Physikpraktikum für Vorgerückte (VP)

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Nr.

Manual

Electronics A
(Operational Amplifier)

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Abstract

This experiment is about the basic usage of some selected analog electrical circuits to simulate physical systems. An operational amplifier is used as a basic building block to assemble and measure different circuits which perform various mathematical operations. In this process, the handling of such components and electrical measurement devices is practised. Finally an analog computer is built in order to solve a differential equation.

Contents

1 Introduction

1.1 Properties of an Operational Amplifier

An operational amplifier (op-amp) is a direct current-coupled voltage amplifier with a high input resistance and a high voltage amplification. It has two inputs and one output. The ideal op-amp has the following characteristics:

1. The voltage amplification is infinitely large.
2. The input resistance is infinitely large, i.e. no current flows into the inputs of the op-amp.
3. The output resistance is zero, i.e. the output voltage of the op-amp is independent of the applied load.
4. There is no phase delay between (non-inverting) input and output signal.
5. The frequency response characteristic is flat and the bandwidth is infinite.
6. The output level is zero if no signal is applied to the input.

These assumptions simplify the layout of circuits with op-amps considerably. Real op-amps don't entirely fulfill these properties but in most cases it is possible to adopt these assumptions as an approximation when constructing a circuit.

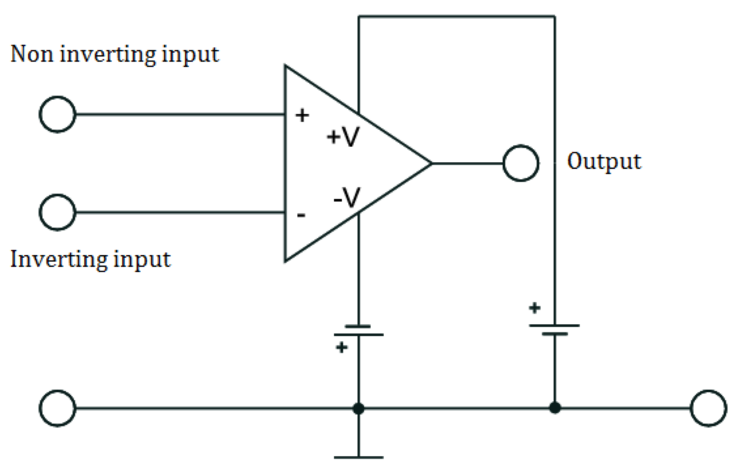


Figure 1: Electronic symbol of an op-amp

Figure 1 shows the electronic symbol of an op-amp. The positive input is called the non-inverting input which is marked with a plus sign, whereas the negative input, marked with a minus sign, is called the inverting input. The op-amp's necessary supply results from two (usually symmetric) feeding voltages $+V$ and $-V$ compared to the ground. The purpose of the offset-inputs is to adjust the output voltage to zero if no signal is applied.

1.2 The Principle of Feedback

From property 1 and 4 of the ideal op-amp, it follows that that the op-amp behaves in such a way that *both its input voltages are held equal.* This will be used in the discussion about the back coupling and about the analysis and layout of the circuit.

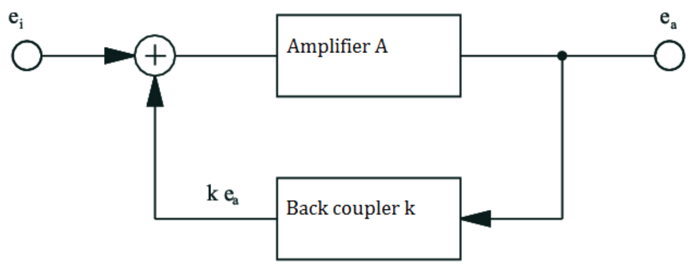


Figure 2: Principle of back coupling

In figure 2 the fundamental layout of the back coupling of an operational amplifier is shown. A part of the output voltage e_a is lead back to the input by a back coupling network, which is characterized by k. This k, as well as A, can be complex, frequency-dependent quantities. The subtraction of the back coupled voltage is called negative feedback; the addition is called positive feedback. With this, one can change the properties of a circuit considerably. It holds true that:

$$(e_i + k\, e_a)\ A \ = \ e_a \ \Longrightarrow \ e_a = \frac{A e_i}{1 - A\, k}$$

The total amplification with feedback is

$$G \ = \ \frac{e_a}{e_i} \ = \ \frac{A}{1 - A\, k}.$$

A distinction is drawn between three cases:

$\lvert G \rvert > \lvert A \rvert$	Positive feedback
$\lvert G \rvert < \lvert A \rvert$	Negative feedback
$G = A$	No feedback

For an ideal operational amplifier it holds that $A \to \infty$. We get for the total amplification:

$$G_{OP} \ = \ \frac{e_a}{e_i} \ = \ -\frac{1}{k}$$

Thus the total amplification depends on k and not anymore on the op-amp.

