ECE3204   Microelectronic Circuits II   D2015

Lab 2

Unity Gain Buffer
Op-Amp Nonidealities: Slew Rate, Output Current Limit
Complementary Emitter Follower Power Amplifier
Frequency Dependence: Low-Pass Filter, Integrator

Objective

One purpose of this lab is to investigate the use of an op-amp to provide buffering: voltage gain is low (unity), but power gain is high since the op-amp provides much more output current than it draws from the input source. Along the way we will encounter some nonideal performance features: slew rate and output current limiting. To overcome the output current limitation, we will investigate the use of external emitter follower transistors to provide even more current gain when driving very low impedance loads. Although the emitter follower by itself distorts the signal severely, this effect can be removed by closing the op-amp feedback loop around the distorting stage.

Finally, we will also examine op-amp circuits with frequency-dependent gain: the active low-pass filter and the integrator.

Prelab

P1. A 5V peak, 1kHz sinusoidal source has a 100kΩ output impedance. This source must drive a 1kΩ load with no loss of signal.

Try the direct approach of Figure 2.1:

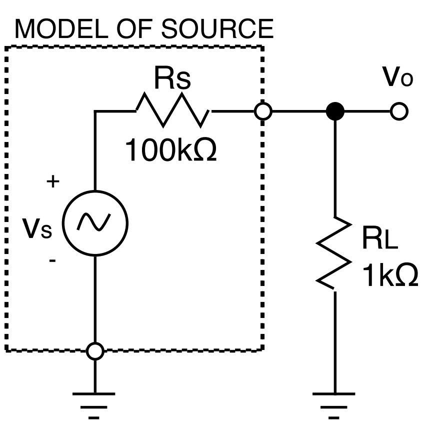

Figure 2.1

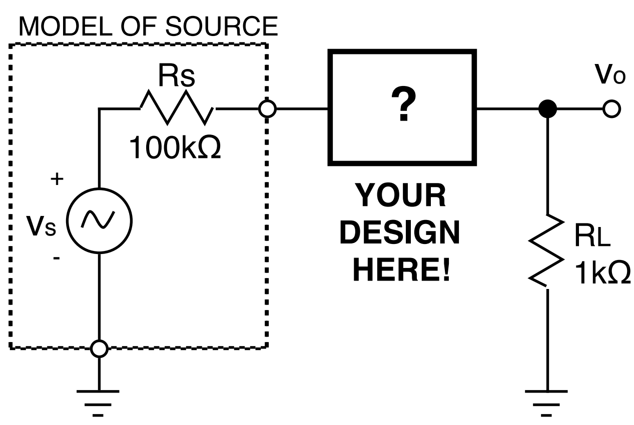

Figure 2.2

P1.1 How well will this work? What is the "gain" from v_S to v_o?

P1.2 Design a circuit to meet the requirement of $v_o = v_S$, as shown in Figure 2.2. R_L and R_S remain as in Figure 2.1. You may assume ±15V supplies are available.

P2. Slew Rate Limiting.

P2.1 The gain-bandwidth product ("Bandwidth" in the data sheet) for the LM741 op-amp is about 1.0 MHz. Based on this figure, what should be the closed loop 3-dB bandwidth of the follower circuit shown in Figure 2.3?

P2.2 Suppose the source in Figure 2.3 is the drive waveform to an ultrasonic transducer: a 100kHz sine wave with a 5V peak amplitude:

$$v_S = (5V)\sin[2\pi(100kHz)t]$$

Based on the expected 3-dB bandwidth from 2.1, and assuming that the op-amp operates in its linear region, what should the output amplitude be? Sketch this waveform.

P2.3 What is the maximum slope (dV/dt) of the output waveform you sketched in 2.2? How does this compare with the slew rate limit of ≈ 0.5 V/µsec for the LM741 op-amp? How would this affect the waveform you would see in the lab?

P2.4 At a peak amplitude of 5V, what is the highest frequency sine wave the LM741 could process without distortion due to slew rate limiting?

