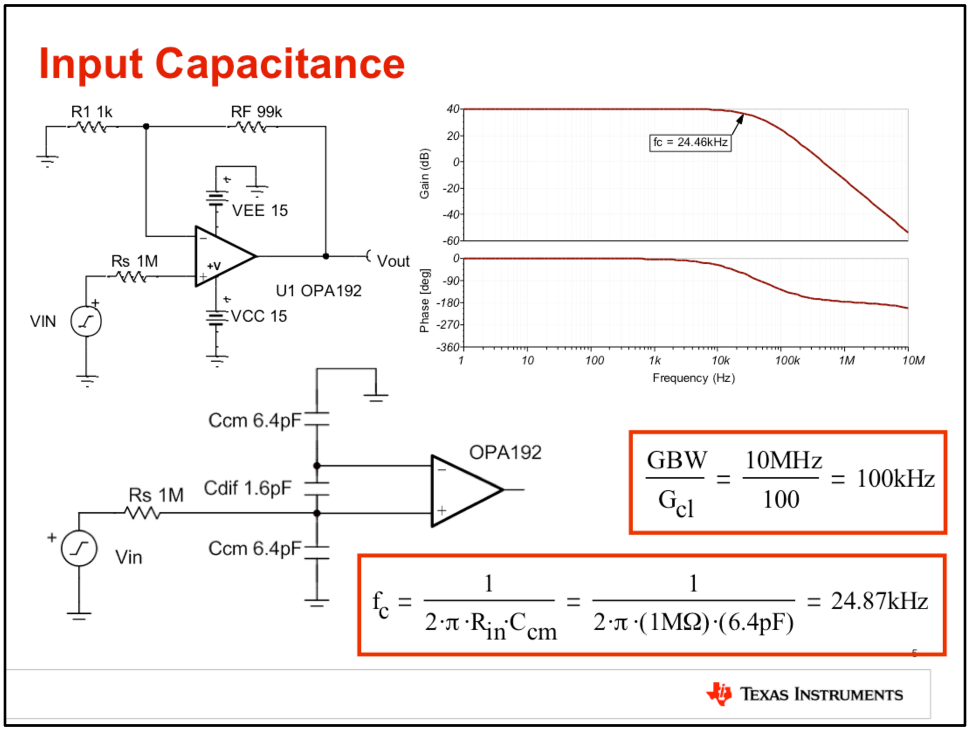
Texas Instruments

Up to this point we have seen how the op amp's gain bandwidth limitation sets the bandwidth. However, in some cases other factors can effect bandwidth. This slide focuses on the effect of input capacitance on bandwidth.

All op amps will have a differential and common mode input capacitance and impedance. This parasitic capacitance is from the semiconductor junctions on the input stage transistors. The differential capacitance is connected between to two inputs and the common mode capacitance is connected on each input with respect to ac ground.

The table at the top of the slide shows how input capacitance is typically specified. In this example the differential capacitance is 1.6pF and the common mode capacitance is 6.4pF. These input capacitances are relatively small, so it is unlikely that you will see bandwidth limitations unless the input signal source has a large series resistance.

In this example, the source resistance is 1Mohms, which is relatively large. The source resistance and common mode input capacitance form a low pass filter. The corresponding cutoff frequency is calculated to be 24.87kHz. Notice that the differential capacitance and the common mode capacitance on the inverting input are not included in the bandwidth calculation. This is because the op-amp feedback eliminates these capacitances. The input capacitance is part of TI's op amp macro models, so let's take a look at simulation results.



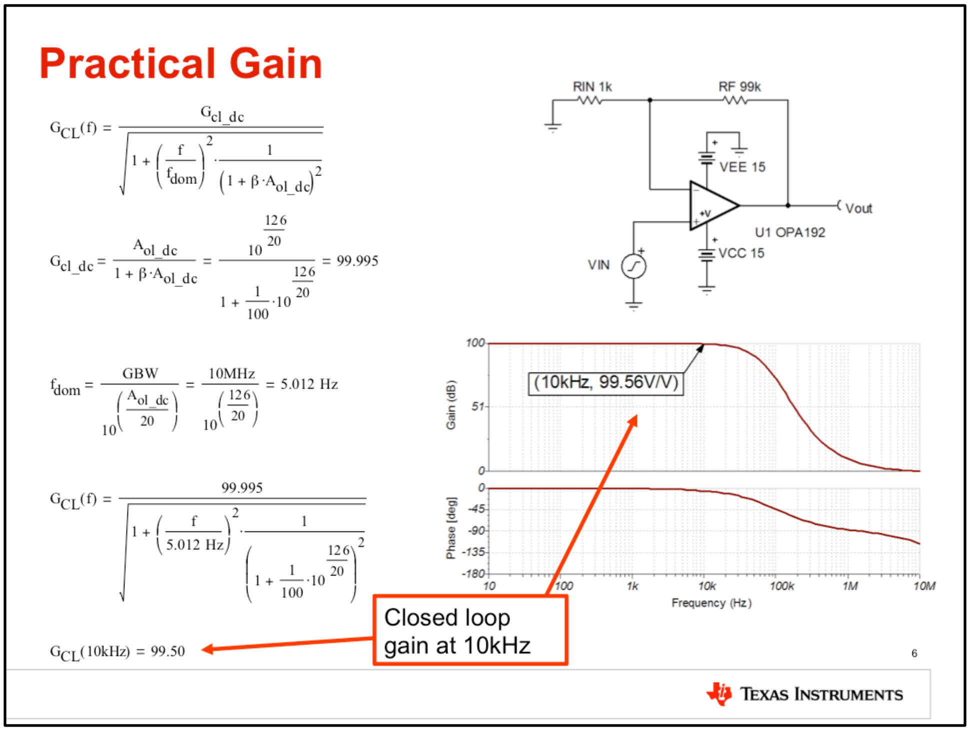
$$\frac{GBW}{G_{cl}} = \frac{10MHz}{100} = 100kHz$$

$$f_c = \frac{1}{2 \cdot \pi \cdot R_{in} \cdot C_{cm}} = \frac{1}{2 \cdot \pi \cdot (1M\Omega) \cdot (6.4pF)} = 24.87kHz$$

This slide shows an ac transfer characteristic sweep for the OPA192. Based on the gain bandwidth of the device and the circuit's closed loop gain of 100V/V, we expect 100kHz of bandwith.

Our simulation, however, yields a bandwidth of 24.46kHz. This discrepancy is due to the low pass filter formed by the 1Mohm source resistance and the 6.4pF common mode input capacitance.

In this example the hand calculated bandwidth of 24.87kHz correlates with the simulated bandwidth of 24.6kHz.



Now let's discuss how to calculate the practical gain of an op amp circuit.

It is often assumed that the closed loop gain of an amplifier circuit is constant until it starts to roll off at the cutoff frequency. In reality the closed loop gain begins to decrease long before the cutoff frequency. The error introduced by this attenuation is usually unexpected.