1.3 Real Operational Amplifier

The technically feasible component does not completely fulfill the prior properties. The voltage amplification lies at about a factor of 10^5. The input resistance in this case is in fact so high that the input currents can be neglected. The output resistance lies at 150 Ω. The frequency response is not flat but rather decreases the amplification with increasing frequency. This is necessarily caused by the (also ideally existing) phase delay between input and output signal. It is further not possible to produce a component that has no offset because of technical tolerances, i.e. even if no input signal is applied there will still be an output signal $\neq 0$. This offset voltage can be compensated in certain op-amp types (compare section 1.1).

1.3.1 Amplification

Assuming an amplification factor of $A = 10^5$ and a maximal output voltage of 10 V the difference of the two input voltages is

$$\Delta U = \frac{Uout}{A} = \frac{10V}{10^5} = 0.1mV \approx 0V$$

and can thus be neglected.

1.3.2 Input Resistance

The input resistance is amplified by the (usually added) negative feedback. This is shown in figure 3 in case of a closed negative feedback.

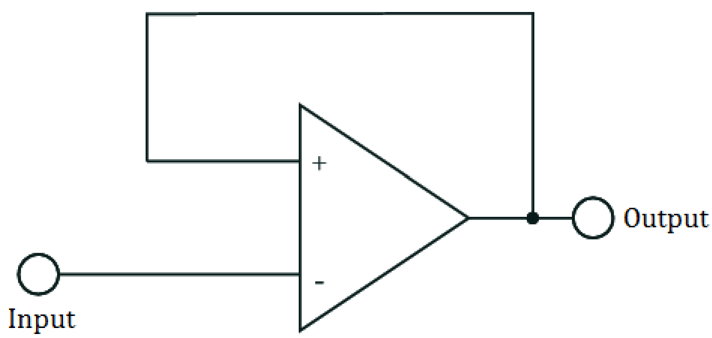


Figure 3: Op-amp with closed negative feedback

The voltage at the inverting input is equal to the one at the output. Changing the input signal by ΔU_i results in a change of the output signal such that the difference of them is $\Delta U = \frac{\Delta U_i}{A}$. With this there is a current of $J_i = \frac{\Delta U}{Z_i} = \frac{\Delta U_i}{AZ_i}$ flowing through the input, which corresponds to an input resistance of AZ_i. In reality this high value is previously limited by isolation currents. But a couple of MΩ are still achieved.

1.3.3 Output Resistance

The output resistance can be reduced through negative feedback. In principle Z_{out} is equal to the inner output resistance times the amplification factor of the circuit. (Why is that so?)

1.3.4 Frequency Dependent Properties

The frequency dependent properties of electrical circuits can be depicted in the so called Bode-plot, which is a double logarithmic coordinate system in which the frequency (on the abscissa) and the output voltage (on the ordinate) are plotted against each other.

