

### Lab 9: Operational Amplifiers

**Object:** To become familiar with the most important building block of linear electronics – the operational amplifier. This experiment involves integrated circuit op amps, feedback, open/closed loop gains, inverting and non-inverting configurations, offset voltage, and bias current.

**Apparatus:** TDS2004B Digital Oscilloscope, HP 260CD Oscillator, Simpson 420 Function Generator, Fluke 73 Digital Multimeter, Circuit Chassis, 741 Op Amp, RCA 3140T Op Amp, Various Resistors and Capacitors, and Cables.

**Introduction:** Operational amplifiers are employed in a broad spectrum of analog circuits designed to amplify, filter, buffer, sum, integrate, differentiate, and so on. Such circuits require few external discrete components beyond the op amps themselves, and they require very little sophistication on the part of the user. All op amp circuits fall in either the “inverting” or the “non-inverting” configurations. A general form for the inverting configuration is shown in Fig. 1. Here, as in virtually all cases, if the “open-loop” gain of the op amp is sufficiently large ( $10^6$  or better), the circuit’s behavior depends only upon the external impedances  $Z_{in}$  and  $Z_f$ . The input/output relations is

$$\frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_{in}}. \quad (1)$$

If both impedances are resistive, the circuit simply amplifies. But, if one of the impedances is a capacitor or inductor and hence is *reactive*, then the circuit serves as a differentiator or integrator. Numerous other variations exist as well. The circuits represented by Fig. 1 are best understood by assuming that the op amp senses the voltage difference across its input terminals and produces an output that is just sufficient to pull the summing point  $S$  back to ground, or *virtual ground* via current drawn through the feedback element  $Z_f$ .

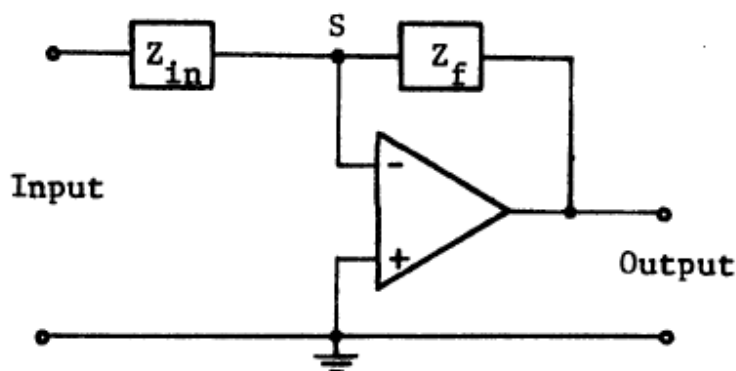


Fig. 1: Layout for inverting op amp circuits. The point  $S$  is the “summing point.”

This experiment covers five circuits; various properties of op amps are investigated, but the primary aim of the experiment is to convince the student that operational amplifiers are friendly and easy to use.

**Exercises:**

1. **Inverting amplifier circuit construction:** Construct the inverting amplifier circuit shown in Fig. 4.4 (on p. 178) of Horowitz and Hill. Use the general purpose 741 op amp, an input resistor  $R_1 = 5.1\text{k}$  and feedback resistor,  $R_2 = 50\text{k}$ . Make use of the pin diagram on the attached datasheet for the 741. This is a “top view” of the pin arrangement; that is, for the pins pointing **away** from you. Use the 8-pin socket on your circuit chassis and note that pin 8 is identified by a small tab on the canister. Think carefully about the pin numbers when viewed from the bottom of the socket where you will solder your connections. Perhaps make a pin diagram from the bottom view in your notebook to make sure you do make the connections correctly. For now disregard pins 1 and 5 (offset null), but make sure you connect your +15 V and -15 V power supplies to the proper pins as the op amp is an active circuit element that requires an external (in this case, split voltage) power supply. Whenever you are soldering to the socket pins, remove the op amp to avoid damaging it.
2. **Gain and frequency response of the inverting amplifier:** Measure the gain of your amplifier by applying a small (100-200 mV peak-to-peak) sinusoidal signal to the input of your amplifier. Take measurements at frequencies ranging from 10 Hz (this amplifier is DC-coupled, unlike the common-emitter amplifier) to 500 kHz. The gain should remain flat over a wide range of frequencies and should agree with the theoretical-predicted gain (within the propagated uncertainty in the measured resistance values). Also note that the output signal is 180 out of phase with the input, *i.e.* it is an inverting amplifier. Show that this flat gain plateau intersects the 741’s open-loop gain curve (see the data sheet) at a frequency where the gain of your amplifier begins to fall off (*i.e.* at the half-power frequency or -3dB point). Determine the approximate “gain bandwidth product” for the 741 from your measurements.
3. **Slew rate for the 741 op amp:** At the highest frequencies you may notice distortion in the output signal (as well as phase shift relative to the flat gain region). This will be especially apparent if you increase the input signal amplitude. The output signal should begin to appear like a triangle wave with linear (rather than sinusoidal) rise and fall. This distortion occurs because of the finite “slew rate” of the op amp. The op amp output has a maximum rate of change in V/s. Attempt to measure the slew rate for the 741 op amp and compare it to the value on the data sheet.
4. **FET vs. BJT –based op amps:** Now replace the 741 with a RCA 3140T op amp. Whereas the 741 is constructed with bipolar junction transistors, the 3140T uses field-effect transistors. The 3140T has the same pin arrangement. Repeat the measurements of gain vs. frequency, the gain-bandwidth product, and the slew rate for this op amp. How do they compare?
5. **Input offset voltage:** Some op amp circuits are sensitive to the presence of a small input offset voltage. Ideally, when there is no input voltage, the output should be zero. Real op amps, unfortunately, depart from this ideal. To correct for this non-ideal behavior one uses an offset compensating circuit composed of a 10k pot as