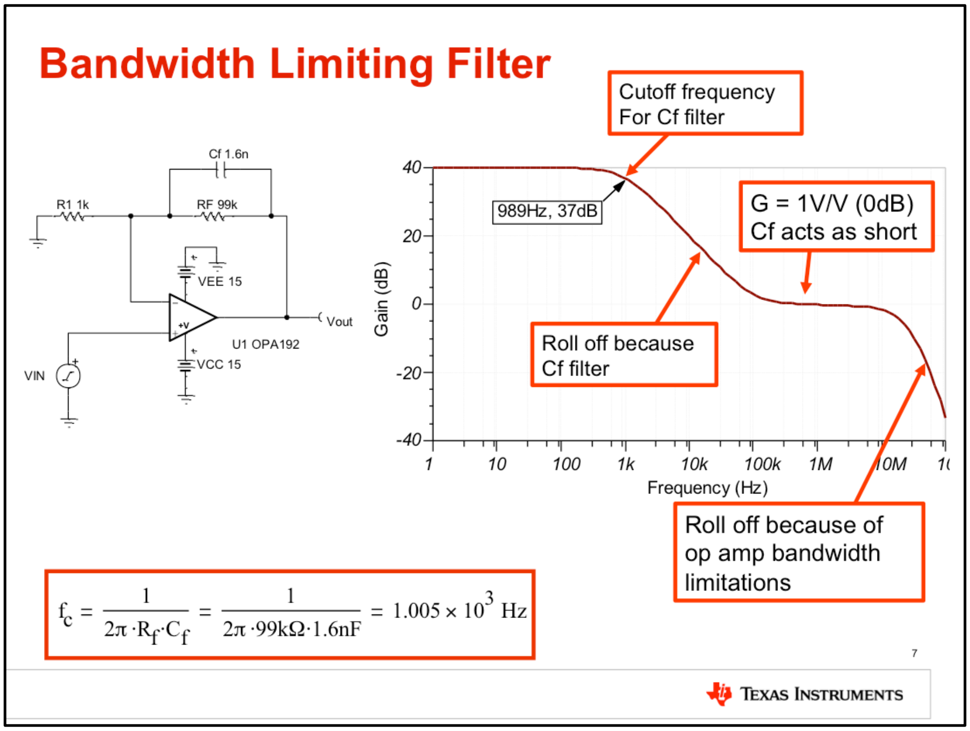
The closed loop gain at any frequency can be calculated using this equation, where

f is frequency
Gcl_dc is the dc closed loop gain
fdom is the dominant pole
beta is the feedback factor
and Aol_dc is the dc open loop gain.

Let's use this equation and apply it to this OPA192 circuit.

The closed loop dc gain is calculated using 126dB, which is the Aol specification from the OPA192 data sheet, and the feedback factor, or beta, from the OPA192 circuit.

The dominant pole is calculated using this equation, which was given in a previous



So far we have considered internal op amp specifications such as gain bandwidth and input capacitance when determining a circuits bandwidth. In some cases it is desirable to use external components to limit bandwidth.

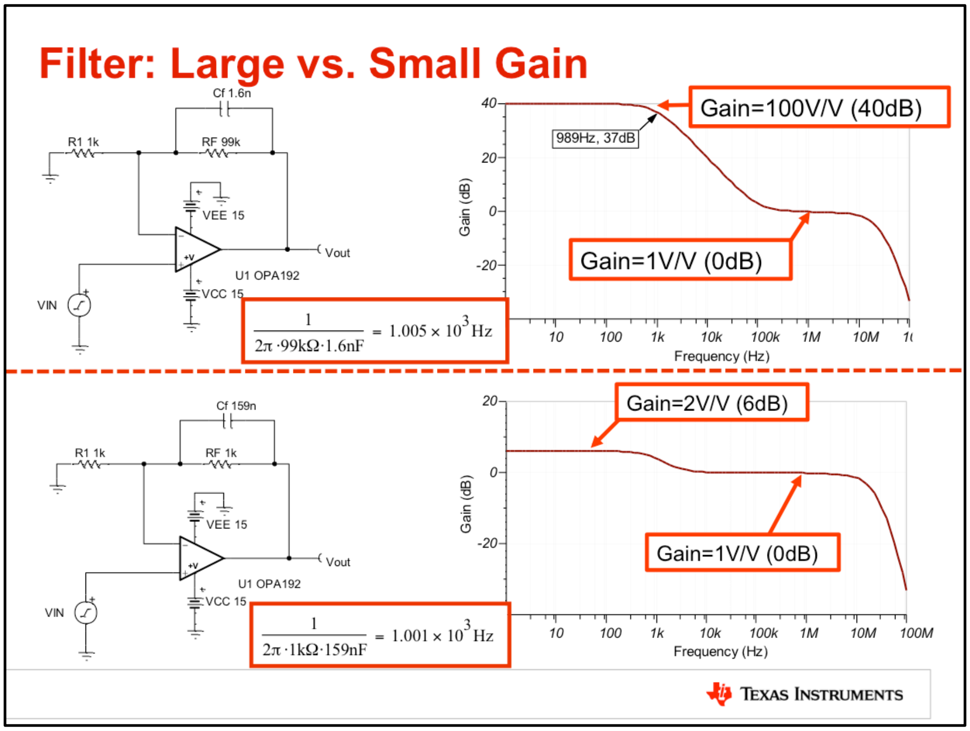
One approach is to use active filters, which use complex R-C combinations to create very effective filters. Active filters will be discussed in a separate series of videos.

A simpler method for limiting a circuit's bandwidth is by placing a capacitor in the feedback path. For this analysis it is best to think of the capacitor as an open circuit for low frequencies and a short circuit at high frequencies.

At low frequencies you can ignore the capacitor in this circuit so the gain will be 100V/V or 40dB. At high frequencies the capacitor will short the 99kohm resistor, so the amplifier circuit will have a gain of 1V/V, or 0dB.

Between the low and high frequencies, the gain will roll off at a rate of -20dB/decade. Note that at very high frequencies the gain will roll off further because of the amplifier's bandwidth limitations.

Note that the cutoff frequency of the filter is set by the feedback capacitor and feedback resistor. The calculated value is 1.005kHz, which correlates well with the



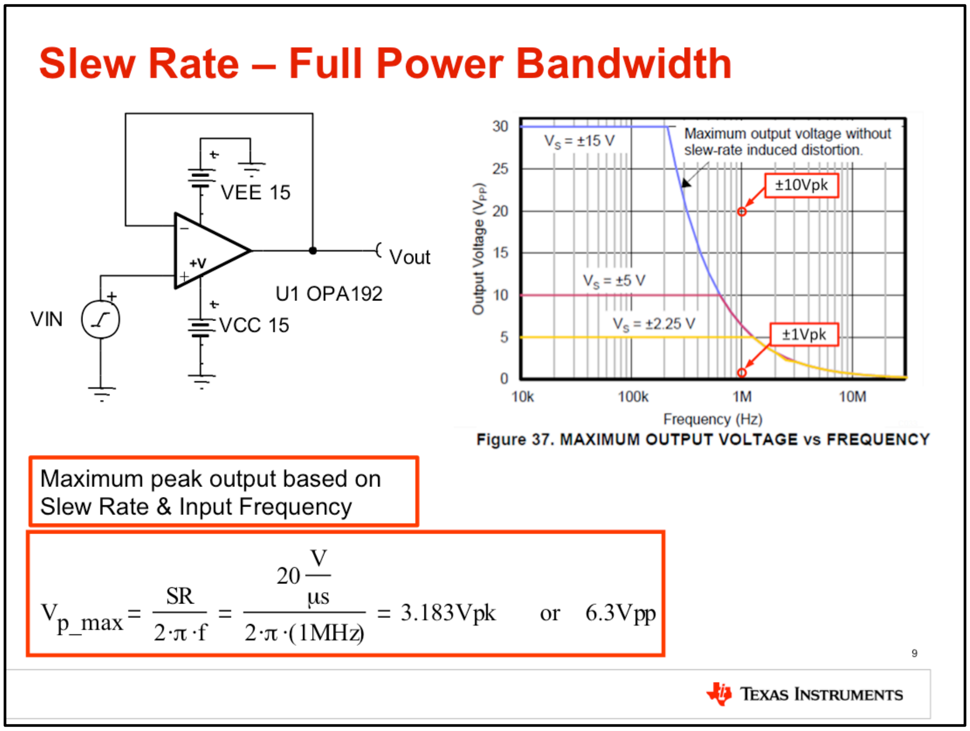
This slide compares how the feedback capacitor filter works for amplifiers in high and low gain. In both cases the cutoff frequency is set to the same value.

As mentioned before, at high frequency the feedback capacitor filter effectively shorts the feedback resistor which forces that gain to 1V/V. So, the feedback capacitor filter will always reduce the gain from the dc value to one.

Thus the maximum attenuation of the filter equal the dc gain. In the case of the high gain circuit the gain is attenuated from 100V/V to 1V/V, or 40dB.

The low gain circuit, however, only attenuates the gain by 6dB.

The point is that a feedback capacitor filter is most effective for high gain circuits. If you need an effective filter for low gain circuits, you should probably look into active filters. In general, active filters are more effective than a feedback capacitor filter, but the feedback capacitor filters are popular because they are simple and inexpensive.



