Experiment 383: Operational Amplifiers

Aim

In this experiment some of the important parameters of operational amplifiers will be measured, and some typical applications of operational amplifiers in linear and non-linear circuits will be investigated.

Introduction

An operational amplifier is a direct-coupled high-gain amplifier to which negative feedback is applied to control the overall response characteristics. Such amplifiers can be obtained as monolithic integrated micro-circuits with typical gains of 10^4 to 10^6 (i.e. 80 to 120 dB).

The use of a large amount of negative feedback around a high gain amplifier in an attempt to control the overall circuit response is likely to fail because high gain amplifiers readily oscillate in such circuits due to parasitic phase-shifts that can turn negative feedback into positive feedback at high frequencies. In order to eliminate this, the gain-versus-frequency and phase-shift-versus-frequency characteristics of the high-gain amplifier must usually be modified by the use of "compensation" components. However, the amplifier used in this experiment, the LM 741, has these compensation components included in the package and is thus said to be "internally compensated". The data sheet for the LM 741 is contained in the Appendix and should be consulted by students.

Note: In this pamphlet, the symbols for voltages, currents and impedances must be interpreted intelligently.

V	may mean	$v(t)$,	or $\mathbf{V}$	or $V(s)$	or just V.
I	may mean	$i(t)$,	or $\mathbf{I}$	or $I(s)$	or just I.
Z	may mean	$z(p)$,	or $z(\mathrm{j}\omega)$	or $z(s)$	or just $\lvert z(\mathrm{j}\omega)\rvert$.

The circuits to be investigated are already assembled on circuit boards. Changes can be made using crocodile-clips on flying leads provided for that purpose. Please **ask a demonstrator** if you feel unsure about how to connect the various flying leads to obtain the desired configuration.

1 Basic Theory and Operational Amplifier Parameters

1.1 Theory

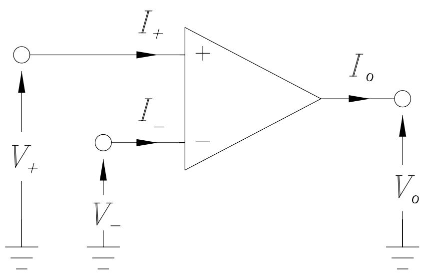


Figure 1: Operational Amplifier

The ideal operational amplifier (see Fig. 1) has the following characteristics:

(a) Infinite input impedance (i.e., $I_+ = I_- = 0$)

(b) Zero output impedance (i.e., V_o is independent of I_o)

(c) Voltage transfer function given by $V_o = A\,(V_+ - V_-)$

(d) A is essentially infinite and frequency independent.

(e) Characteristics are temperature independent.

If V_o remains within the supply range (say between $+15\,\mathrm{V}$ and $-15\,\mathrm{V}$) then since $V_o = A\,(V_+ - V_-)$ and A is very large, it follows that $(V_+ - V_-)$ must be very small, in fact in the ideal case as $A \to \infty$, $(V_+ - V_-) \to 0$, i.e. $V_+ \approx V_-$. This fact is useful in simplifying the analysis of many operational amplifier circuits. It is important to note that this argument is valid only provided that the output voltage V_o is still in the linear range of the amplifier. In practice, this will usually only be the case only if there is negative feedback around the amplifier.

In Fig. 2(a), since $V_+ = 0$, it follows that $V_- = 0$. Equating the currents in Z_i and Z_f (since the amplifier input current is zero), and rearranging we obtain the following equation for the voltage gain:

$$\frac{V_o}{V_i} = -\frac{Z_f}{Z_i}$$

Since the voltage at the inverting input is zero, this point is called a "virtual earth".