shown in the diagram on the datasheet for the 741 op amp. This approach lets one “trim” the offset voltage (at the output) to zero by reaching inside the op amp to make the necessary adjustments. Implement this voltage offset null circuit for your inverting amplifier (using the 741 op amp) and use it to trim the output voltage to zero. To do this, ground the input and adjust the pot until the DC output signal is zero. Make this adjustment carefully, eventually advancing the gain of the oscilloscope (*i.e.* the volts per division) to its highest (more sensitive) level. Your scope must be DC-coupled for this procedure.

6. **Summing amplifier:** Modify your amplifier to make it a summing amplifier. See Fig. 4.19 (p. 185) of Horowitz and Hill for an example of a summing amplifier. You can continue to use the 5.1k input resistor for one of your input signals and 50k for the feedback resistor. Couple a second input to the summing point (or *virtual ground*) through a second 50k resistor. This will make the output a weighted (and amplified) sum of the input signals. As a first test of your summing amplifier, connect the +5 V DC available from the power supply in your circuit chassis to the second input and apply a sinusoidal input to the other input. Verify that the output is the expected (weighted) sum of the input signals. Note that you have constructed a DC-coupled amplifier. Use the Fluke meter to verify that the summing point is a virtual ground. Next use the Simpson function generator to add two sinusoidal signals of different frequencies and observe the amplifier behavior.
7. **Op amp buffer:** Construct a unity-gain follower using the 741 op amp (see Fig. 4.8 on p. 179 of H&H). This circuit falls in the *non-inverting* configuration category. Measure the gain as accurately as you can. You might use the Fluke meter in AC voltage mode to maximize the accuracy of your amplitude measurements. This circuit is useful as a high input-impedance, low output-impedance *buffer* between amplifier stages, or as an output stage to drive a low impedance load. Attempt to measure the output impedance of this circuit using the push-button switch and a small fixed load resistor (try 5  $\Omega$ ) as you did for the common-emitter amplifier. How much does the output voltage droop when the load is connected? Use the voltage divider formula to determine the output resistance. Next attempt to measure the input impedance. Insert a 1 M $\Omega$  resistor (in series) between the oscillator and the input. Measure the amplitude of the signal on either side of this resistor using the 10X probe (why?) when the circuit is on and use that measurement to determine the input impedance.
8. **Integrator:** Construct the integrator circuit shown in Fig. 2. The resistor  $R_2$  is included to balance the small (non-ideal) “input bias current” to the two inputs of the op amp. It is often included in the inverting amplifier configurations to improve performance and its resistance should be the parallel combination of the resistors connected to the inverting input (including the feedback resistor). See pages 194-195 of Horowitz and Hill for more details. In this circuit, use  $R_2=10k$ . Begin by grounding the circuit’s input. An integrator should always be initialized by shorting the capacitor to remove any stored charge. After depressing and releasing the push-button in the discharge circuit you will observe the op amp’s output gradually drift

away from zero even though the integrator's input is grounded. This drift is due to non-ideal voltages and/or currents at the op amp inputs. Adjust the offset voltage null using the 10k pot (with the integrator input grounded) to minimize the rate of drift. Once you have made this adjustment, the remaining drift is due primarily to input bias current. The rate of drift (in V/s) can be used to measure the input bias current for the 741 op amp. Since the summing point is a virtual ground, the output measures the voltage across the capacitor in this circuit. The bias current is the rate at which charge is being delivered to the capacitor, so  $\Delta V_{out}/\Delta t = I_B/C$ . Measure the drift rate (make sure the scope is DC coupled) and compare it to the value on the data sheet. Now observe the integrator action by connecting a variety of input waveforms from the Simpson function generator (sine, triangular, and square waves). You might find that using the RUN/STOP button is useful for capturing and analyzing the integrator output before the effects of input bias current cause the output to saturate. Note the amplitude (and shape) of the integrated waveform as a function of frequency. Why does the output amplitude vary with frequency? Make a quantitative comparison of the output amplitude to the theoretical prediction for four different frequencies.