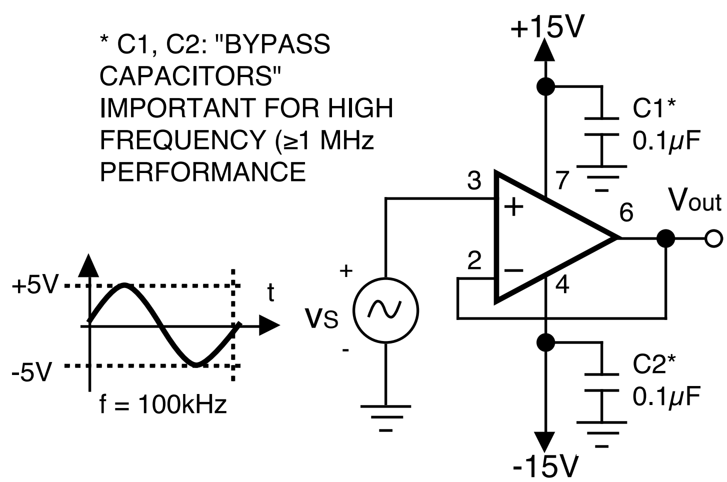

Figure 2.3

P3. Complementary Emitter Follower ("Push-Pull") Power Amplifier

Suppose we have a requirement to drive a 1V peak audio signal into a speaker. The audio signal can be represented as a 1kHz sine wave and the speaker as an 8Ω load resistance, as shown in Figure 2.4.

P3.1 Suppose we try to use the LM741 in an op-amp follower as shown in Figure 2.4. What is the peak current required by the load from the op-amp output? How does this compare with the LM741 maximum output current of approximately 25mA? What would you expect for the actual output voltage if you built this circuit in the lab?

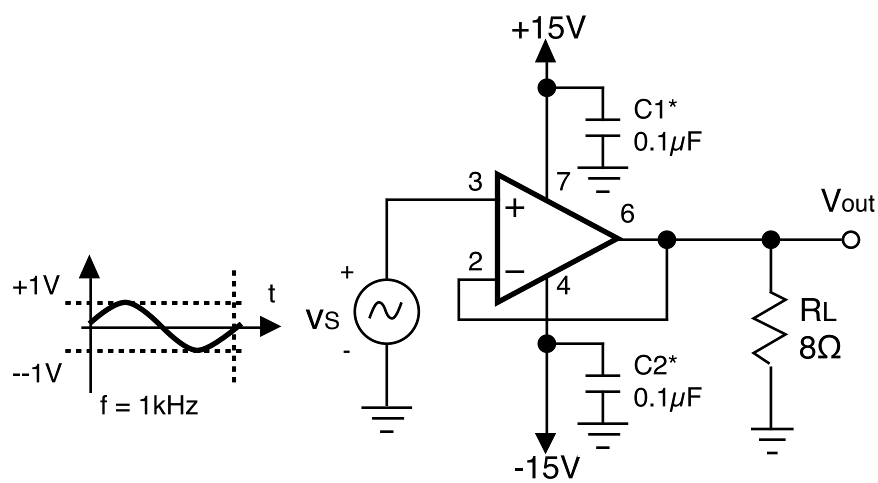

Fig. 2.4

P4. Integrator

We have seen that the gain of the inverting configuration can be written as $-Z_2/Z_1$, where Z_1 and Z_2 are impedances which are functions of complex frequency s. This allows us to make "active filters:" op-amp circuits with a gain that varies with frequency.

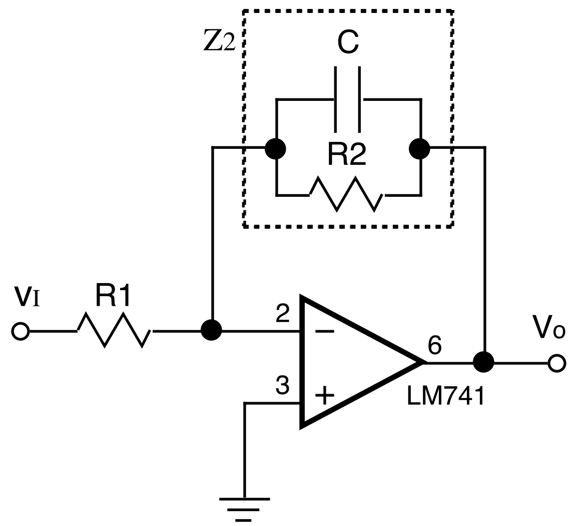

Figure 2.5

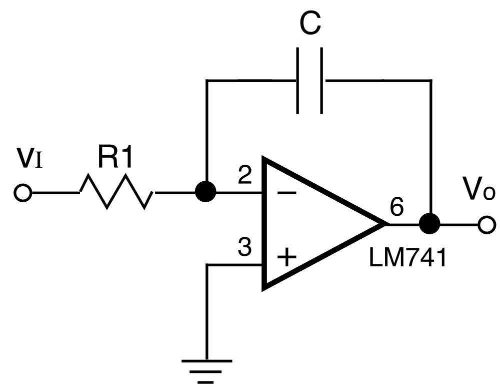

Figure 2.6

Figure 2.5 shows a simple low-pass active filter.

P4.1 Write an expression for the transfer function $H(s)=v_o/v_i$ in terms of R_1, R_2, C, and complex frequency s. Then, let $s=j\omega$ and sketch a Bode plot of the magnitude $|H(j\omega)|$ vs. ω. What is the 3dB bandwidth of this low-pass filter?