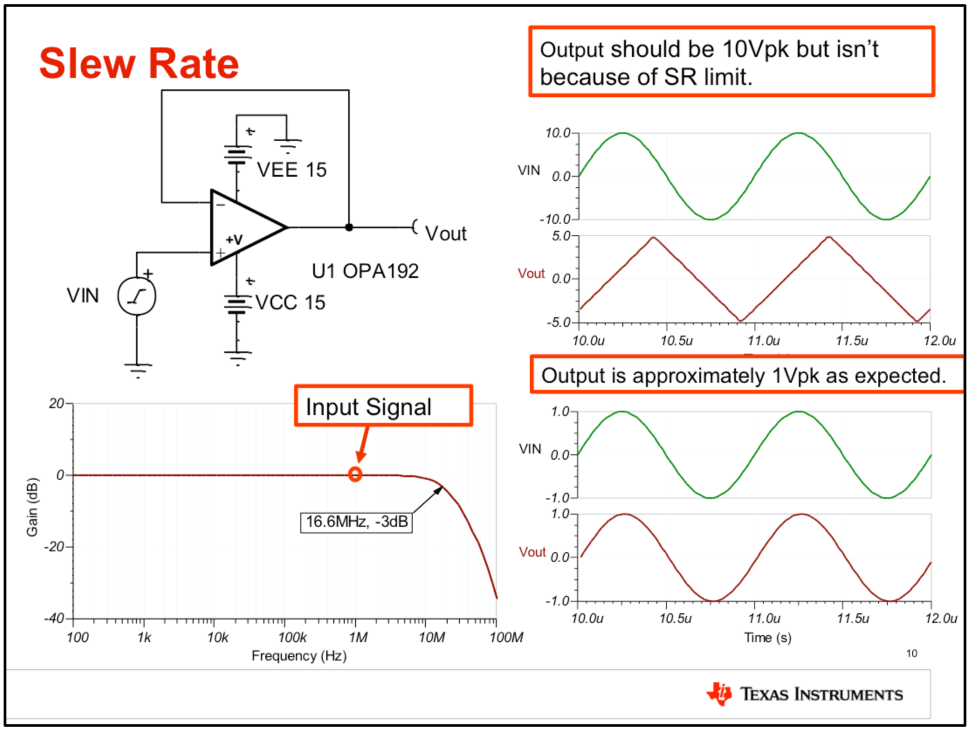
Finally, let's discuss slew rate and full power bandwidth.

The slew rate of an op amp is the maximum rate of change of the output signal. If you're interested in learning about the details of slew rate, please view the slew rate video series.

The slew rate of a device can affect how an op amp behaves over frequency, and this effect can be misinterpreted as a bandwidth limitation. In fact the maximum output voltage vs. frequency depends on slew rate and is often called full power bandwidth.

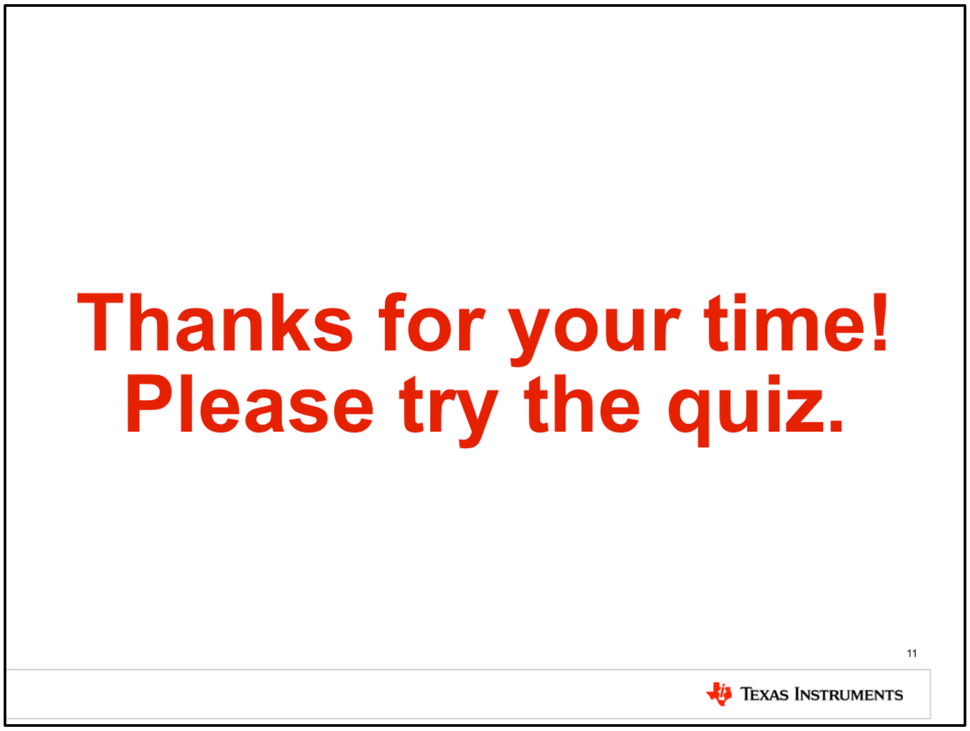
Let's look at how the full power bandwidth affects two different signals applied to the opa192 unity gain follower. The graph of the "Maximum Output Voltage vs. Frequency" tells what maximum undistorted peak-to-peak output can be achieved at a given frequency. For example, let's apply a 1Vpk signal at a frequency of 1MHz. This signal is well below the maximum output limitation, so there should not no distortion. However, a 10Vpk signal at a frequency of 1MHz is outside the full-power bandwidth, so the signal will be distorted.

Now let's look at a time domain simulation to see how the output is affected in both cases.



This slide shows the opa192 output with a 10Vpk and 1Vpk input at 1MHz. Notice that the output for a 1Vpk input is 1Vpk as expected. Also, the 1Vpk output does not appear distorted. The output for the 10Vpk input, however, is 5Vpk and appears very distorted. In fact the output looks more like a triangle wave than a sinusoidal wave. This is often the case for amplifiers that are in slew rate limit. These results makes sense based on the full power bandwidth graph on the previous slide.

One final thing to notice is that the input signal is well inside the bandwidth of the OPA192 buffer. Sometimes attenuation of the output signal cause by slew rate limitation is incorrectly interpreted as a bandwidth limitation. To avoid this problem, always make sure that your output signal amplitude does not violate the "maximum output vs. frequency".



In summary, this video discussed how the slope of the Aol curve affects gain bandwidth, op amp input capacitance, calculating the practical gain of a circuit, slew rate limitations, and some simple ways to implement an op amp filter.

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

Bandwidth 4

Multiple Choice Quiz

TI Precision Labs – Op Amps

Quiz: Bandwidth 4

1. (T/F) A second pole in the Aol curve can cause deviation in the gain bandwidth product.

a. True
b. False

2. Deviation in the ____ can help identify small bends in the Aol curve that may not be obvious otherwise.

a. dc Aol
b. Phase shift
c. Slew rate
d. Input capacitance

3. The input capacitance of an op amp can affect bandwidth if____.

a. The amplifiers gain bandwidth product is high.
b. The amplifiers slew rate is low.
c. A large source resistance is connected in series with the input.
d. The amplifier is an zero drift type amplifier.