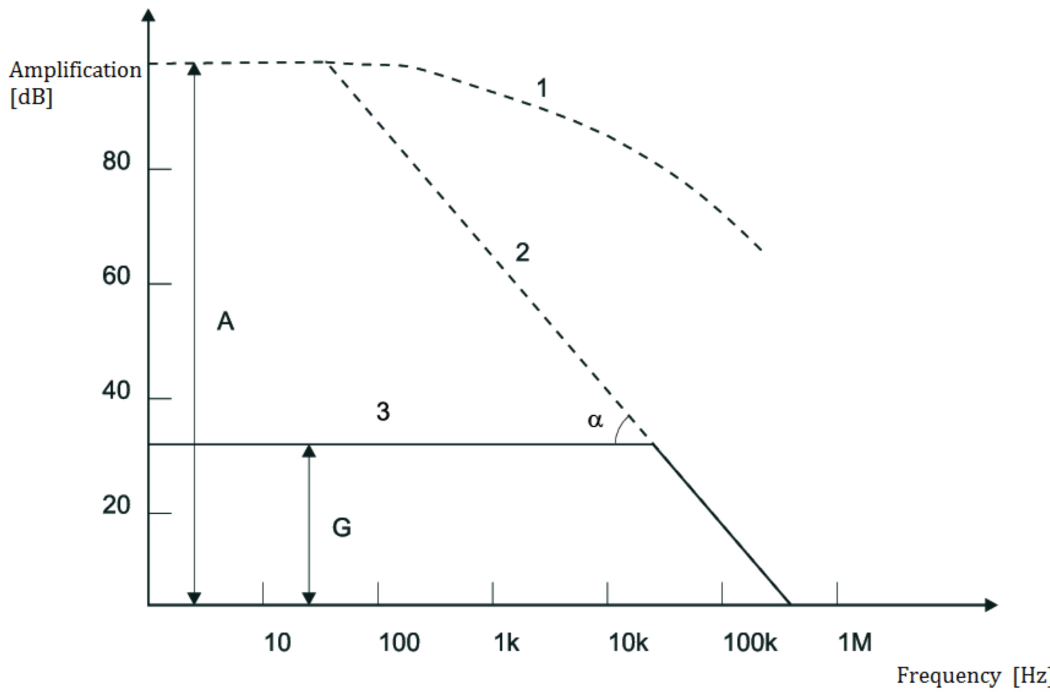


Figure 4: Bode-plot of an operational amplifier

The output voltage is given here relative to the input voltage in dB, i.e. it is actually an amplification-frequency diagram. A decibel is defined as: $1\,\mathrm{dB} = 20 \cdot log\left(\frac{U_{out}}{U_{in}}\right)$. In the plot A stands for the direct current amplification for an open loop and G stands for the amplification for back coupling. The angle of intersection α between curve 2 and 3 is decisive for the stability of the circuit. It should not be bigger than 12 dB/octave[1] or else the circuit becomes unstable and starts to oscillate. The frequency response in the operational amplifier is adjusted such that this is not the case. Curve 2 shows the frequency response of an op-amp, curve 1 shows that of an op-amp without such a frequency correction (these components are called comparators).

1.3.5 Practical Considerations

An operational amplifier only works correctly for a specific input voltage range, which is fixed by the supply voltage. In order to have a zero point that definitely is in the range of the input voltage, the zero point is usually put in the middle of the input voltage, i.e. two equal input voltages are used, one negative and one positive.
While working with electrical components the maximum permissible values of the supply voltage and input voltage for example have to be adhered to or else the component will be destroyed. Apart from that, the utilized 741 are very robust and are not prone to errors which are almost unavoidable during practical experimentation.

[1] An octave corresponds to the doubling or halving of a frequency, which means that the number of octaves=$\log_2(\frac{f_2}{f_1})$.

1.3.6 Pin Assignment

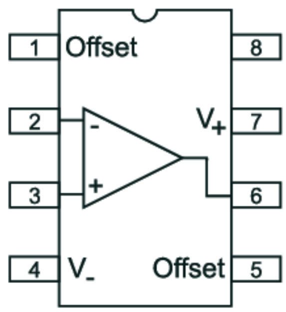


Figure 5: Pin assignment of the 741

Figure 5 shows how the operational amplifier should be connected. Pin number 1 is marked by the dent at the top, where the op-amp 741 is seen from above. Pin number 1 and 5 are used for compensation of output offset voltages (compare section 1.3), which is not needed for this experiment. As mentioned denote V_+ and V_- the pins for the supply voltages.

1.4 Layout of the Operational Amplifier

The most basic setup of an operational amplifier is shown in figure 6, where the first two transistors are connected as differential amplifiers, the third one (counted from the left) is connected as an emitter-follower. The differential amplifier causes the voltage amplification and the emitter-follower causes current amplification. An op-amp's typical layout is shown in the appendix on page 3-32.