P4.2 At low frequencies: what does v_o/v_i approach as $s \rightarrow 0$?

P4.3 At high frequencies: what does v_o/v_i approach as $s \rightarrow \infty$?

P4.4 At what frequency does the behavior "cross over" from the low frequency limit to the high frequency limit?

Figure 2.6 shows an integrator.

P4.5 Write a frequency domain expression for $H(s)=v_o/v_i$ in terms of R_1, C, and complex frequency s. Let $s=j\omega$ and plot the magnitude $|v_o/v_i|$ vs. ω.

P4.6 Over what range of frequencies does the lowpass filter transfer function from 4.1 "look like" that of the ideal integrator?

P4.7 Write a <u>time domain</u> expression for the integrator output in terms of R_1, C, and time t.

Lab

1. Construct the circuit of Figure 2.1 with a 5V, 1kHz sinusoidal source.

1.1 Verify the "gain" from v_s to v_o for the direct approach that you calculated in prelab sec. P1.1. How well does this approach meet the requirement $v_s = v_o$?

1.2 Verify your design for a circuit to meet the requirement of $v_o = v_s$, as shown in Figure 2.2.

2. Slew Rate Limiting.

Construct the circuit of Figure 2.3. Adjust the signal generator voltage v_s until the op-amp input is a 100kHz sine wave of amplitude 5V peak.

2.1 Observe the op-amp output voltage v_{out}. How does it compare with the output you expect if the op-amp is in its linear region?

2.2 Reduce the generator frequency until the v_{out} sine wave is undistorted. How does this frequency compare with your calculation from prelab P2.4?

Note how much lower this frequency is than the maximum frequency limit imposed by the gain-bandwidth product. For large output signals and moderate gains, op-amp frequency performance is often limited by the maximum slew rate, not the gain-bandwidth product!

2.3 To measure the effect of slew rate on the rise and fall times, adjust the signal generator so that v_s is a 10 kHz square wave with a 5V peak-to-peak amplitude. Now measure the rise time at v_{out}. Using the bandwidth predicted in prelab P2.1, how well does this rise time conform to the BW x t_r = 0.35 relationship? (Hint: it should be way off!). This should illustrate that BW x t_r = 0.35 holds only for **linear** systems, since it was derived assuming an exponential step response. When something nonlinear happens (such as slewing or clipping) that distorts the exponential response of a linear system, all bets are off.

2.4 Measure the slew rate in both directions (positive going and negative going). How do your results compare with the data sheet specification of 0.5 V/µsec?

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Slew Rate	T_A = 25˚C, Unity Gain	0.3	0.7			0.5			0.5		V/µs

3. Complementary Emitter Follower "Push-Pull" Power Amplifier

Construct the circuit of Figure 2.4. To simulate the 8Ω speaker load resistance, use a parallel combination of 10Ω||51Ω. The input should be a 1kHz sine wave of peak amplitude 1V.

3.1 Observe the output waveform. How does it compare with the input v_S? How does it compare with what you expected from prelab P3.1?

3.2 Based on your observation of the output waveform, what are the output current limits (source and sink) of your LM741 op-amp? Compare with the data sheet specification of approximately 25mA.

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Output Short Circuit	$T_A = 25^\circ C$	10	25	35		25			25		mA
Current	$T_{AMIN} \le T_A \le T_{AMAX}$	10		40							mA

Remembering that the bipolar transistor acts as a current amplifier, you build the circuit in Figure 2.7. The BJTs operate as emitter followers providing most of the load current demanded by R_L. We will examine the behavior of the circuit when the op-amp feedback is taken from different points P and Q in the emitter follower stage.

Note: be very careful in wiring this circuit. Double-check your connections; pay attention to the pin assignment diagram in Figure 2.7. Turn off power before making any wiring changes. All resistors (except R_L) are for protection of the op-amp and/or transistors.