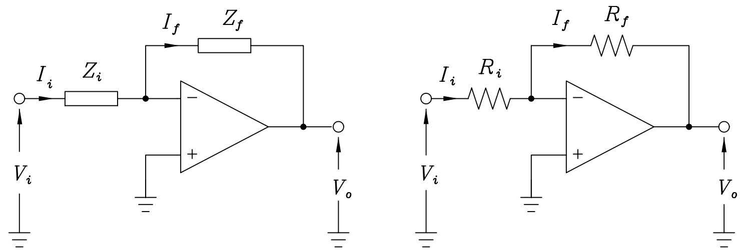


Figure 2: Operational amplifier in inverting configuration

(1) Real operational amplifiers have characteristics that approximate to those given above. If the open-loop gain A is finite, show that:

$$\frac{V_o}{V_i} = -\left(\frac{Z_f}{Z_i}\right)\left[\frac{1}{1 + \frac{1}{A}\left(1 + \frac{Z_f}{Z_i}\right)}\right]$$

Clearly as $A \to \infty$, this reduces to the simpler expression above.

1.2 Maximum Output Voltage and Slew Rate

Use circuit board 1 for this part of the experiment. Connect the power supplies to the tags labelled $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

(2) Set up the circuit shown in Fig. 2(b) with $R_1 = 10\,\mathrm{k\Omega}$ and $R_f = 10\,\mathrm{k\Omega}$. Apply a triangular input waveform (e.g. 100 Hz, 10 V p-p) and observe V_o-versus-V_i on the oscilloscope in XY mode. Verify the voltage gain expression:

$$\frac{V_o}{V_i} = -\frac{R_f}{R_i}$$

(3) Repeat (2) with $R_f = 100\,\mathrm{k\Omega}$.

(4) From your result of (3) measure the maximum output voltage range of the amplifier.

(5) With $R_f = 100\,\mathrm{k\Omega}$, observe V_o and V_- simultaneously using the oscilloscope in the dual-trace mode. Explain your observation and comment on the validity of the virtual earth concept, which asserts that V_- should remain small.

(6) With $R_f = 10\,\mathrm{k\Omega}$ and using a 10 kHz, 10 V p-p square wave input, observe V_o and V_i in time synchronisation. Observe that the output voltage cannot change instantaneously, and measure the maximum rate of change of output voltage. This is called the **slew rate** of the amplifier. Compare your result with the manufacturer's specifications.

(7) Calculate the frequency at which slew rate distortion would commence for a sinusoidal input of 10 V p-p with $R_f = 10\,\mathrm{k\Omega}$. Experimentally verify the result of your calculation.

1.3 Amplifier Open-Loop Gain

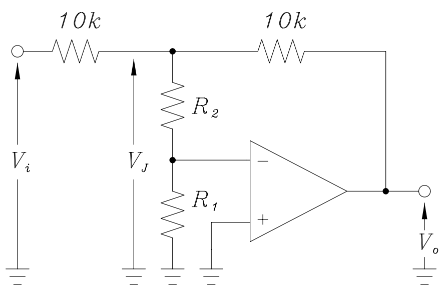


Figure 3: Circuit for measuring open-loop gain

The open-loop gain is far too large to measure directly. By measuring V_o and V_J in the circuit of Fig. 3, the open-loop gain can be obtained from:

$$A = -\frac{V_o}{V_-} = -\left(\frac{R_1 + R_2}{R_1}\right)\frac{V_o}{V_J} \quad \text{since} \quad V_- = \left(\frac{R_1}{R_1 + R_2}\right)V_J$$

Since the gain varies by several orders of magnitude over the range 10 Hz to 1 MHz, a range of values of R_2, viz., $100\,\mathrm{k\Omega}$, $10\,\mathrm{k\Omega}$ and $0\,\Omega$ may be used in conjunction with $R_1 = 1\,\mathrm{k\Omega}$.

Use the ***left-hand*** *operational amplifier on circuit board 2 for this part of the experiment. Connect the power supplies to the tags labelled* $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

(8) Set up the circuit of Fig. 3 with $R_2 = 100\,\mathrm{k\Omega}$ and with a 10 Hz sinusoidal input voltage for V_i. By observing V_o and V_J in time synchronisation, determine A.

(9) Taking about 1 reading per decade over the range 10 Hz to 1 MHz, plot graphs of $|A|_{\mathrm{dB}}$ and $\arg A$-versus-frequency on 5 cycle semi-log paper **as readings are taken**. Note that as the amplifier gain decreases, it will be necessary to select the appropriate value of R_2 to maintain V_J at a convenient value. The output should be undistorted for the measurements to be valid.

