Experiment 10
Operational Amplifier Circuits

1 Motivation

Operational amplifiers (op amps) are highly versatile integrated circuits that have numerous applications. They can create nearly ideal linear circuits that evaluate addition, subtraction, differentiation, and integration. They are also important for nonlinear applications like voltage comparators, latches, and controlled oscillators. Their large input impedance and low output impedance facilitates building a series of amplifying stages that are buffered from each, simplifying information processing steps.

2 Background

In this experiment you will examine the properties of several of the most often used op amp circuits. Circuits that perform close to perfect mathematical operations (addition, subtraction, integration, and differentiation) can be constructed using negative and operational feedback. Non-linear op amp circuits that employ positive feedback are also useful. You will be using the general purpose "741" integrated circuit, often considered the prototypical operational amplifier. The circuit diagram for the single-amplifier version of the "741" is shown in Fig. 1. The test circuit board you will use provides banana-terminal connections to the op amp IC to which you will connect other components using banana patch cables.

The "741" has a typical DC input bias current of about 80 nA (a non-ideal characteristic of an op amp), and it can source a maximum output current of about ±25 mA. Together these imply that resistors in the range 1 kΩ to 100 kΩ should be used to construct feedback circuits. The attached data sheet provides information regarding the device's properties and limits as well as suggestions for use. It also shows the full internal integrated circuit, which is similar to Fig. 9.1 in Sprott. Many commonly used integrated circuits are manufactured by several companies. The base part number, e.g. "741", is combined with other labeling that identifies the manufacture and other information like "grades" of performance. Analog Devices labels their's AD741, while Texas Instruments labels their's LM741, etc. Usually devices with the same base labeling are interchangeable, but you should always check the manufacturers' data sheets and verify compatibility.

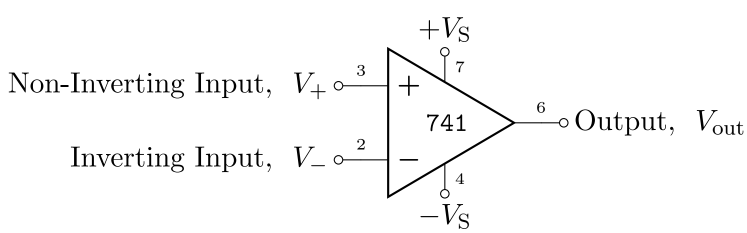


Figure 1: The "741" operational amplifier integrated circuit. The numbers refer to the device's "pins" (terminals). The "offset null" control (pins 1 and 5) are not shown. Pin 8 has no internal connection. The pin assignment is somewhat standardized, e.g., "3" is often the non-inverting input and "2" is often the inverting input for a single-amp package. But there is no enforced standard for pin assignments.

3 Equipment

For this experiment, you will use:

- One white DC power supply
- One Tektronix MSO 2014B Digital Storage Oscilloscope
- One AFG2021 Arbitrary Function Generator
- One circuit board for testing operational amplifier circuits ("741" already in socket)
- Two ELC variable resistance boxes
- One ELC variable capacitance box
- One small circuit board with three diodes

4 Procedure

Linear Op Amp Circuits: The op amp requires a $\pm V_S$ DC voltage source, called a "dual power supply." For this experiment, use the white DC power supply to provide fixed voltages $V_S = \pm 15\,\text{V}$ plus ground (a.k.a. common). These are the three color-coded terminals on the right side of the power supply chassis. Leave the dual supply connected to the circuit for all steps in the procedure (since it powers the op amp.) Use the oscilloscope to make all of your voltage measurements.

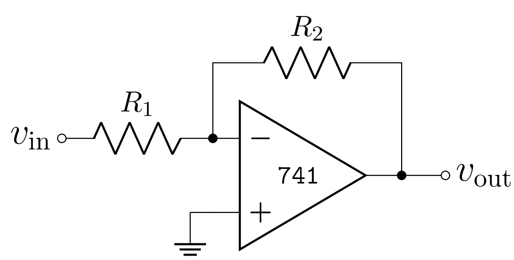


Figure 2: Operational feedback amplifier ("inverting amplifier")

1. Construct the operational feedback amplifier shown in Fig. 2 with $R_1 = 1\,\text{k}\Omega$ and $R_2 = 20\,\text{k}\Omega$. Note that the DC supply voltages are not shown in the circuit diagram. The voltage supply connections are often not shown in op amp circuits, but they are nevertheless required. You must connect $V_S = \pm 15\,\text{V}$ across the proper terminals and ground (common), even though not shown in the schematic.
   (a) What is the ideal closed-loop gain for your amplifier?
   (b) Set $v_{\text{in}} = 0$ by grounding the input using a patch cable. Use a small screw driver and adjust the potentiometer on the circuit board until $v_{\text{out}} \approx 0\,\text{V}$. It is possible that v_{out} is already small from prior use of the circuit. If so, try turning the potentiometer anyway so that you see what it does, then re-zero the output. The potentiometer is connected to the op amp's "offset null" control terminals. Circuitry inside the op amp allows nulling residual DC errors associated with finite input offset voltage and current. (See data sheet for details)
   (c) Remove the ground on the input. Set the function generator to make a sine wave with $|v_{\text{in}}| = 0.5\,\text{V}$ peak-to-peak and input this to your amplifier circuit. Measure and tabulate $|v_{\text{in}}|$ and $|v_{\text{out}}|$ and their relative phase for $1\,\text{kHz} < f < 1\,\text{MHz}$. Take measurements at three points per decade (1, 2, 5, 10, 20, 50, ...). Plot the amplifier's gain (log-log) and relative phase (semi-log) versus frequency.