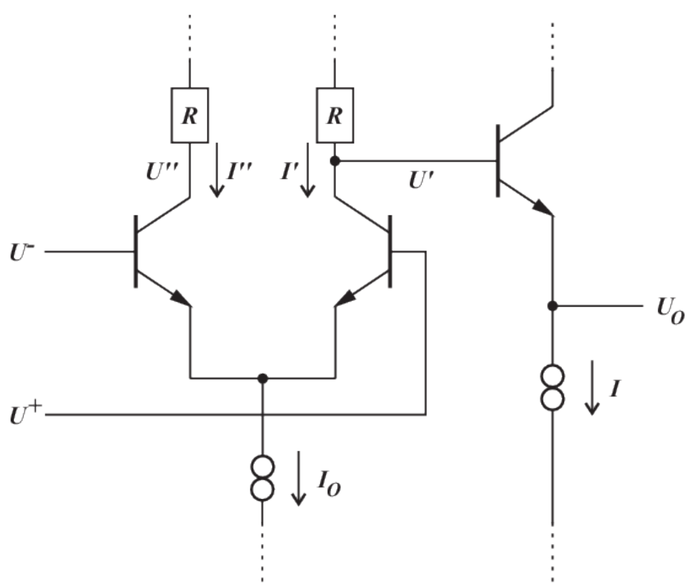


Figure 6: Simple layout of an operational amplifier

To calculate the voltage amplification of the differential amplifier the low-level signal model of the bipolar transistor (figure 7) is used. For small signals a linear behavior between basic current and voltage with the proportionality factor g is assumed:

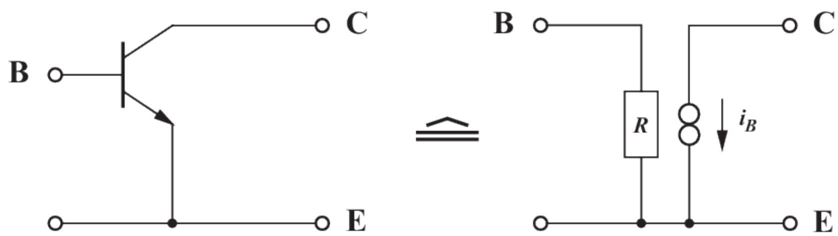


Figure 7: Low-level signal model of the bipolar transistor

$$i_B = g\,U_{BE}$$

and from that follows for the collector current

$$i_C = \beta\, i_B,$$

where β stands for the direct current amplification. For the differential amplifier it follows that:

$$I' = \beta\, g\, U^{+} \text{ and}$$

$$I'' = \beta\, g\, U^{-}$$

The input voltage difference is equal to

$$\Delta U := U^{+} - U^{-} = \frac{I' - I''}{\beta g}.$$

The sum of the collector currents is held constant:

$$I' + I'' = I_O, \text{ from which follows that}$$

$$U' = RI' = \tfrac{1}{2} R\,(\Delta U\, \beta g + I_O).$$

The amplification is thus

$$\frac{\partial U'}{\partial \Delta U} = \frac{1}{2} R\, \beta\, g.$$

The output voltage U_0 is approximately equal to the voltage U' minus a constant. The negative output current is maximal I.

2 Basic Circuits

2.1 The Inverting Amplifier

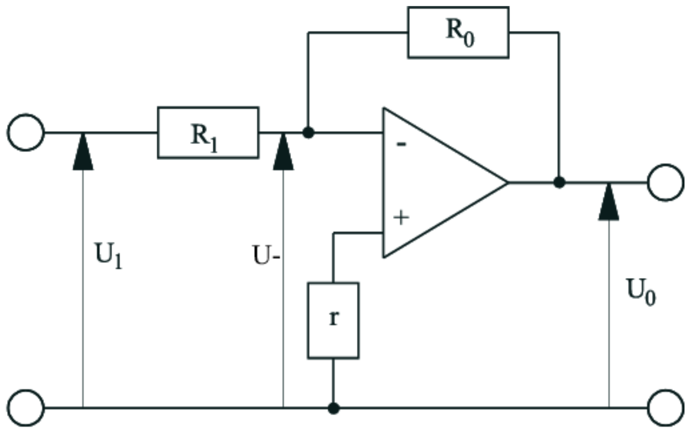


Figure 8: Circuit diagram of the inverting amplifier

Because of the infinitely large input impedance of the ideal op-amp, it follows for the current through the resistances R_0 and R_1:

$$I = \frac{U_1 - U_-}{R_1} = \frac{U_- - U_0}{R_0}$$

where ideally $U_- = 0$. Thus this holds true for the total amplification:

$$\boxed{G = \frac{U_0}{U_1} = -\frac{R_0}{R_1}} \tag{1}$$

The output signal is inverted, i.e. a positive input signal results in a negative output signal. For a sinusoidal signal this results in a phase shift of 180°. As the resistance r does not come up in the calculation it can be replaced by a direct link. Circuits with op-amps are made such that both inputs are connected to the same impedance $r = \frac{R_0 R_1}{R_0 + R_1}$ to minimize the offset voltage drift.