(10) From the Bode plots obtained in (9), deduce an equivalent circuit for the operational amplifier.

(11) Calculate the percentage error in the equation $V_o/V_i = -R_f/R_i$ for the circuit of Fig.2(b) owing to the finite open-loop gain of the amplifier obtained above at frequencies of 10 Hz, 1 kHz, 100 kHz and 1 MHz, assuming (N.B. remember that A is complex, and that you have measured both $|A|$ and $\arg A$).

1.4 Amplifier Input Offset Voltage

Ideally the output voltage is given by $V_o = A\,(V_+ - V_-)$ but in practice it is found that V_o is nonzero even when $V_+ = V_-$. A better approximation to the transfer function (at very low frequencies) is $V_o = A\,(V_+ - V_- + V_{io})$ where V_{io} is called the **input offset voltage**. Typically it is less than 5 mV and can be measured by the circuit of Fig.4(a).

Use circuit board 1 for this part of the experiment. Connect the power supplies to the tags labelled $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

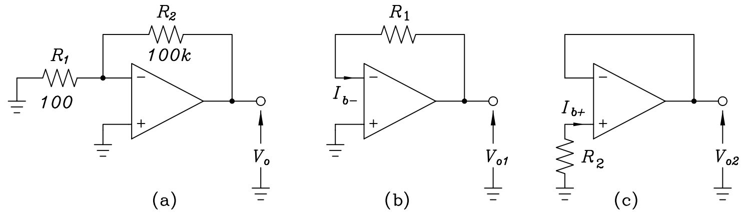


Figure 4: (a) Circuit for measuring input offset voltage, (b) and (c) circuits for measuring input bias currents

(12) Show that if $A \rightarrow \infty$,

$$V_{io} = \left(\frac{R_1}{R_1 + R_2}\right) V_o$$

(13) Set up the circuit of Fig. 4(a) and measure V_{io} and its polarity. Compare with the manufacturer's specifications.

1.5 Input Bias Currents and Input Offset Currents

The ideal situation of zero input currents is also not realisable in practice. Small bias currents and flow into the inputs, and these can be measured by the circuits of Fig.4(b) and (c).

Use circuit board 1 for this part of the experiment. Connect the power supplies to the tags labelled $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

(14) Show that if $A \rightarrow \infty$ and input offset voltage can be neglected,

$$I_{b-} = \frac{V_{o1}}{R_1} \quad \text{and} \quad I_{b+} = -\frac{V_{o2}}{R_2}$$

The **input offset current** is the difference between I_{b+} and I_{b-}.

(15) Using $R_1 = R_2 = 10\,\mathrm{M\Omega}$, measure and and determine the input offset current. Compare this with the manufacturer's specification.

1.6 Common-Mode Rejection Ratio

In the ideal operational amplifier the output depends solely on $V_+ - V_-$. In practice, the output voltage is given by:

$$V_o = A_d\,(V_+ - V_-) + A_c\left(\frac{V_+ + V_-}{2}\right)$$

A_d and A_c are called the **difference-mode gain** and the **common-mode gain** respectively. The ratio A_d/A_c is called the **common-mode rejection ratio**. It is typically 10^4 to 10^6, and is very difficult to measure experimentally.

1.7 Output Impedance

Real operational amplifiers have a non-zero output impedance. Due to the presence of feedback components, the output impedance of the amplifier itself will differ from that of the overall circuit.

The output impedance of the amplifier can be measured by the circuit of Fig. 5. The output impedance of the amplifier together with feedback is given by $Z_o' = V_o/I$.

Use the ***left-hand*** *operational amplifier on circuit board 2 for this part of the experiment. Connect the power supplies to the tags labelled* $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

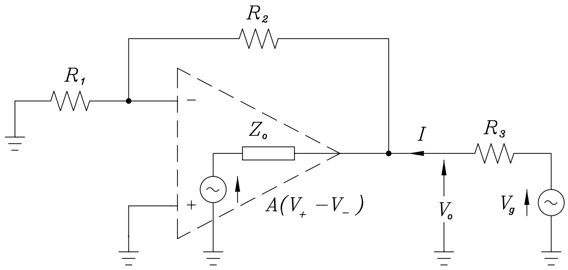


Figure 5: Circuit for measuring the output impedance

(16) Check that:

$$Z'_o = (R_1 + R_2) \parallel \left[\frac{Z_o}{1 + \left(\frac{AR_1}{R_1 + R_2} \right)} \right]$$

If A is large, Z'_o is very small. To make Z'_o measurable, we need to reduce the value of $AR_1 / (R_1 + R_2)$ by using a high frequency and making $R_2 \gg R_1$.