(d) The closed-loop gain for the operational feedback (inverting) amplifier is given by

$$A(\omega) = \left|\frac{v_{\text{out}}}{v_{\text{in}}}\right| = \frac{A_0(\omega)R_2}{A_0(\omega)R_1 + R_2}. \tag{1}$$

The *open-loop* gain, $A_0(\omega)$, depends on frequency and is well-approximated as

$$A_0(\omega) = \frac{A_{0,\text{dc}}}{1 + j\omega/\omega_0} \tag{2}$$

where for the "741" op amp, $\omega_0 \approx 10\pi$ rad/s. For $\omega \gg \omega_0$, Eq. 1 can be written

$$A(\omega) = \frac{R_2/R_1\, e^{j\phi}}{\sqrt{1 + (\omega/\omega_c)^2}}, \qquad \omega_c = \frac{R_1}{R_2} A_{0,\text{dc}}\, \omega_0, \qquad \phi = \pi - \tan^{-1}\left(\frac{\omega}{\omega_c}\right) \tag{3}$$

This resembles the response of a low-pass filter but with low-frequency gain, $A = R_2/R_1$. Your data for the closed-loop gain, $A(\omega)$, should reveal the corner frequency, ω_c. Use your measured value for ω_c to estimate the *open-loop* DC gain, $A_{0,\text{dc}}$. (You may want to take a couple extra measurements to better resolve ω_c.) Compare your measurement with the plot of "Open-Loop Gain vs. Frequency" in the AD741 data sheet. Note that the amplifier's "gain-bandwidth product," $A\Delta\omega = A(\omega_c)\omega_c = A_{0,\text{dc}}\,\omega_0$. (The closed-loop bandwidth, $\Delta\omega$, is DC to ω_c.) There is always a tradeoff in the closed-loop gain and frequency bandwidth—both cannot be simultaneously large.

2. Change $R_2 = 10\,\text{k}\Omega$ and set $f = 1\,\text{kHz}$. Increase the amplitude of v_{in} until v_{out} exhibits saturation at both positive and negative voltages. Measure the saturation voltages and make a sketch of the waveform at saturation in your lab notebook.
3. An amplifier's "slew rate" is the maximum possible rate of change of the output voltage. Set the function generator to produce a square wave with $f = 10\,\text{kHz}$. Adjust v_{in} to obtain $|v_{\text{out}}| = 10\,\text{V}$ peak-to-peak. Measure the slew rate by observing $\delta v_{\text{out}}(t)/\delta t$ and compare your result to the typical value listed in the AD741's data sheet.

The next steps investigate linear operational amplifier circuits that perform "analog" differentiation and integration.

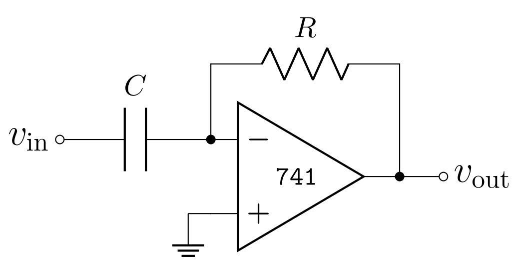


Figure 3: "Differentiator" amplifier

4. Construct the differentiating amplifier circuit shown in Fig. 3 with $C = 100\,\text{nF}$ and $R = 2\,\text{k}\Omega$. Set the function generator to produce a triangle wave with $f = 1\,\text{kHz}$ and $|v_{\text{in}}| = 2.0\,\text{V}$ peak-to-peak.
   (a) Measure $|v_{\text{out}}|$ and sketch the input and output waveforms in your lab notebook. Compare your measurement with the expected result, $v_{\text{out}}(t) = -RC\,\frac{d}{dt}\,[v_{\text{in}}(t)]$.

(b) Vary the function generator frequency and comment on the relationship between $|v_{\text{out}}|$ and $|v_{\text{in}}|$.

(c) Set the function generator for a square wave ($f = 1\,\text{kHz}$) and reduce the input voltage to $|v_{\text{in}}| = 0.5\,\text{V}$ peak-to-peak. Sketch v_{in} and v_{out}. Why does v_{out} look the way it does? It will help to think about the Fourier series representation of a square wave and the impact of the amplifier's finite bandwidth.

5. Construct the integrating amplifier circuit shown in Fig. 4 with $C = 100\,\text{nF}$, $R_1 = 10\,\text{k}\Omega$ and $R_2 = 200\,\text{k}\Omega$. Set the function generator to produce a square wave with $f = 1\,\text{kHz}$ and $|v_{\text{in}}| = 2.0\,\text{V}$ peak-to-peak.
   (a) Sketch the v_{out} and v_{in} waveforms in your lab notebook and compare with the expected result, $v_{\text{out}}(t) = -(1/RC)\int v_{\text{in}}(t)\,dt$.
   (b) Vary the function generator frequency and comment on the relationship between $|v_{\text{out}}|$ and $|v_{\text{in}}|$.
   (c) Set the function generator to make a triangle wave ($f = 1\,\text{kHz}$ and $|v_{\text{in}}| = 2.0\,\text{V}_{\text{pp}}$). Can you explain the functional form of v_{out}?
   (d) Observe what happens to v_{out} as you make R_2 larger or smaller. What happens when R_2 is removed from the circuit entirely, i.e., $R_2 \to \infty$? Why must feedback resistance be included in any practical integrating circuit?