Quiz: Bandwidth 4

4. (T/F) The gain of an amplifier is constant until you reach the cutoff frequency.

a. True
b. False

5. (T/F) The Cf filter is most effective for amplifiers in low gain.

a. True
b. False

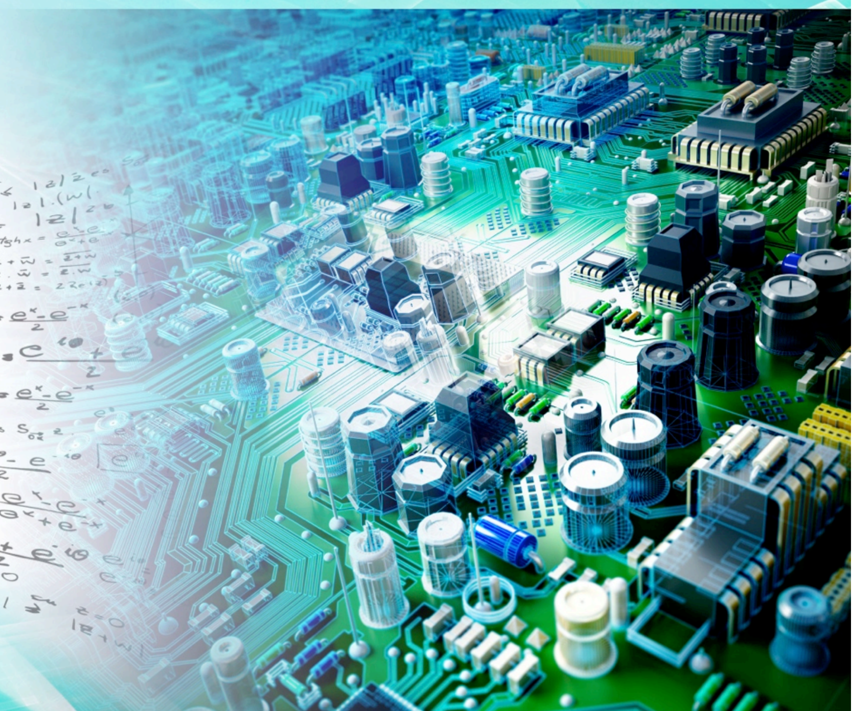
6. Assume a sinusoidal waveform is applied to the input of an amplifier. What could cause the output to look like a triangle wave?

a. Slew-induced distortion
b. Bandwidth limitation
c. The input capacitance and source resistance create a low pass filter.
d. Output swing limitations.

Bandwidth 4

Multiple Choice Quiz: Solutions

TI Precision Labs – Op Amps



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Quiz: Bandwidth 4

4. (T/F) The gain of an amplifier is constant until you reach the cutoff frequency.

a. True
b. False

5. (T/F) The Cf filter is most effective for amplifiers in low gain.

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b. False

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a. Slew-induced distortion
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c. The input capacitance and source resistance create a low pass filter.
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Bandwidth 4

Exercises

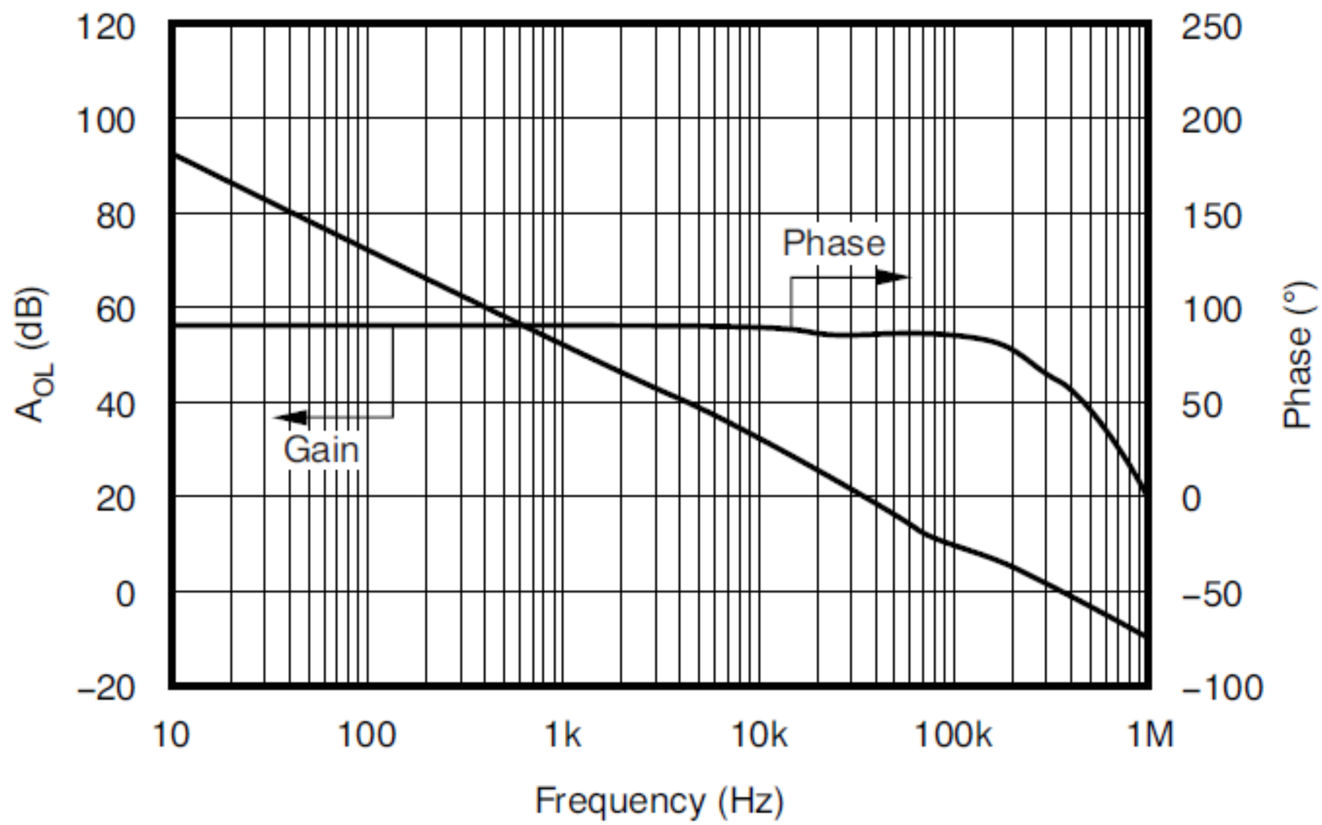
TI Precision Labs – Op Amps

1. Find gain x bandwidth at Aol = 0dB, 20dB, 40dB, and 60dB.

ELECTRICAL CHARACTERISTICS: V_S = +1.8 V to +5.5 V

At T_A = +25°C, R_L = 10 kΩ connected to V_S / 2, V_{CM} = V_S / 2, and V_{OUT} = V_S / 2, unless otherwise noted.

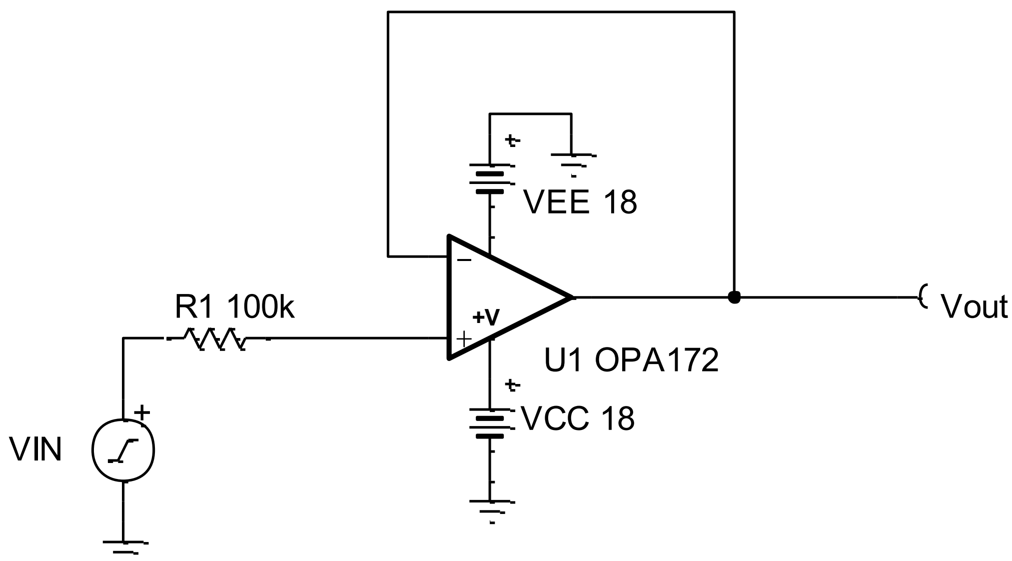
PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
FREQUENCY RESPONSE						
GBW	Gain-bandwidth product	C_L = 100 pF		350		kHz
SR	Slew rate	G = +1		0.16		V/μs



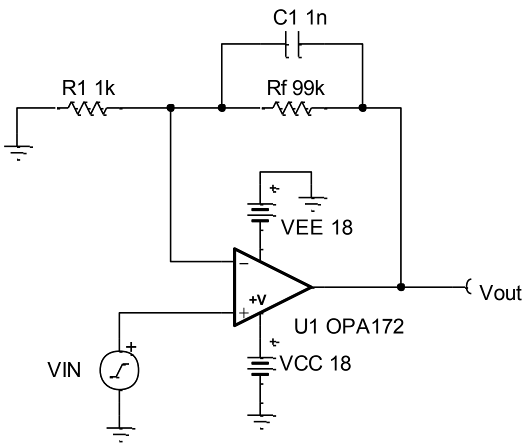
2. Calculate and simulate the bandwidth for the circuit below.