(17) Set up the circuit of Fig. 5 with $R_1 = 1\,\mathrm{k\Omega}$, $R_2 = 100\,\mathrm{k\Omega}$ and $R_3 = 100\,\Omega$. Use a sinusoidal input waveform at 10 kHz for V_g.

(18) Observe V_g and V_o measure and and their relative phase. The amplitude of V_g must be such that V_o is not slew-rate limited.

(19) Calculate I and Z'_o. From the Bode plots of A obtained earlier, calculate Z_o. (Note: These quantities are, in general, complex). Compare $\mathrm{Re}\, Z_o$, the output resistance, with the manufacturer's specifications.

1.8 Input Impedance

The input impedance of the operational amplifier is very high. However in the feedback amplifier circuit of Fig.2(b), the input impedance as seen by V_i is independent of that of the operational amplifier.

Use circuit board 1 for this part of the experiment. Connect the power supplies to the tags labelled $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

(20) Show that the input impedance of the circuit of Fig. 2(b) is essentially R_i.

2 Typical Applications

In the following circuits, analysis will be considerably simplified by assuming that the operational amplifiers are ideal in which case $V_+ = V_-$. Only brief outlines of each circuit are presented and students are encouraged to make additional tests and measurements to verify the operation of these circuits.

2.1 Non-inverting Amplifier

Use circuit board 1 for this part of the experiment. Connect the power supplies to the tags labelled $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

(21) For the circuit of Fig. 6(a) show that:

$$V_o(s) = \left[1 + \frac{R_2}{R_1} \right] V_i(s)$$

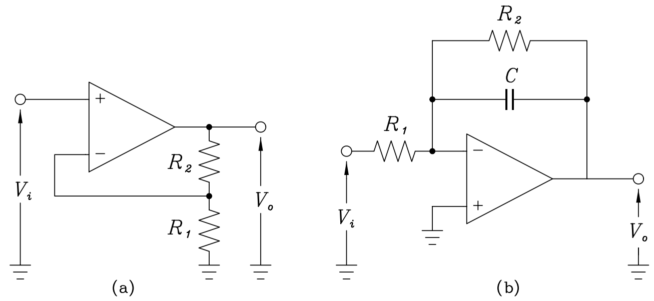


Figure 6: (a) Non-inverting amplifier and (b) Quasi-integrator

(22) Set up the circuit of Fig. 6(a) with $R_1 = 10\,\mathrm{k\Omega}$ and a range of values for R_2. Check that the gain and phase shift agree with theoretical predictions.

(23) Suggest a means of constructing a unity gain buffer with very high input impedance and low output impedance based on the circuit of Fig. 6(a). Test your suggested circuit.

2.2 Operational Integrators

Use circuit board 1 for this part of the experiment. Connect the power supplies to the tags labelled $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

(24) For the circuit of Fig. 6(b) show that:

$$V_o(s) = -\frac{1}{R_1 C}\left[\frac{1}{s + \frac{1}{R_2 C}}\right] V_i(s)$$

(25) Test the response of the circuit of Fig. 6(b) to square waves of various frequencies for $R_1 = R_2 = 10\,\mathrm{k\Omega}$ and $C = 0.1\mu\mathrm{F}$. Explain your results. Compare the levels etc. of your results with the theoretical predictions.

(26) Repeat (25) for $R_2 = 100\,\mathrm{k\Omega}$ and $1\,\mathrm{M\Omega}$ (keeping $R_1 = 10\,\mathrm{k\Omega}$). What does $V_o(s)/V_i(s)$ tend towards? What happens if R_2 is removed completely?