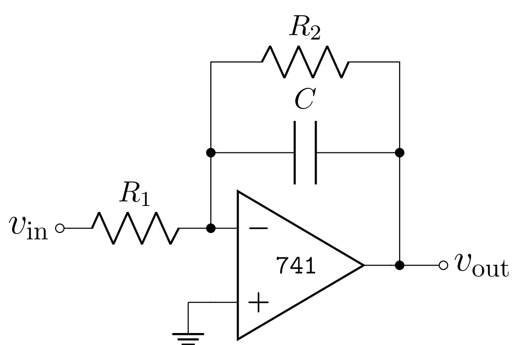


Figure 4: "Integrator" amplifier

Non-linear Op Amp Circuits: An operational amplifier can be used in logic-like applications to make voltage comparators and "latch" circuits that memorize signal states. These are useful in process control. When used with a diode, an op amp can perform non-linear mathematical operations like logarithmic or exponential amplification. For this section of the experiment, please note that it is possible to burn out the op-amp by applying a voltage to the op amp inputs that exceeds the supply voltages, $V_S = \pm 15\,\text{V}$.

1. Construct the voltage comparator circuit shown in Fig. 5. The white power supply has a separate, single-output DC voltage supply (left side of the box). The voltage of this single-output supply is variable $\pm 9\,\text{V}$ (might be $\pm 5\,\text{V}$). Use this to provide the reference voltage, V_1, for the comparator. It will help you understand the circuit if you monitor V_1 using a third channel on the scope, even though the voltage is constant in time. Use the function generator to apply a sine wave, $v_2(t)$, to the inverting input. Use a frequency, $f = 200\,\text{Hz}$, and amplitude, $|v_2| = 4\,\text{V}$, peak-to-peak. Observe what happens at $v_{\text{out}}(t)$ as you increase and decrease V_1. Write a brief explanation in your log notebook of the comparator circuit's function. Make a sketch of the input and output voltages for one particular comparator

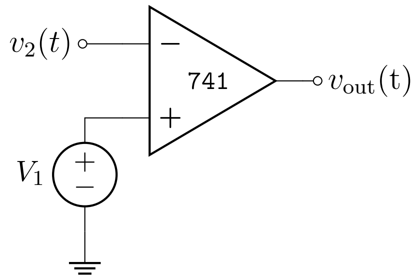


Figure 5: Voltage comparator circuit

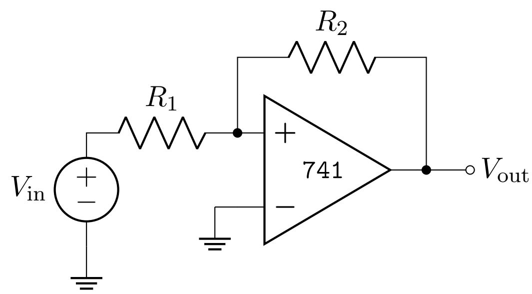


Figure 6: Op amp "latch" circuit

setting, say $V_1 = 1.5\,\mathrm{V}$.

2. Construct the latch circuit shown in Fig. 6 with $R_1 = 1\,\mathrm{k}\Omega$ and $R_2 = 25\,\mathrm{k}\Omega$. (The circuit looks almost the same as the negative feedback amplifier, so pay close attention to the op amp input assignments.) Use the variable $\pm 9\,\mathrm{V}$ DC voltage supply for V_{in} (might be $\pm 5\,\mathrm{V}$ DC). Describe the behavior of V_{out} as you increase and decrease V_{in}. Determine the values of V_{in} at which the output changes states. A latch circuit "memorizes" the polarity of the last input signal (typically voltage pulses in real applications). Explain the role of resistor, R_2, in this circuit.
3. Construct the logarithmic amplifier shown in Fig. 7 using $R = 500\,\Omega$ and the germanium diode (mounted on the circuit board with two other diodes). The output voltage of a logarithmic amplifier is
$$V_{\mathrm{out}} = -\alpha \ln\left(\frac{V_{\mathrm{in}}}{I_0 R}\right) \qquad (V_{\mathrm{in}} > 0) \tag{4}$$
with $\alpha \approx kT/e$. For V_{in}, use the variable $\pm 9\,\mathrm{V}$ (might be $\pm 5\,\mathrm{V}$) DC voltage supply. Measure and tabulate the amplifier's input and output voltages by adjusting V_{in} to make $V_{\mathrm{out}} = -100\,\mathrm{mV}$ to $-450\,\mathrm{mV}$ in $-50\,\mathrm{mV}$ steps. You can use two DMMs to make more precise DC voltage measurements. Plot V_{out} versus V_{in}. Do you see why the amplifier is logarithmic?