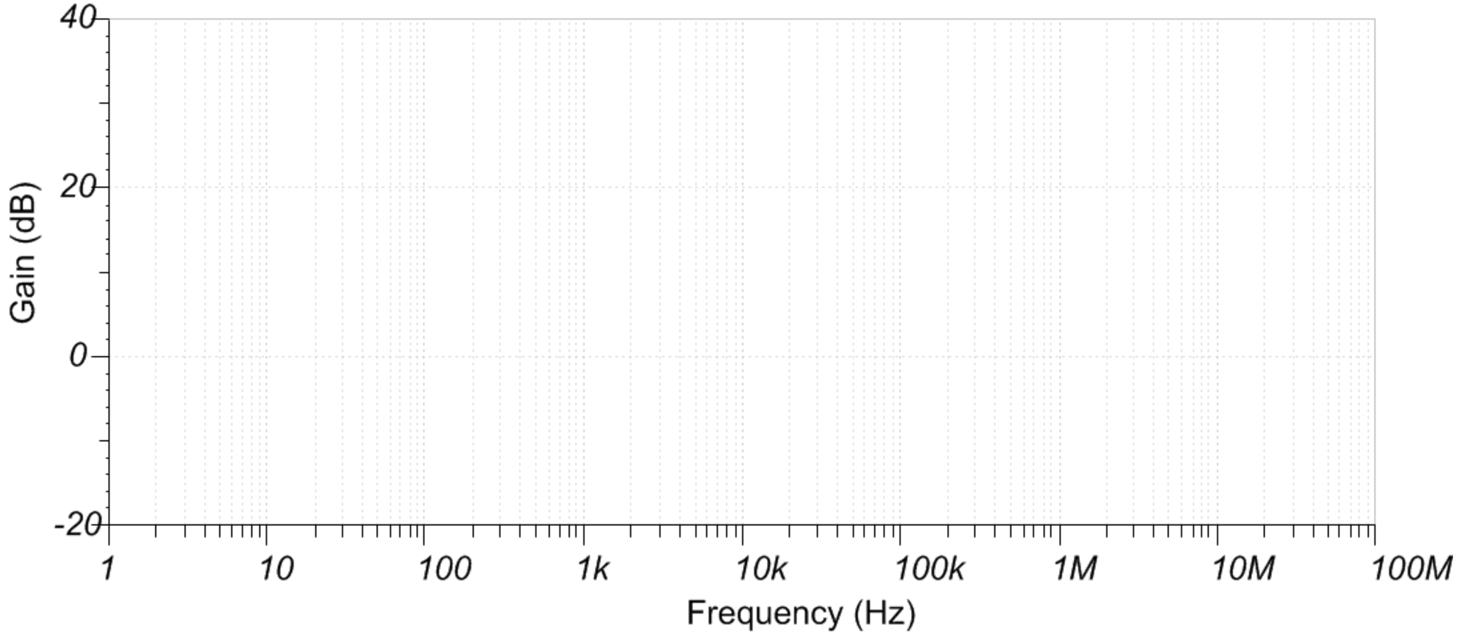
At T_A = +25°C, V_S = ±2.25 V to ±18 V, V_{CM} = V_{OUT} = $V_S/2$, and R_L = 10 kΩ connected to $V_S/2$, unless otherwise noted.

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
INPUT IMPEDANCE					
Differential			100 || 4		MΩ || pF
Common-mode			6 || 4		10^{13}Ω || pF

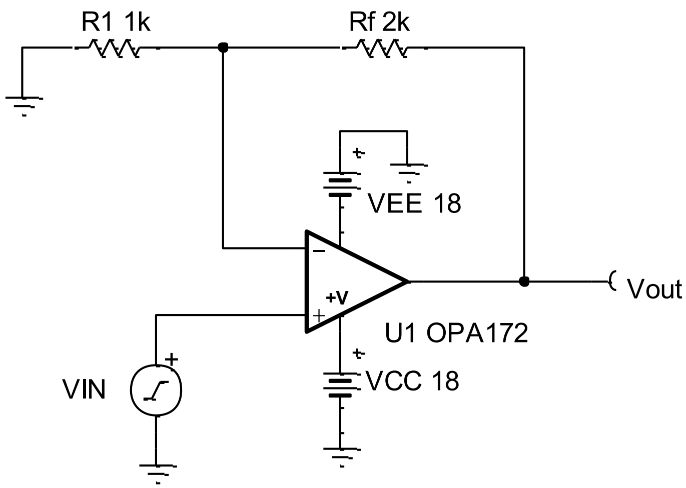


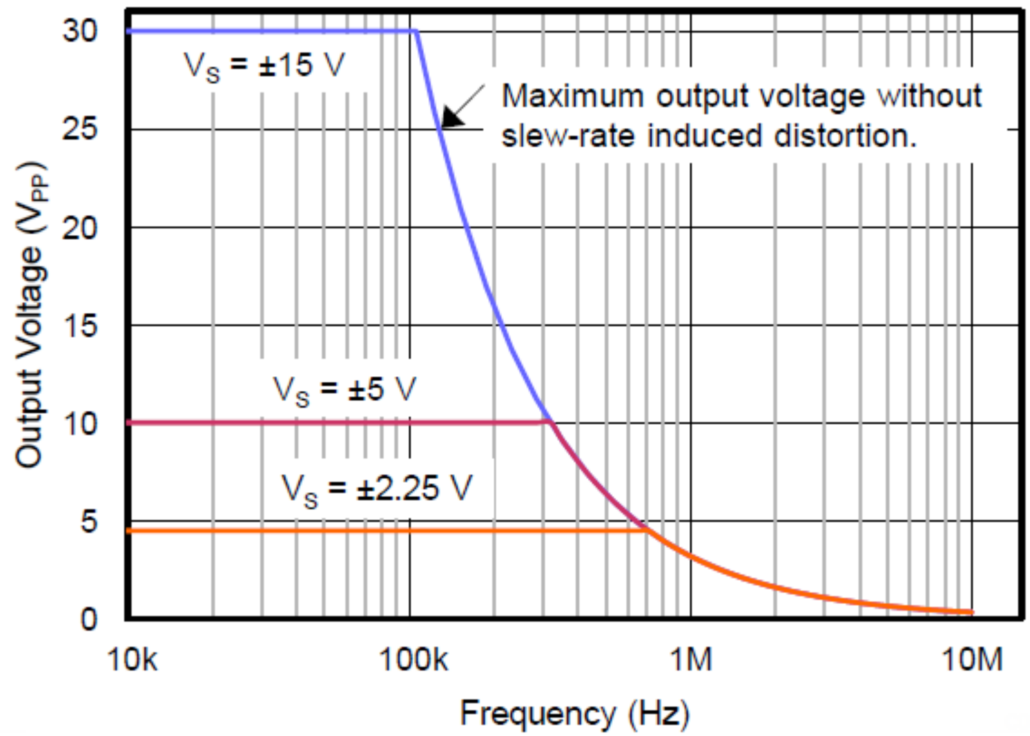
3. Predict the output for the circuit below with hand calculation. Confirm results with simulation.





4. The input signal for the circuit below is 3Vpk (6Vpp) at 300kHz. What will the output look like? Confirm with simulation.