2.2 The Non-Inverting Amplifier

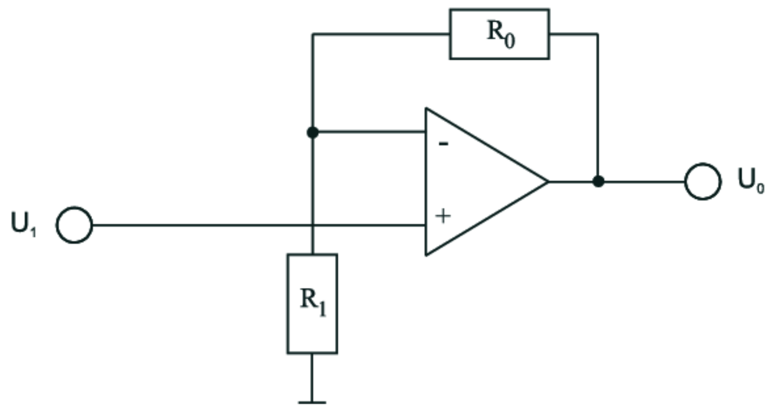


Figure 9: Circuit diagram of the non-inverting amplifier

It holds true that $U_{-} = U_1 = U_0 \frac{R_1}{R_0+R_1}$ and thus for the amplification:

$$\boxed{G = \frac{R_0 + R_1}{R_1}} \tag{2}$$

2.3 Summing Amplifier

The summation of two currents in one point of connection can be used to add voltages:

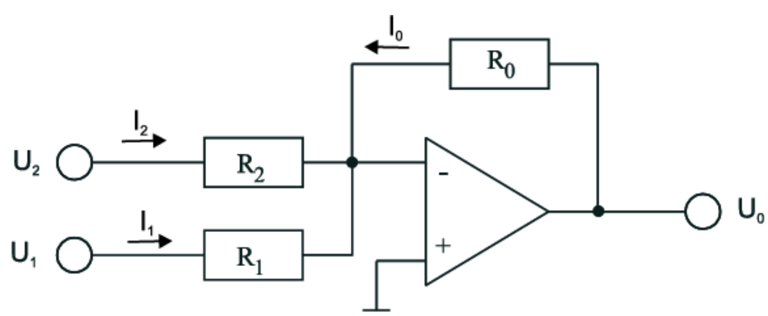


Figure 10: Circuit diagram of the inverting voltage summer

$$I_0 = I_1 + I_2$$
$$U_0 = -R_0 I_0 = -(U_1 \frac{R_0}{R_1} + U_2 \frac{R_0}{R_2})$$

This is the weighted summation of U_1 and U_2 (with the addition weights $\alpha_i = -\frac{R_o}{R_i}$). This circuit can of course be extended to an arbitrary amount of inputs.

2.4 Constant Current Source

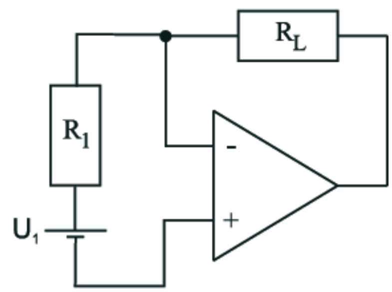


Figure 11: Circuit diagram of the constant current source

For this setup it holds true that $I_1 = I_L$, because no input currents are flowing and $I_L = \frac{U_1}{R_1}$. It is thus independent of the load resistance R_L.