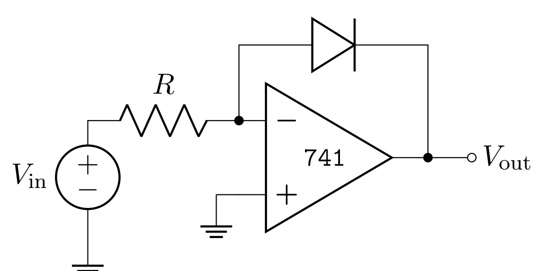


Figure 7: Logarithmic amplifier

ANALOG DEVICES

Low Cost, High Accuracy IC Op Amps

AD741 Series

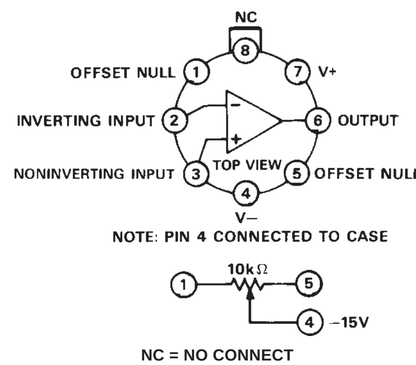
FEATURES
Precision Input Characteristics
- **Low V_{OS}: 0.5 mV max (L)**
- **Low V_{OS} Drift: 5 μV/°C max (L)**
- **Low I_b: 50 nA max (L)**
- **Low I_{OS}: 5 nA max (L)**
- **High CMRR: 90 dB min (K, L)**

High Output Capability
- **A_{OL} = 25,000 min, 1 kΩ Load (J, S) T_{MIN} to T_{MAX}**
- **V_O = ±10 V min, 1 kΩ Load (J, S)**

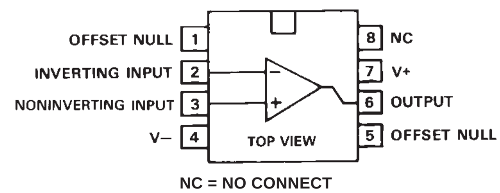
Chips and MIL-STD-883B Parts Available

CONNECTION DIAGRAMS

TO-99 (H) Package



Mini-DIP (N) Package



GENERAL DESCRIPTION

The Analog Devices AD741 Series are high performance monolithic operational amplifiers. All the devices feature full short circuit protection and internal compensation.

The Analog Devices AD741J, AD741K, AD741L, and AD741S are specially tested and selected versions of the standard AD741 operational amplifier. Improved processing and additional electrical testing guarantee the user precision performance at a very low cost. The AD741J, K and L substantially increase overall accuracy over the standard AD741C by providing maximum limits on offset voltage drift and significantly reducing the errors due to offset voltage, bias current, offset current, voltage gain, power supply rejection and common-mode rejection. For example, the AD741L features maximum offset voltage drift of 5 μV/°C, offset voltage of 0.5 mV max, offset current of 5 nA max, bias current of 50 nA max and a CMRR of 90 dB min. The AD741S offers guaranteed performance over the extended temperature range of –55°C to +125°C, with max offset voltage drift of 15 μV/°C, max offset voltage of 4 mV, max offset current of 25 nA, and a minimum CMRR of 80 dB.

HIGH OUTPUT CAPABILITY

Both the AD741J and AD741S offer the user the additional advantages of high guaranteed output current and gain at low values of load impedance. The AD741J guarantees a minimum gain of 25,000 swinging ±10 V into a 1 kΩ load from 0°C to +70°C. The AD741S guarantees a minimum gain of 25,000 swinging ±10 V into a 1 kΩ load from –55°C to +125°C.

All devices feature full short circuit protection, high gain, high common-mode range and internal compensation. The AD741J, K and L are specified for operation from 0 to +70°C and are available in both the TO-99 and mini-DIP packages. The AD741S is specified for operation from –55°C to +125°C, and is available in the TO-99 package.

REV. A

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Tel: 617/329-4700 World Wide Web Site: http://www.analog.com
Fax: 617/326-8703

AD741 Series–SPECIFICATIONS (typical @ +25°C and ±15 V dc, unless otherwise noted)