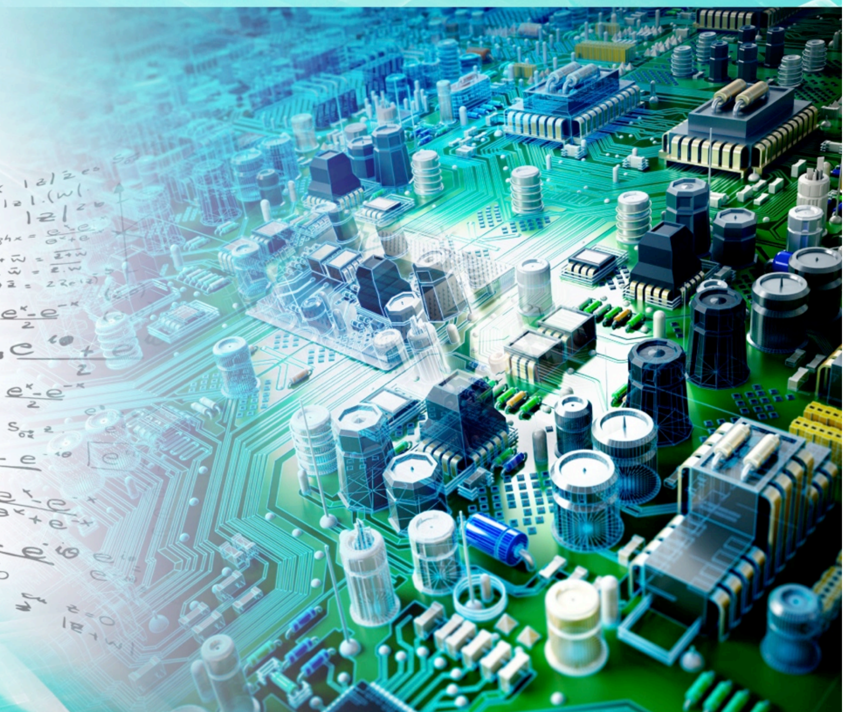




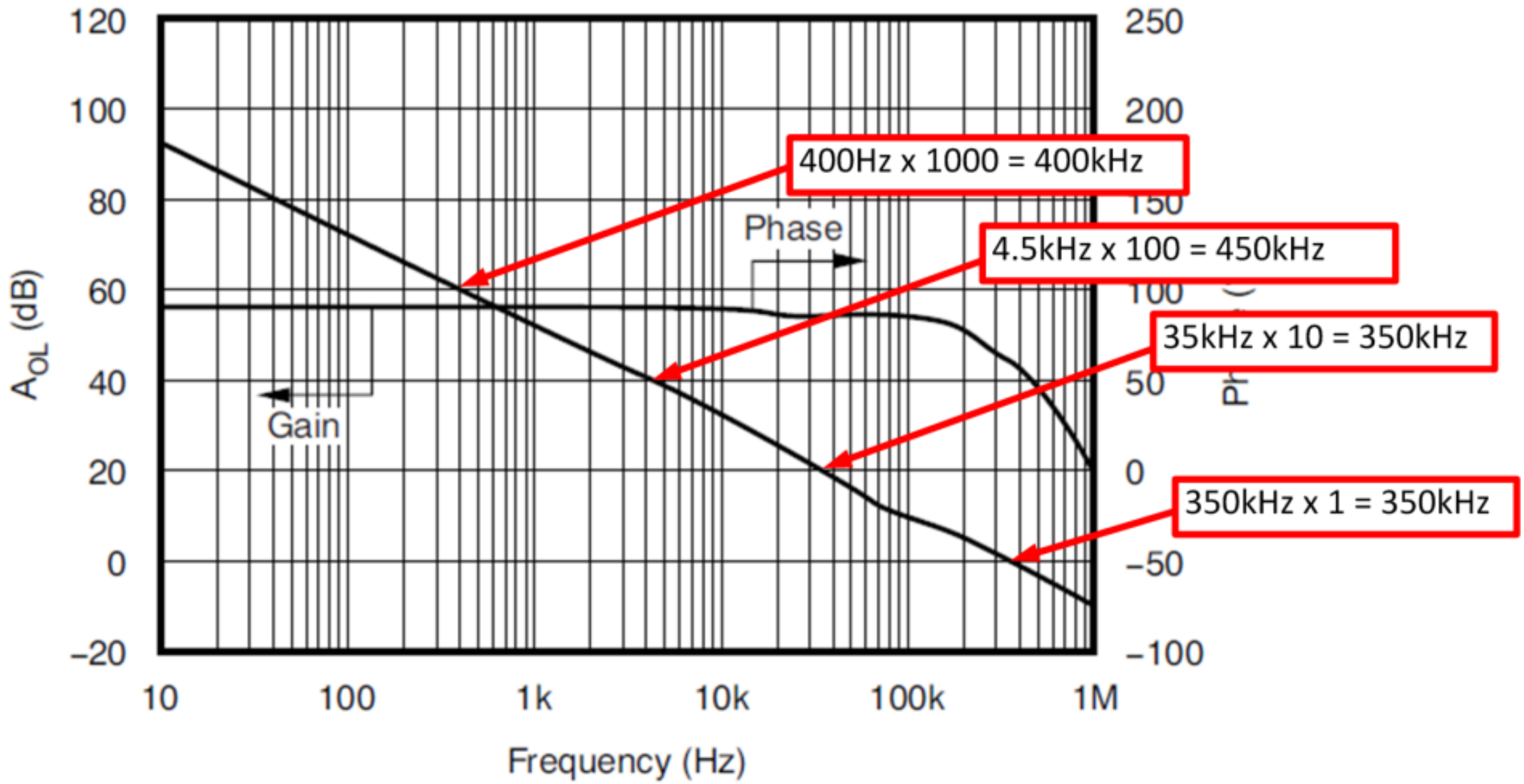
Bandwidth 4

Solutions

TI Precision Labs – Op Amps



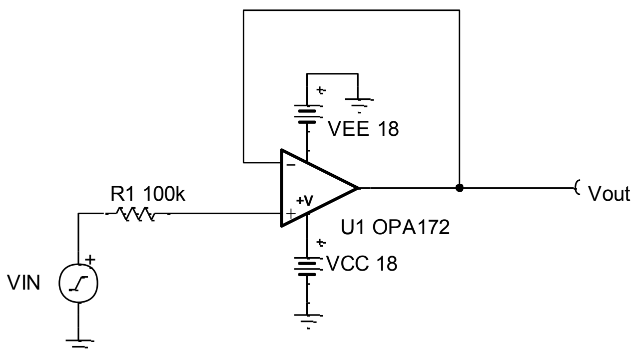
1. Find gain x bandwidth at Aol = 0dB, 20dB, 40dB, and 60dB.



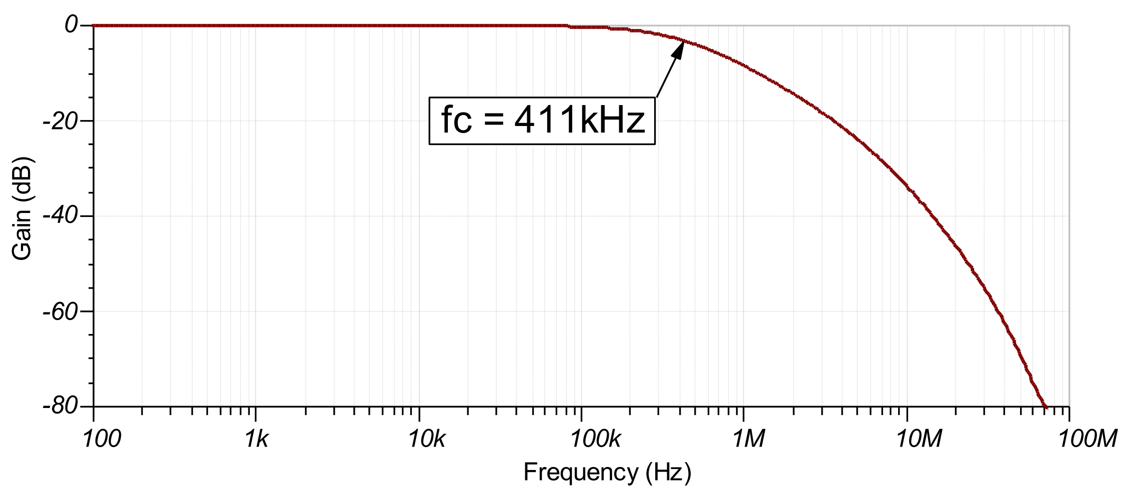
2. Calculate and simulate the bandwidth for the circuit below.