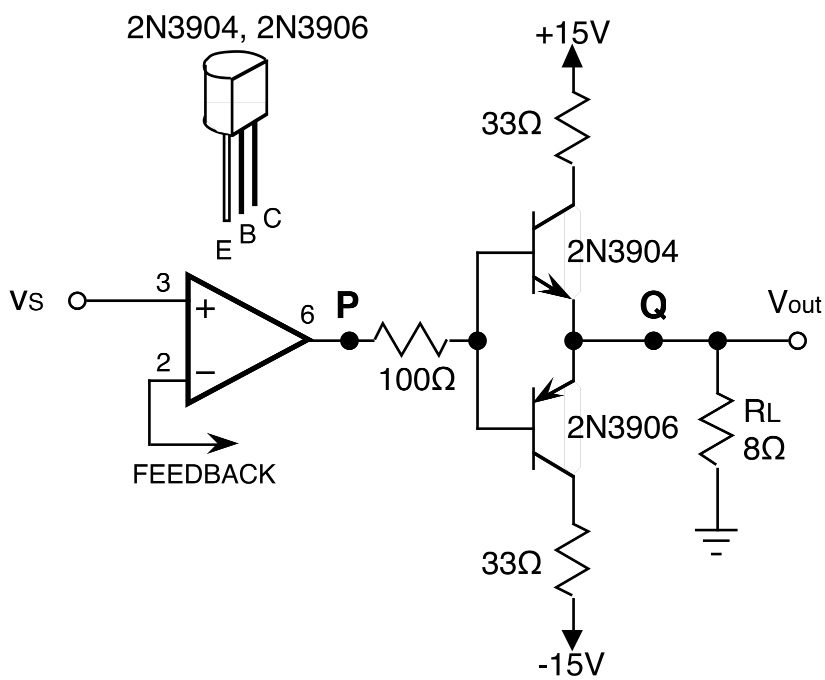

Figure 2.7

3.3 Using three channels of your oscilloscope, look at the input v_S, the op-amp output at point P, and the overall output v_{out} at point Q. Use the same scale on all three (consider 0.5V/div) and align the 0V reference levels on the oscilloscope display to help you visualize the voltages in the circuit relative to each other.

With feedback to the op-amp inverting input connected to point P, observe v_{out} when v_s is the 1V peak, 1 kHz sine wave. Record the waveforms at the op-amp output (point P) and v_{out}. Is there any distortion at v_{out}? Is it different from the distortion observed in part 3.1? Explain.

3.4 Turn off the power, and change the feedback connection to point Q. Again, observe and record the waveforms at the op-amp output (point P) and v_{out}. How has circuit operation changed? Explain.

Optional: use a small speaker in place of R_L to listen to the waveforms in each case. Is there any audible difference?

4. Integrator

Construct the low-pass active filter of Figure 2.5, with $R_1 = 1k\Omega$, $R_2 = 100k\Omega$, and $C = 1000pF$. The 1000pF capacitor has a value code of "102".

4.1 Measure the 3dB bandwidth, using an input sine wave of amplitude 50mV peak. How does this compare with the bandwidth predicted for these values of R_1, R_2, and C from your analysis in prelab P4.1?

4.2 Set the input to be a square wave of frequency 100Hz and amplitude ±100mV. Is the circuit acting more like a lowpass filter or more like an integrator?

4.3 Gradually increase the square wave frequency to 10kHz, keeping the amplitude ±100mV. At what frequency does the behavior "cross over" from the low frequency limit to the high frequency limit?

4.4 At 10kHz, is the circuit acting more like a lowpass filter or more like an integrator? How does the output compare to what you would expect from an ideal integrator, based on the result of your prelab P4.7?

4.5 In an effort to make the circuit act like an integrator at all frequencies, remove resistor R_2 to obtain the circuit of Figure 2.6. What happens to the op-amp output?

The problem is that a real op-amp has small DC errors at its inputs. Even though the errors are small, an integrator will faithfully integrate them until the op-amp output saturates. The dominant error may be either the input offset voltage or the input bias current:

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25^\circ C$										
	$R_S \leq 10\ k\Omega$					1.0	5.0		2.0	6.0	mV
	$R_S \leq 50\Omega$		0.8	3.0							mV
Input Bias Current	$T_A = 25^\circ C$		30	80		80	500		80	500	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			0.210			1.5			0.8	μA

Another way of understanding the problem is stated as "an integrator has infinite gain at DC" - which makes sense since the integrator transfer function is $H(j\omega) = 1/j\omega RC$ and DC corresponds to $\omega=0$. This means that even though the op-amp DC errors are small (of order mV, nA) -- no matter how small they are, it's just a matter of time until the integral of the error exceeds the op-amp's output range.

Methods of dealing with this problem depend on the application. If the circuit needs to function as an integrator only above a certain frequency, then the topology of Figure 2.5 can be used. If the integrator must work down to DC, then the integrating capacitor in the op-amp feedback of Figure 2.6 can be periodically reset (shorted) before the op-amp saturates. Another option is to enclose the integrator in a larger negative feedback loop to compensate for op-amp DC errors with an external correction.

Lab Writeup

Organize your lab writeup in sections.

Be sure to (at a minimum) answer any questions posed in this lab handout. Additionally, if any other insights come to you in the course of your analyzing and thinking about your data, discuss those as well.

Feel free to use screen shots of the oscilloscope to illustrate your measurements.

See the Sample Lab Writeup for general tips on writeup presentation style.