Model	AD741C Min	AD741C Typ	AD741C Max	AD741 Min	AD741 Typ	AD741 Max	AD741J Min	AD741J Typ	AD741J Max	Units
OPEN-LOOP GAIN										
R_L = 1 kΩ, V_O = ±10 V							**50,000**	200,000		V/V
R_L = 2 kΩ, V_O = ±10 V	**20,000**	200,000		**50,000**	200,000					V/V
T_A = min to max R_L = 2 kΩ	**15,000**			**25,000**			**25,000**			V/V
OUTPUT CHARACTERISTICS										
Voltage @ R_L = 1 kΩ, T_A = min to max							**±10**	±13		V
Voltage @ R_L = 2 kΩ, T_A = min to max	**±10**	±13		**±10**	±13					V
Short Circuit Current		25			25			25		mA
FREQUENCY RESPONSE										
Unity Gain, Small Signal		1			1			1		MHz
Full Power Response		10			10			10		kHz
Slew Rate		0.5			0.5			0.5		V/µs
Transient Response (Unity Gain)										
Rise Time C_L ≤ 10 V p-p		0.3			0.3			0.3		µs
Overshoot		5.0			5.0			5.0		%
INPUT OFFSET VOLTAGE										
Initial, R_S ≤ 10 kΩ, Adjust to Zero		1.0	**6.0**		1.0	**5.0**		1.0	**3.0**	mV
T_A = min to max		1.0	**7.5**		1.0	**6.0**			**4.0**	mV
Average vs. Temperature (Untrimmed)									20	µV/°C
vs. Supply, T_A = min to max								30	100	µV/V
INPUT OFFSET CURRENT										
Initial		20	**200**		20	**200**		5	**50**	nA
T_A = min to max		40	**300**		85	500			**100**	nA
Average vs. Temperature								0.1		nA/°C
INPUT BIAS CURRENT										
Initial		80	**500**		80	**500**		40	**200**	nA
T_A = min to max		120	**800**		300	1,500			**400**	nA
Average vs. Temperature								0.6		nA/°C
INPUT IMPEDANCE DIFFERENTIAL	0.3	2.0		0.3	2.0			1.0		MΩ
INPUT VOLTAGE RANGE[1]										
Differential, max Safe									±30	V
Common-Mode, max Safe	±12	±13		±12	±13			±15		V
Common-Mode Rejection,										
R_S = ≤ 10 kΩ, T_A = min to max,										
V_{IN} = ±12 V	**70**	90		**70**	90		**80**	90		dB
POWER SUPPLY										
Rated Performance		±15			±15			±15		V
Operating							±5		±18	V
Power Supply Rejection Ratio		30	**150**		30	**150**				µV/V
Quiescent Current		1.7	**2.8**		1.7	**2.8**		2.2	**3.3**	mA
Power Consumption		50	85		50	85		50	85	mW
T_A = min					60	100				mW
T_A = max					45	75				mW
TEMPERATURE RANGE										
Operating Rated Performance	0		+70	–55		+125	0		+70	°C
Storage	–65		+150	–65		+150	–65		+150	°C

NOTES

[1]For supply voltages less than ±15 V, the absolute maximum input voltage is equal to the supply voltage.

All min and max specifications are guaranteed. Specifications shown in **boldface** are tested on all production units at final electrical test. Results from those tests are used to calculate outgoing quality levels.

Specifications subject to change without notice.

Model	AD741K Min	AD741K Typ	AD741K Max	AD741L Min	AD741L Typ	AD741L Max	AD741S Min	AD741S Typ	AD741S Max	Units
OPEN-LOOP GAIN										
R_L = 1 kΩ, V_O = ±10 V							**50,000**	200,000		V/V
R_L = 2 kΩ, V_O = ±10 V	**50,000**	200,000		**50,000**	200,000					V/V
T_A = min to max R_L = 2 kΩ	**25,000**			**25,000**			**25,000**			V/V
OUTPUT CHARACTERISTICS										
Voltage @ R_L = 1 kΩ, T_A = min to max										V
Voltage @ R_L = 2 kΩ, T_A = min to max	**±10**	±13		**±10**	±13		**±10**	±13		V
Short Circuit Current		25			25			25		mA
FREQUENCY RESPONSE										
Unity Gain, Small Signal		1			1			1		MHz
Full Power Response		10			10			10		kHz
Slew Rate		0.5			0.5			0.5		V/µs
Transient Response (Unity Gain)										
Rise Time		0.3			0.3			0.3		µs
Overshoot		5.0			5.0			5.0		%
INPUT OFFSET VOLTAGE										
Initial, R_S ≤ 10 kΩ, Adjust to Zero		0.5	**2.0**		0.2	**0.5**		1.0	**2**	mV
T_A = min to max			**3.0**			**1.0**			**4**	mV
Average vs. Temperature (Untrimmed)		6.0	15.0		2.0	5.0		6.0	15	µV/°C
vs. Supply, T_A = min to max		5	15.0		5	15.0		30	100	µV/V
INPUT OFFSET CURRENT										
Initial		2	**10**		2	5		2	**10**	nA
T_A = min to max			**15**			**10**			**25**	nA
Average vs. Temperature		0.02	0.02		0.02	0.1		0.1	0.25	nA/°C
INPUT BIAS CURRENT										
Initial		30	**75**		30	**50**		30	**75**	nA
T_A = min to max			**120**			**100**			**250**	nA
Average vs. Temperature		0.6	1.5		0.6	1.0		0.6	2.0	nA/°C
INPUT IMPEDANCE DIFFERENTIAL		2.0			2.0			2.0		MΩ
INPUT VOLTAGE RANGE[1]										
Differential, max Safe		±30			±30			±30		V
Common-Mode, max Safe		±15			±15			±15		V
Common-Mode Rejection, R_S = ≤ 10 kΩ, T_A = min to max, V_{IN} = ±12 V	**90**	100		**90**	100		**90**	100		dB
POWER SUPPLY										
Rated Performance		±15			±15			±15		V
Operating	±5		±22	±5		±22	±5		±22	V
Power Supply Rejection Ratio		20			20			20		µV/V
Quiescent Current		1.7	**2.8**		1.7	**2.8**		2.0	**2.8**	mA
Power Consumption		50	85		50	85		50	85	mW
T_A = min								60	100	mW
T_A = max								75	115	mW
TEMPERATURE RANGE										
Operating Rated Performance	0		+70	0		+70	–55		+125	°C
Storage	–65		+150	–65		+150	–65		+150	°C

ABSOLUTE MAXIMUM RATINGS

Absolute Maximum Ratings	AD741, J, K, L, S	AD741C
Supply Voltage	±22 V	±18 V
Internal Power Dissipation	500 mW[1]	500 mW
Differential Input Voltage	±30 V	±30 V
Input Voltage	±15 V	±15 V
Storage Temperature Range	–65°C to +150°C	–65°C to +150°C
Lead Temperature (Soldering, 60 sec)	+300°C	+300°C
Output Short Circuit Duration	Indefinite[2]	Indefinite

NOTES
[1]Rating applies for case temperature to +125°C. Derate TO-99 linearity at 6.5 mW/°C for ambient temperatures above +70°C.
[2]Rating applies for shorts to ground or either supply at case temperatures to +125°C or ambient temperatures to +75°C.