At T_A = +25°C, V_S = ±2.25 V to ±18 V, V_{CM} = V_{OUT} = $V_S/2$, and R_L = 10 kΩ connected to $V_S/2$, unless otherwise noted.

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
INPUT IMPEDANCE					
Differential			100 || 4		MΩ || pF
Common-mode			6 || 4		10^{13}Ω || pF

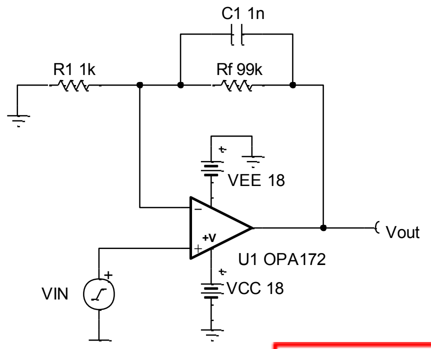


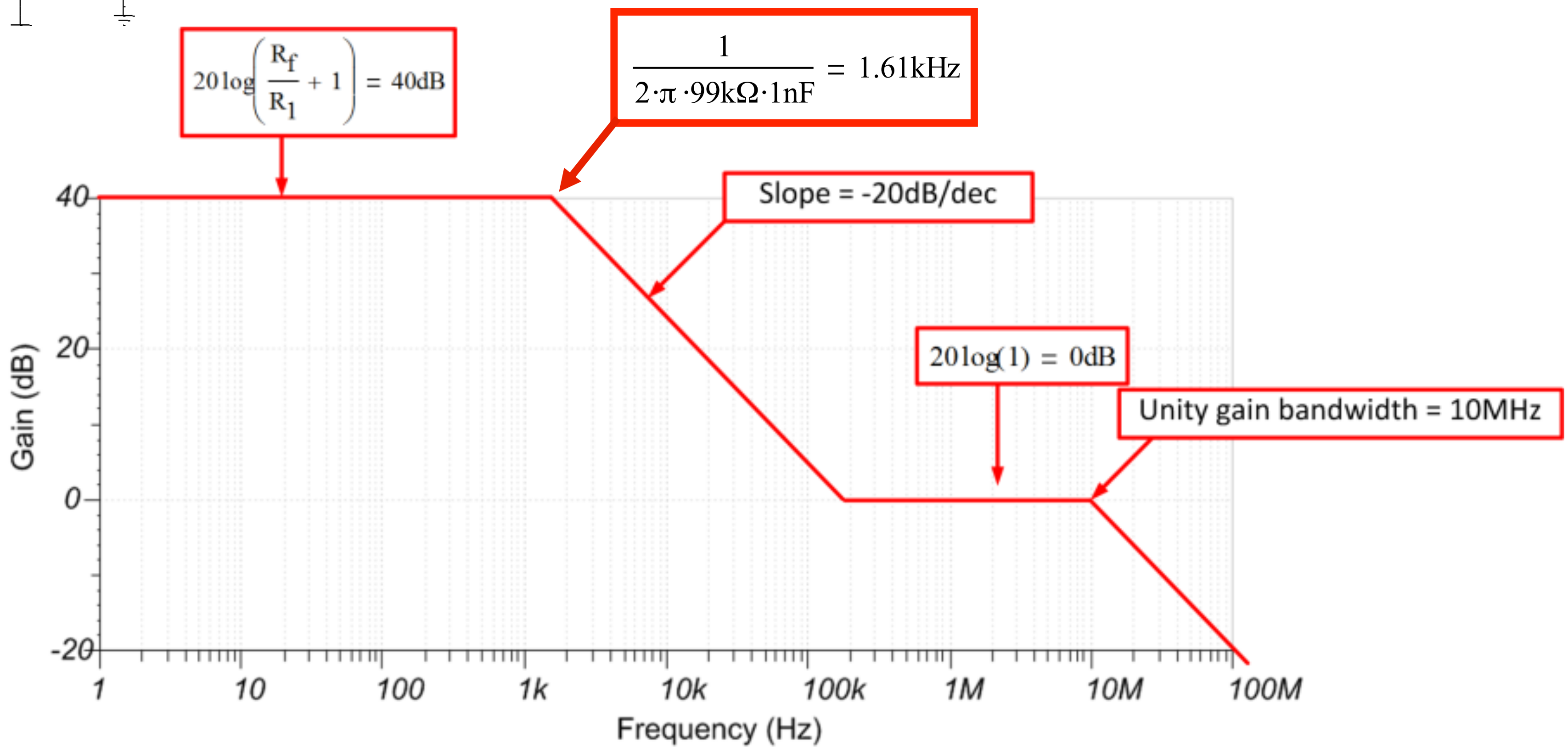
$$\frac{1}{2\cdot\pi\cdot 100k\Omega\cdot 4pF} = 397.9\times 10^{3}\,\text{Hz}$$



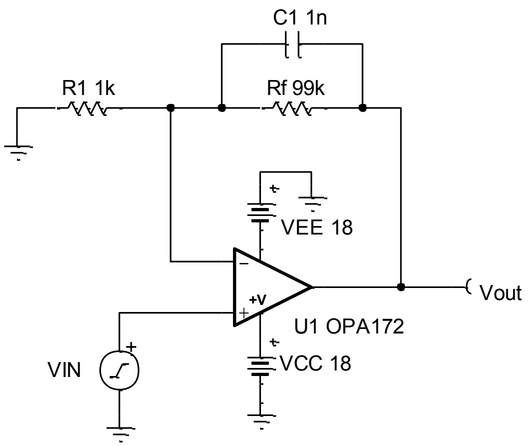
1214 - Bandwidth 4 - exercise 2.TSC

3. Predict the output for the circuit below with hand calculation. Confirm results with simulation.

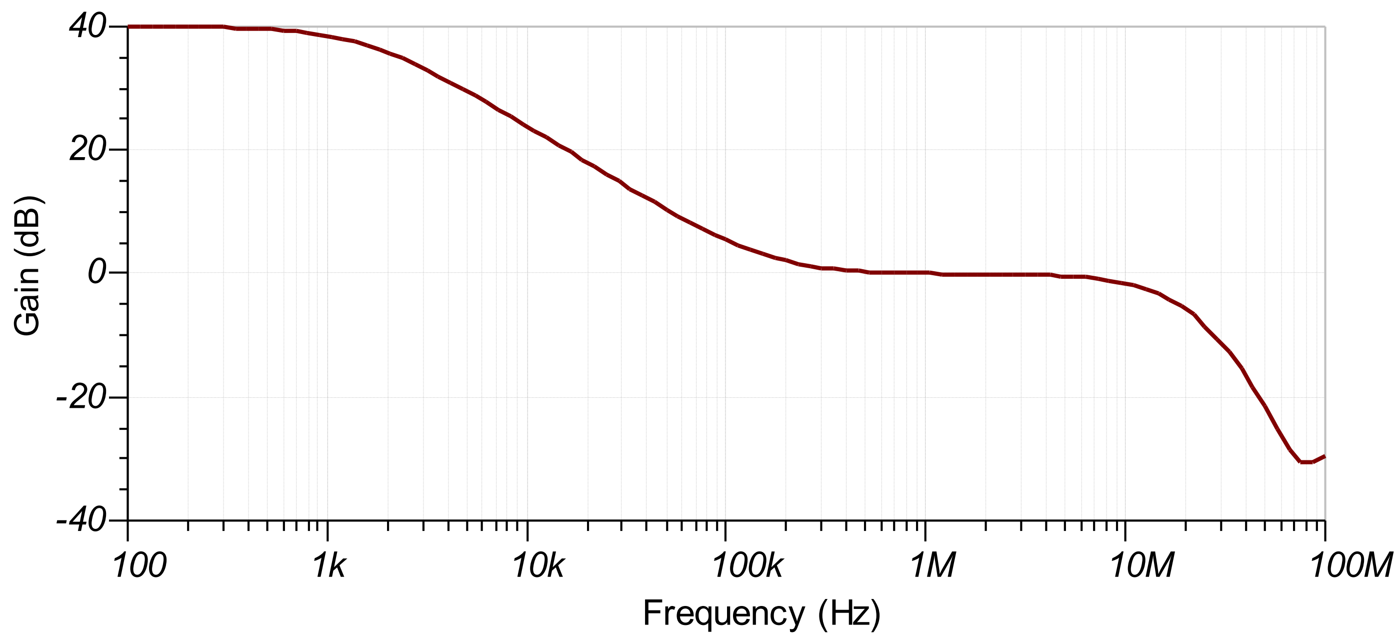




3. Predict the output for the circuit below with hand calculation. Confirm results with simulation. (simulation results below)