(27) Observe and discuss the response of the circuit to sinusoidal and triangular waveforms of different frequencies for $R_1 = R_2 = 10\,\mathrm{k\Omega}$.

2.3 Precision Rectifier

Use the circuits on the ***right-hand side*** *of circuit board 2 for this part of the experiment. Connect the power supplies to the tags labelled* $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

(28) Display V_o-vs-V_i on the oscilloscope for the circuits of Fig. 7(a) and (b) using a triangular input waveform. Carefully compare the behaviour of the characteristics for V_i near 0 V. Observe that the circuit of Fig. 7(b) exhibits idealised diode characteristics and is known as a **precision rectifier**.

(29) Explain the operation of the circuit of Fig. 7(b). (It may be helpful to observe the waveforms at various points in time synchronisation.)

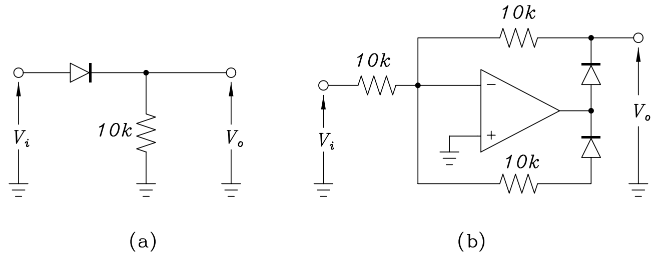


Figure 7: (a) Simple rectifier and (b) precision rectifier

2.4 Voltage-to-Current Convertor

Use the operational amplifier on the ***left-hand side*** *of circuit board 3 for this part of the experiment. Connect the power supplies to the tags labelled* $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

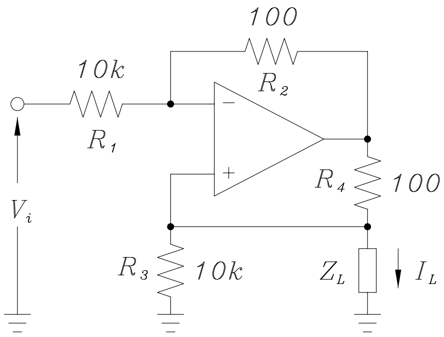


Figure 8: Voltage to current converter

(30) By noting that $V_+ = V_-$ in Fig. 8 and using the nodal equations for the amplifier input terminals, show that:

$$\text{if } \frac{R_2}{R_1} = \frac{R_4}{R_3} \quad \text{then} \quad I_L = -\frac{V_i}{R_3} \quad \text{(i.e., independent of } Z_L)$$

(31) Verify the above expressions experimentally using appropriate input waveforms and various loads for Z_L, e.g.

- (a) $10\,\mathrm{k}\Omega$ resistor,
- (b) $1\,\mathrm{k}\Omega$ resistor, and
- (c) $1\,\mathrm{k}\Omega$ resistor in parallel with $0.1\,\mu\mathrm{F}$ capacitor.

(32) Try using $Z_L = 100\,\mathrm{k}\Omega$. At what point does the circuit fail to act as predicted? Explain your results.

2.5 Negative Immitance Convertor (NIC)

Use the operational amplifier on the ***right-hand side*** *of circuit board 3 for this part of the experiment. Connect the power supplies to the tags labelled* $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$. *Note that connections are made under the circuit board for the power supply to the operational amplifier.*

(33) For the circuit of Fig. 9 show that:

$$\frac{V_1}{I_1} = -kZ_L \quad \text{where} \quad k = \frac{R_1}{R_2}$$

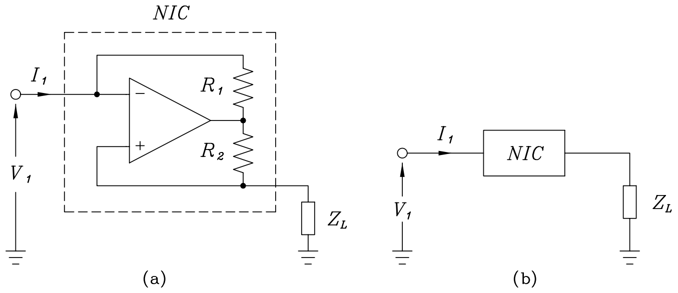


Figure 9: The negative immitance converter

i.e., the impedance looking into the input is $-k$ times the impedance of Z_L. This circuit is called a **negative immitance convertor** (NIC).