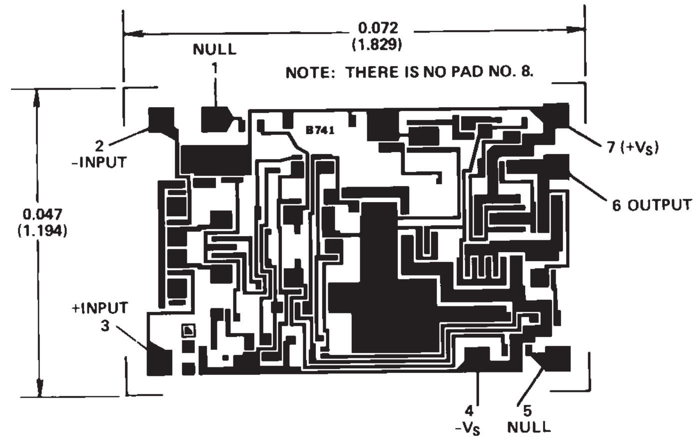
ORDERING GUIDE

Model[1]	Temperature Range	Initial Off Set Voltage	Package Description	Package Option
AD741CN	0°C to +70°C	6.0 mV	Mini-DIP	(N-8)
AD741CH	0°C to +70°C	6.0 mV	TO-99	(H-08A)
AD741JN	0°C to +70°C	3.0 mV	Mini-DIP	(N-8)
AD741JH	0°C to +70°C	3.0 mV	TO-99	(H-08A)
AD741KN	0°C to +70°C	2.0 mV	Mini-DIP	(N-8)
AD741KH	0°C to +70°C	2.0 mV	TO-99	(H-08A)
AD741LN	0°C to +70°C	0.5 mV	Mini-DIP	(N-8)
AD741LH	0°C to +70°C	0.5 mV	TO-99	(H-08A)
AD741H	–55°C to +125°C	5.0 mV	TO-99	(H-08A)
AD741SH	–55°C to +125°C	2.0 mV	TO-99	(H-08A)

NOTE
[1]J, K and S grade chips also available.

METALIZATION PHOTOGRAPH

All versions of the AD741 are available in chip form.
Contact factory for latest dimensions.
Dimensions shown in inches and (mm).

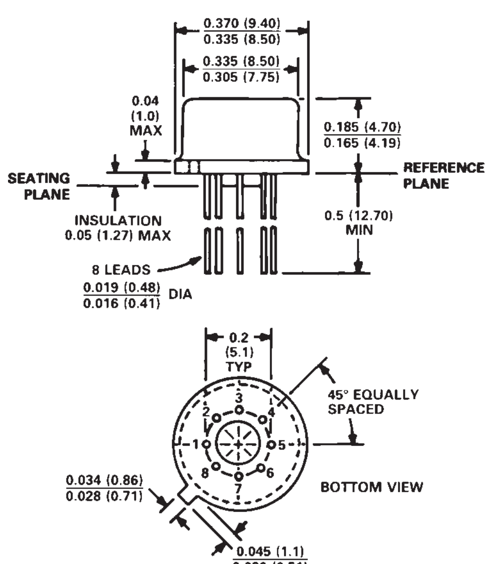


PAD NUMBERS CORRESPOND TO PIN NUMBERS FOR THE TO-99 8-PIN METAL PACKAGE.

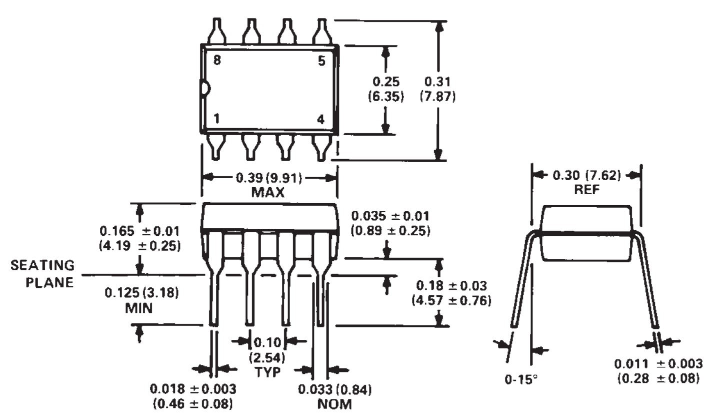
OUTLINE DIMENSIONS

Dimensions shown in inches and (mm).