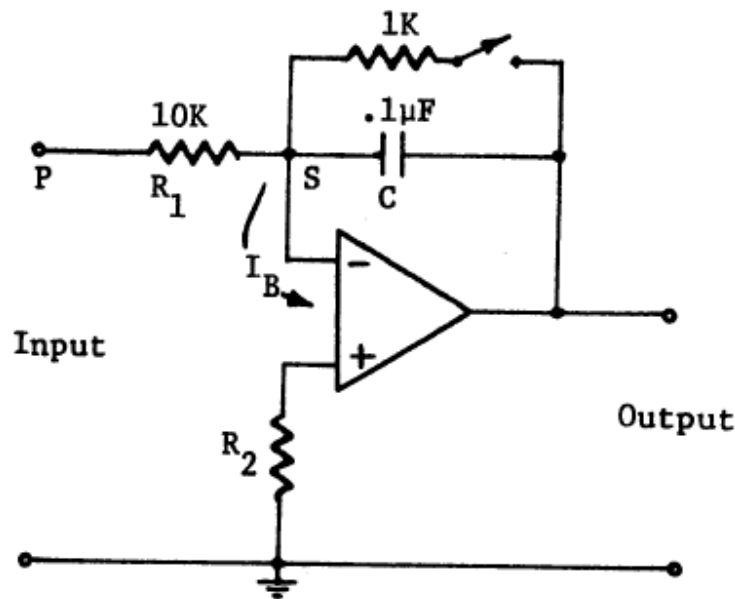


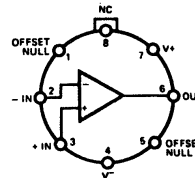
Fig. 2: Op amp integrator circuit.

# μA741 FREQUENCY-COMPENSATED OPERATIONAL AMPLIFIER

**GENERAL DESCRIPTION** — The μA741 is a high performance monolithic Operational Amplifier constructed using the Fairchild Planar<sup>®</sup> epitaxial process. It is intended for a wide range of analog applications. High common mode voltage range and absence of latch-up tendencies make the μA741 ideal for use as a voltage follower. The high gain and wide range of operating voltage provides superior performance in integrator, summing amplifier, and general feedback applications. Electrical characteristics of the μA741A and E are identical to MIL-M-38510/10101.

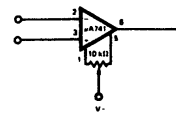
- NO FREQUENCY COMPENSATION REQUIRED
- SHORT CIRCUIT PROTECTION
- OFFSET VOLTAGE NULL CAPABILITY
- LARGE COMMON MODE AND DIFFERENTIAL VOLTAGE RANGES
- LOW POWER CONSUMPTION
- NO LATCH-UP

**Top View!**



PARAMETER	MIN.	TYP.	MAX.	UNITS	TEST CONDITIONS
<b>μA741C</b>					
Input Offset Voltage		2.0	6.0	mV	$R_S < 10k\Omega$
Input Offset Current		20	200	nA	
Input Bias Current		80	500	nA	
Input Resistance	0.3	2.0		MΩ	
Input Capacitance		1.4		pF	
Offset Voltage Adjustment Range		±15		mV	
Input Voltage Range	±12	±13		V	
Common Mode Rejection Ratio	70	90		dB	$R_S < 10k\Omega$
Supply Voltage Rejection Ratio		10	150	μV/V	$R_S < 10k\Omega$
Large-Signal Voltage Gain	20,000	200,000			$R_L > 2k\Omega, V_{out} = \pm 10V$
Output Voltage Swing	±12	±14		V	$R_L > 10k\Omega$
	±10	±13		V	$R_L > 2k\Omega$
Output Resistance		75		Ω	
Output Short-Circuit Current		25		mA	
Supply Current		1.4	2.8	mA	
Power Consumption		50	85	mW	
Transient Response (unity gain)					$V_{in} = 20mV, R_L = 2k\Omega, C_L < 100pF$
Risettime		0.3		μs	
Overshoot		5.0		%	
Slew Rate		0.5		V/μs	$R_L > 2k\Omega$
The following specifications apply for $0^\circ C < T_A < +70^\circ C$					
Input Offset Voltage			7.5	mV	
Input Offset Current			300	nA	
Input Bias Current			800	nA	
Large-Signal Voltage Gain	15,000				$R_L > 2k\Omega, V_{out} = \pm 10V$
Output Voltage Swing	±10	±13		V	$R_L > 2k\Omega$

**VOLTAGE OFFSET NULL CIRCUIT**



**OPEN LOOP VOLTAGE GAIN AS A FUNCTION OF FREQUENCY**