(34) Set up the NIC of Fig. 9 with $R_1 = R_2 = 10\,\text{k}\Omega$. Use it in the configuration of Fig. 10 with:

(a) $Z_A = 10\,\text{k}\Omega$, $Z_B = 3.3\,\text{k}\Omega$

(b) $Z_A = 10\,\text{k}\Omega$, $Z_B = 1\,\text{k}\Omega$

Plot V_o-vs-V_i in each case for a suitable triangular input waveform. Explain your results.

(35) Again using the circuit of Fig. 10, show theoretically that if Z_A consists of R and C in series and Z_B consists of R and C in parallel,

$$\frac{V_o\,(s)}{V_i\,(s)} = -\frac{k}{RC}\left[\frac{s}{s^2 + \frac{(2-k)}{RC}s + \frac{1}{(RC)^2}}\right]$$

which is the form of a second order bandpass transfer function with centre frequency f_o and Q given by:

$$f_o = \frac{1}{2\pi RC} \quad \text{and} \quad Q = \frac{1}{2-k}$$

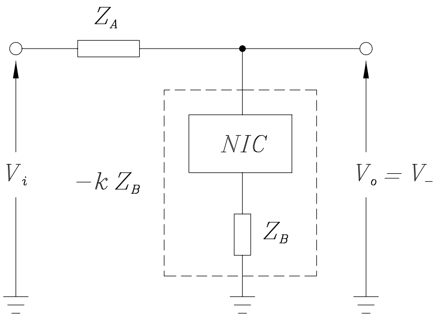


Figure 10: Voltage divider with a negative immitance converter

(36) Set up the NIC with $k = 1.8$ ($R_1 = 18\,\text{k}\Omega$, $R_2 = 10\,\text{k}\Omega$) and use $R = 3.3\,\text{k}\Omega$, $C = 0.1\,\mu\text{F}$. Obtain a Bode plot of $|V_o\,(\text{j}\omega)\,/V_i\,(\text{j}\omega)|$ from 50 Hz to 5 kHz. Ensure that slew-rate distortion does not occur by suitably adjusting the input amplitude. Compare this with theoretical predictions.

(37) Confirm that V_o/V_i has a bandpass characteristic. Measure f_o and Q and compare them with values obtained from above expressions.

APPENDIX

Manufacturer's Specifications for LM 741/μA 741

GENERAL DESCRIPTION — The μA741 is a high performance monolithic Operational Amplifier constructed using the Fairchild Planar* 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.

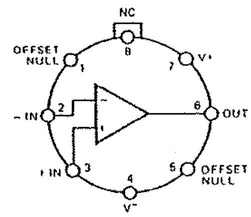
- NO FREQUENCY COMPENSATION REQUIRED
- SHORT CIRCUIT PROTECTION
- OFFSET VOLTAGE NULL CAPABILITY
- LARGE COMMON MODE AND DIFFERENTIAL VOLTAGE RANGES
- LOW POWER CONSUMPTION
- NO LATCH-UP

ABSOLUTE MAXIMUM RATINGS

Supply Voltage	
μA741A, μA741, μA741E	±22 V
μA741C	±18 V
Internal Power Dissipation (Note 1)	
Metal Can	500 mW
Molded and Hermetic DIP	670 mW
Mini DIP	310 mW
Flatpak	570 mW
Differential Input Voltage	±30 V
Input Voltage (Note 2)	±15 V
Storage Temperature Range	
Metal Can, Hermetic DIP, and Flatpak	−65°C to +150°C
Mini DIP, Molded DIP	−55°C to +125°C
Operating Temperature Range	
Military (μA741A, μA741)	−55°C to +125°C
Commercial (μA741E, μA741C)	0°C to +70°C
Lead Temperature (Soldering)	
Metal Can, Hermetic DIPs, and Flatpak (60 s)	300°C
Molded DIPs (10 s)	260°C
Output Short Circuit Duration (Note 3)	Indefinite