TO-99 (H)



Mini DIP (N)



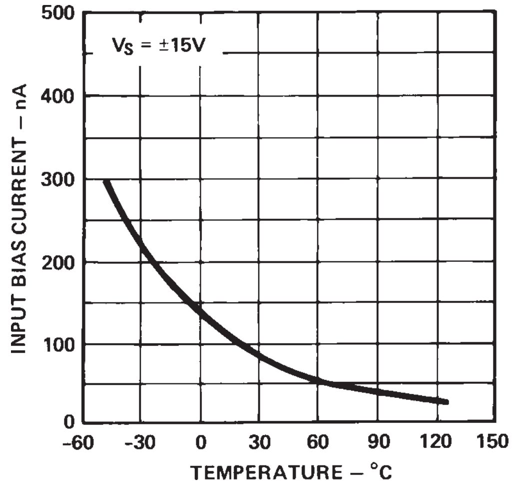


Figure 1. Input Bias Current vs. Temperature

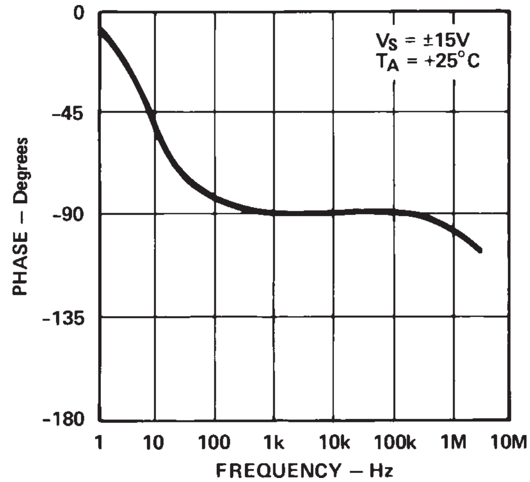


Figure 4. Open-Loop Phase Response vs. Frequency

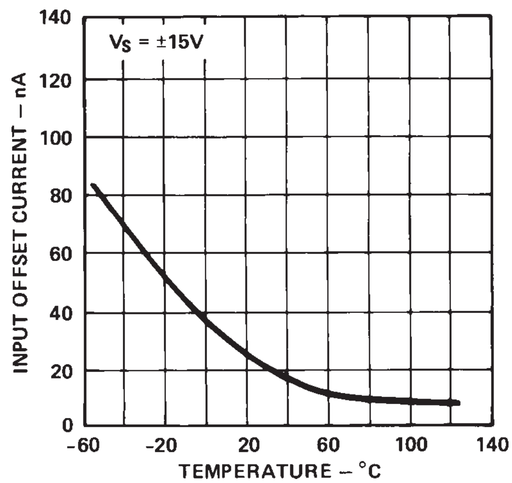


Figure 2. Input Offset Current vs. Temperature

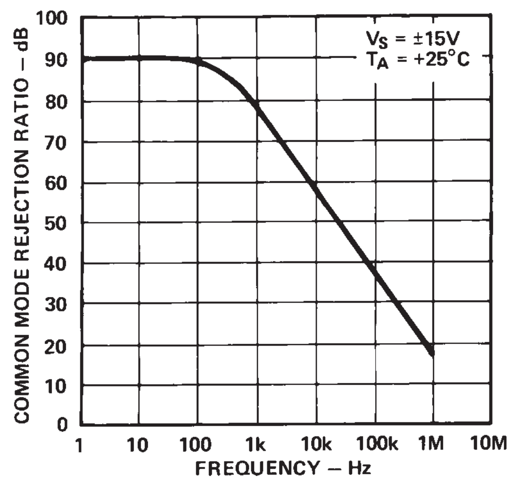


Figure 5. Common-Mode Rejection vs. Frequency

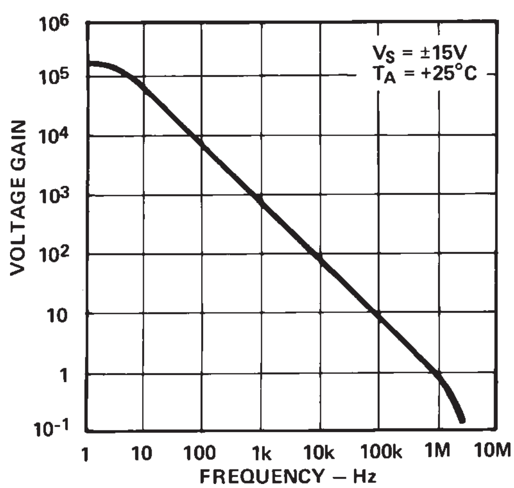


Figure 3. Open-Loop Gain vs. Frequency

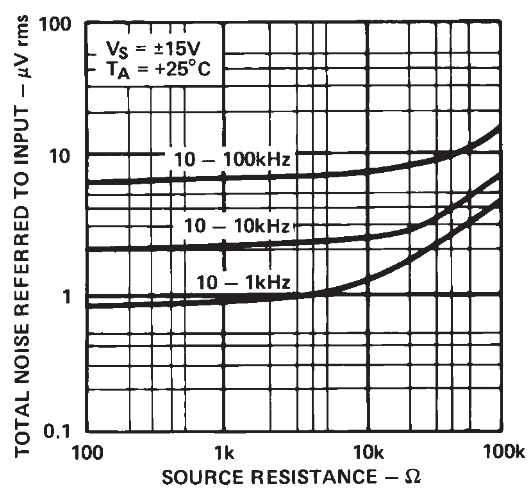


Figure 6. Broad Band Noise vs. Source Resistance