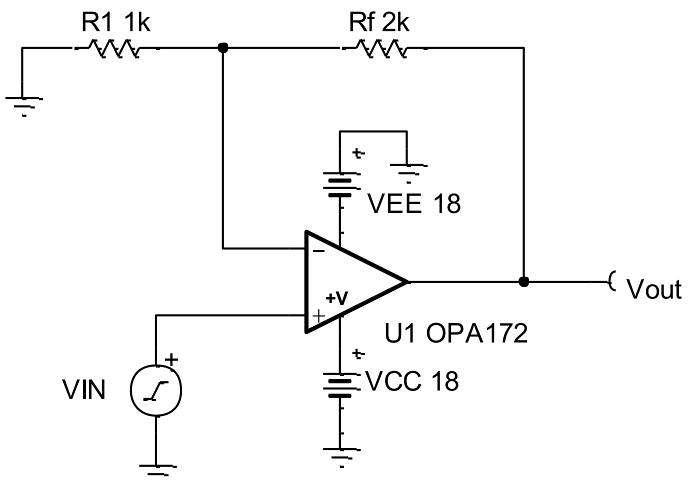


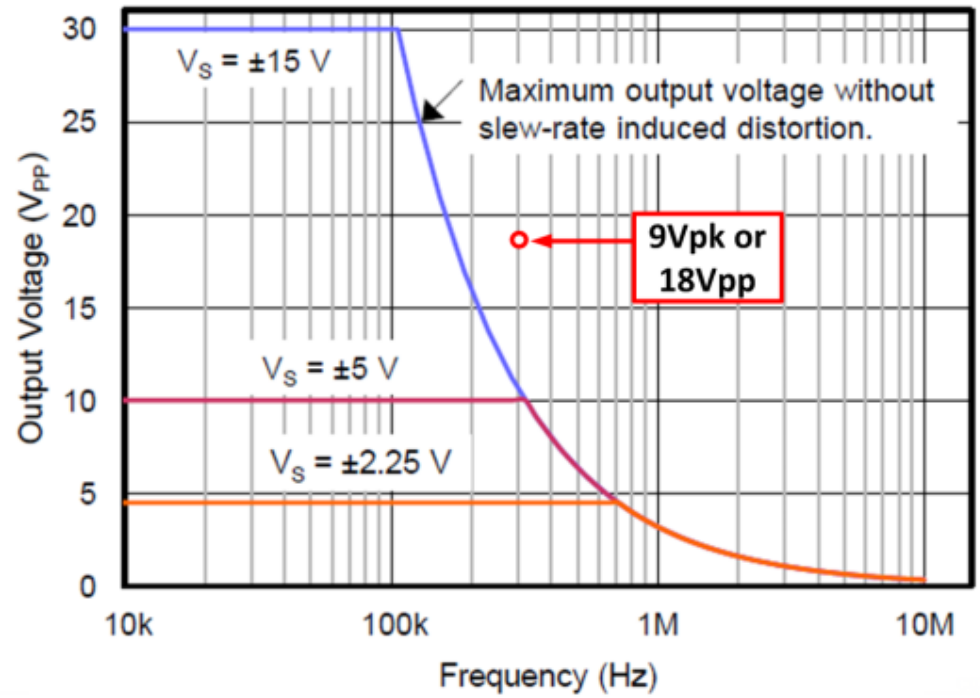
1214 - Bandwidth 4 - exercise 3.TSC



4. The input signal for the circuit below is 3Vpk (6Vpp) at 300kHz. What will the output look like? Confirm with simulation.

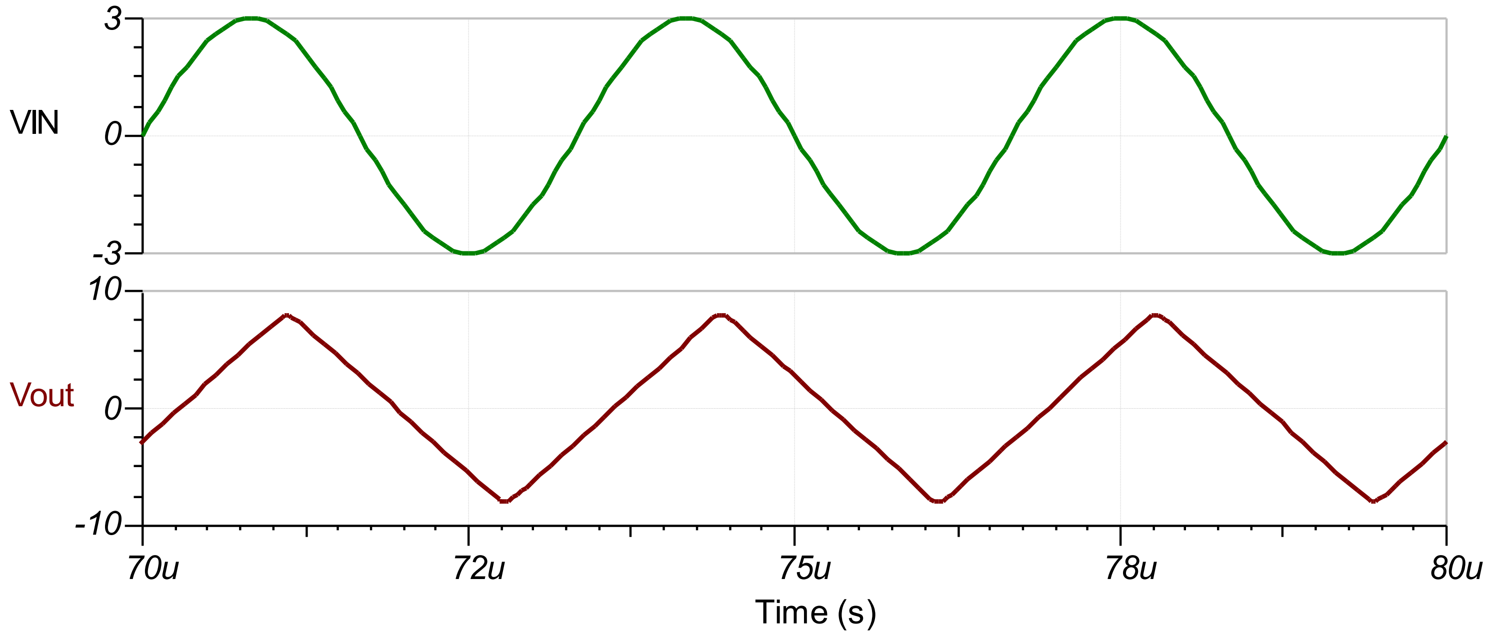
Gain = Rf/R1 +1 = 2k/1k +1 = 3
Vout = Vin x Gain = (6Vpp)x(3) = 18Vpp (see on graph)





The output will have slew induced distortion.

4. The input signal for the circuit below is 3Vpk at 300kHz. What will the output look like? Confirm with simulation. (simulation results below)



1214 - Bandwidth 4 - exercise 4.TSC