CONNECTION DIAGRAMS

8-LEAD METAL CAN
(TOP VIEW)
PACKAGE OUTLINE 5B

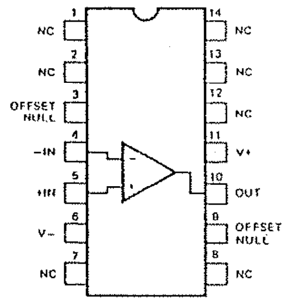


Note: Pin 4 connected to case

ORDER INFORMATION

TYPE	PART NO.
μA741A	μA741AHM
μA741	μA741HM
μA741E	μA741EHC
μA741C	μA741HC

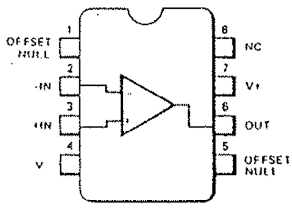
14-LEAD DIP
(TOP VIEW)
PACKAGE OUTLINE 6A, 9A



ORDER INFORMATION

TYPE	PART NO.
μA741A	μA741ADM
μA741	μA741DM
μA741E	μA741EDC
μA741C	μA741DC
μA741C	μA741PC

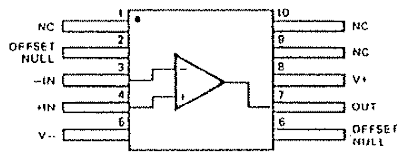
8-LEAD MINIDIP
(TOP VIEW)
PACKAGE OUTLINES 6T 9T
PACKAGE CODES T R



ORDER INFORMATION

TYPE	PART NO.
μA741C	μA741TC
μA741C	μA741RC

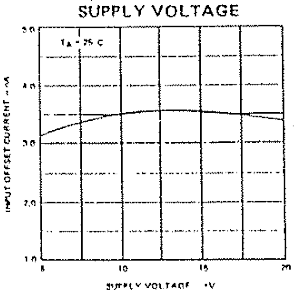
10-LEAD FLATPAK
(TOP VIEW)
PACKAGE OUTLINE 3F



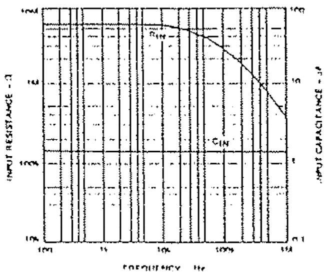
ORDER INFORMATION

TYPE	PART NO.
μA741A	μA741AFM
μA741	μA741FM

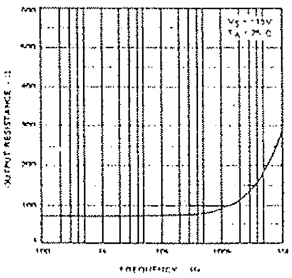
INPUT OFFSET CURRENT AS A FUNCTION OF SUPPLY VOLTAGE



INPUT RESISTANCE AND INPUT CAPACITANCE AS A FUNCTION OF FREQUENCY



OUTPUT RESISTANCE AS A FUNCTION OF FREQUENCY



μA741

ELECTRICAL CHARACTERISTICS ($V_S = \pm 15$ V, $T_A = 25°C$ unless otherwise specified)

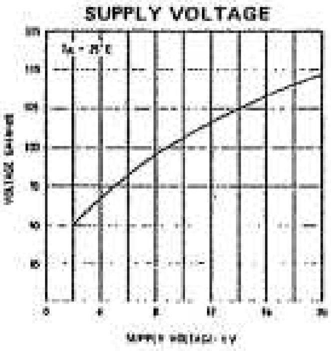
PARAMETERS (see definitions)		CONDITIONS	MIN	TYP	MAX	UNITS
Input Offset Voltage		$R_S \leq 10$ kΩ		1.0	6.0	mV
Input Offset Current				20	200	nA
Input Bias Current				80	500	nA
Input Resistance			0.3	2.0		MΩ
Input Capacitance				1.4		pF
Offset Voltage Adjustment Range				±15		mV
Large Signal Voltage Gain		$R_L \geq 2$ kΩ, $V_{OUT} = \pm 10$ V	50,000	200,000		
Output Resistance				75		Ω
Output Short Circuit Current				25		mA
Supply Current				1.7	2.8	mA
Power Consumption				50	85	mW
Transient Response (Unity Gain)	Rise time	$V_{IN} = 20$ mV, $R_L = 2$ kΩ, $C_L \leq 100$ pF		0.3		μs
	Overshoot			5.0		%
Slew Rate		$R_L \geq 2$ kΩ		0.5		V/μs