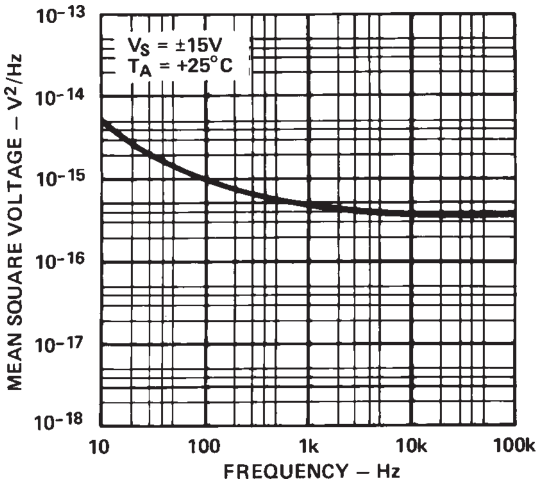


Figure 7. Input Noise Voltage vs. Frequency

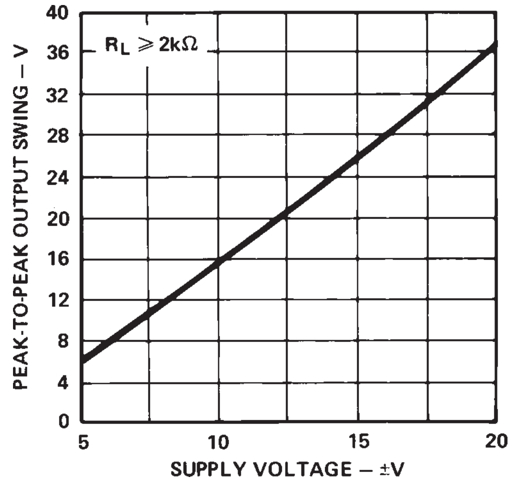


Figure 10. Output Voltage Swing vs. Supply Voltage

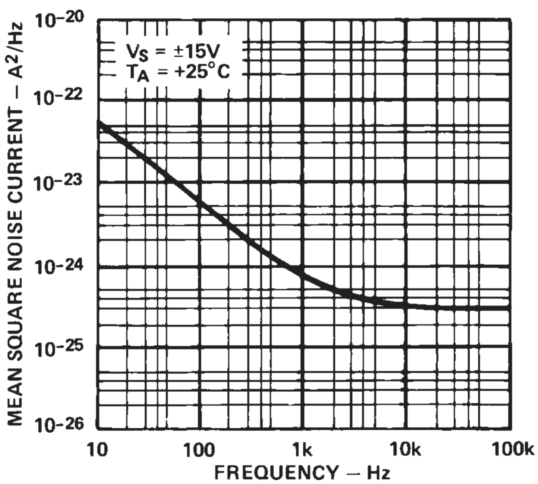


Figure 8. Input Noise Current vs. Frequency

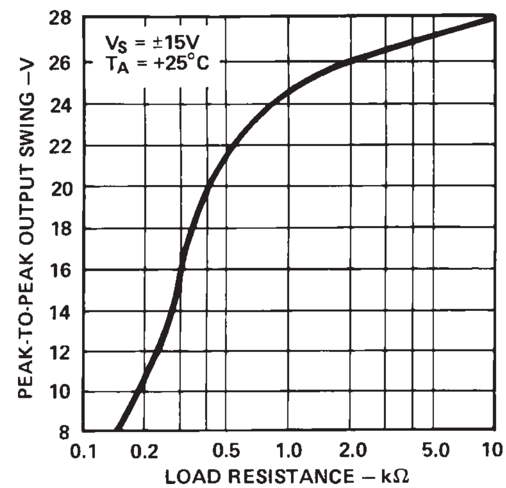


Figure 11. Output Voltage Swing vs. Load Resistance

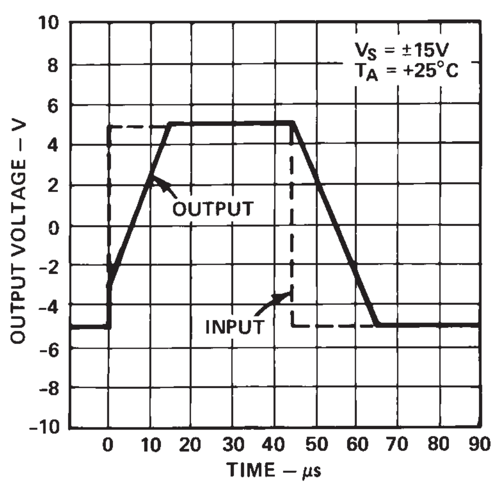


Figure 9. Voltage Follower Large Signal Pulse Response

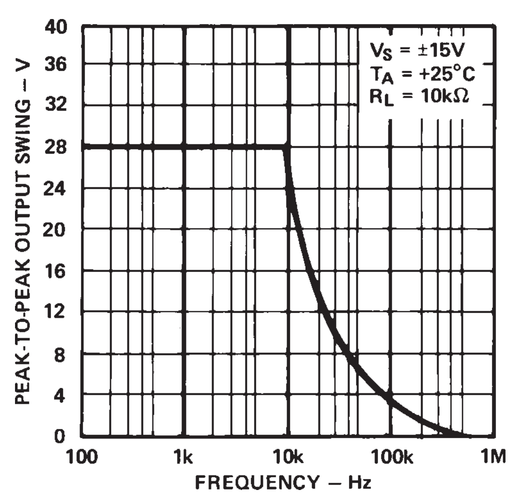


Figure 12. Output Voltage Swing vs. Frequency

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