The following specifications apply for $-55°C \leq T_A \leq +125°C$:

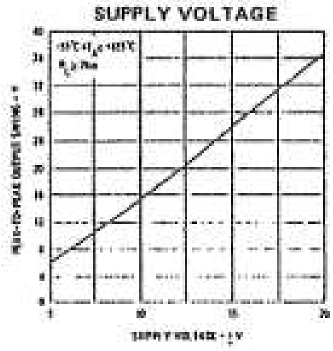
PARAMETERS	CONDITIONS	MIN	TYP	MAX	UNITS
Input Offset Voltage	$R_S \leq 10$ kΩ		1.0	6.0	mV
Input Offset Current	$T_A = +125°C$		7.0	200	nA
	$T_A = -55°C$		85	500	nA
Input Bias Current	$T_A = +125°C$		0.03	0.5	μA
	$T_A = -55°C$		0.3	1.5	μA
Input Voltage Range		±12	±13		V
Common Mode Rejection Ratio	$R_S \leq 10$ kΩ	70	90		dB
Supply Voltage Rejection Ratio	$R_S \leq 10$ kΩ		30	150	μV/V
Large Signal Voltage Gain	$R_L \geq 2$ kΩ, $V_{OUT} = \pm 10$ V	25,000			
Output Voltage Swing	$R_L \geq 10$ kΩ	±12	±14		V
	$R_L \geq 2$ kΩ	±10	±13		V
Supply Current	$T_A = +125°C$		1.5	2.5	mA
	$T_A = -55°C$		2.0	3.3	mA
Power Consumption	$T_A = +125°C$		45	75	mW
	$T_A = -55°C$		60	100	mW

TYPICAL PERFORMANCE CURVES FOR μA741A AND μA741

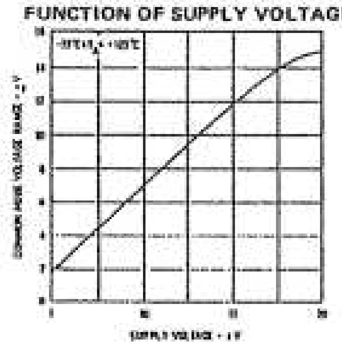
OPEN LOOP VOLTAGE GAIN AS A FUNCTION OF SUPPLY VOLTAGE



OUTPUT VOLTAGE SWING AS A FUNCTION OF SUPPLY VOLTAGE



INPUT COMMON MODE VOLTAGE RANGE AS A FUNCTION OF SUPPLY VOLTAGE



Use the following Matlab commands to draw the planes

`>> hold off`	this enables the previous graphs to be drawn over
`>> ezsurf('2*x+y+2')`	this draws the plane $z=2x+y+2$ or $2x+y-z=-2$
`>> hold on`	this enables more than one graph to be drawn on a set of axes
`>> ezsurf('(x+3)/3')`	this draws the plane $z=(x+3)/3$ or $x-3z=-3$

How do these two planes intersect? Why?
Use the rotation tool to turn the planes around and get a good look at the line of intersection.

Now we will add the third plane. What do think it will look like?
Use

```
>> ezsurf('1-x-2*y')
```

How do the three planes intersect? How does this relate to the answers in parts (a) and (b)? Write your answers here

The intersection of the planes is

Can you use Matlab to find the exact intersection of the planes?

List of Equipment

1. Noy-Tronics Function Generator Model 300 MSTPC/2
2. Hitachi Oscilloscope Model V-1565
3. Circuit Board Housing with 15 V power supply
4. Three pre-built circuit boards

S.M. Tan

Z.C. Tan

July 21, 2008