2.5 Integrator

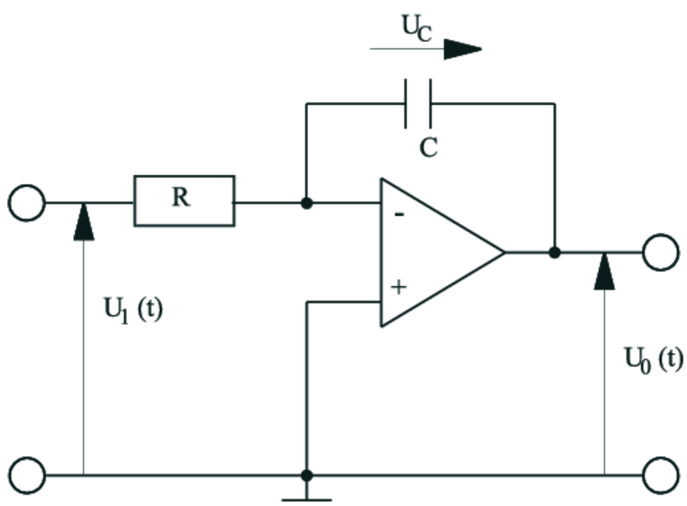


Figure 12: The integrator

Through the capacitor C runs a back-coupling current of $I_c = \frac{dQ}{dt} = C\frac{dU_c}{dt}$. Because of $U_0 = -U_c$ and $I_c = I_R$ it follows that for the output voltage

$$U_0(t) = \frac{1}{C}\left(-\int_0^t I_C(\tau)\,d\tau + Q_0\right) = -\frac{1}{RC}\int_0^t U_1(\tau)\,d\tau + U_0(t=0), \tag{3}$$

with $I_C = U_1/R$, where Q_0 is the charge, which was on the capacitor at the beginning of the integration at $t = 0$.

2.6 Filter

The behavior of linear circuit elements towards periodic voltages and currents with fixed frequency can be described using complex impedances which are defined as the following:

Ohmic resistance R	$Z_R = R$
Capacitor C	$Z_C = \frac{1}{i\,\omega\,C}$
Solenoid L	$Z_L = i\,\omega\,L$

The resistance R_0 in figure 8 (inverting amplifier) can now, for example, be exchanged with $Z_C = \frac{1}{i\omega C}$. The amplification thus results in

$$g = \frac{1}{i\,\omega\,R\,C} \qquad |g| = \frac{1}{\omega\,R\,C}$$

where $\omega = 2\pi f$ is the angular frequency. The equations mentioned above for the amplification $|g|$ are only valid for a harmonic oscillation with angular frequency ω. For more complicated signals the Fourier components have to be considered separately. Each component with angular frequency ω_k of the Fourier-series of the input signal is amplified by

$$|g_k| = \frac{1}{\omega_k\,R\,C}.$$

3 Experiments

The following instructions are to be understood as suggestions. There are numerous other possibilities which are not mentioned here but are nonetheless interesting to be studied.
The measurements are conducted with a cathode ray oscilloscope (CRO), with which the input and output amplitudes of the circuits are measured. Normally the peak to peak value is taken, because it is the easiest to be determined. The input signal is normally a sinusoidal signal.

3.1 Measurement of the Frequency-Dependence

Depending on the circuit, the frequency will be varied over a wide range. The set frequency can be determined with the CRO. There are also frequency counters at hand with which very precise measurements can be taken.
For example, the frequency dependence, the phase shift between the input and the output signal, the signal distortion or other properties, can be tested by means of a basic circuit.

3.2 The Integrator

The circuit in figure 12 can integrate signals over time. Available as input signals are sinusoidal, rectangular and triangular signals. These are converted and phase shifted accordingly. Furthermore, the output amplitude according to equation (3), is strongly dependent on the frequency.
Note that for direct current there is no negative feedback as the capacitor blocks it. As a result, the output voltage of the integrator decays more or less quickly down to the (positive or negative) limit which is given by the supply voltage, as seen on the CRO. The integrator thus has to be discharged by short-circuiting the capacitor every now and then. Another possibility is to connect a resistance in parallel to the capacitor. It should be big enough not to significantly affect the measurement results but provide a stable operation.

3.3 The Schmitt Trigger

A Schmitt trigger is a circuit which transforms any arbitrary input signal into a rectangular one: when the input signals reaches a certain level the output signals becomes "high" and when it falls below a certain value the output signals becomes "low". For this it is necessary that there is a hysteresis of the output signal to avoid undefined states at the threshold voltage and to have a range for which the output signal does not change although the input signal is overlaid with voltage fluctuations. The circuit is shown in figure 13.

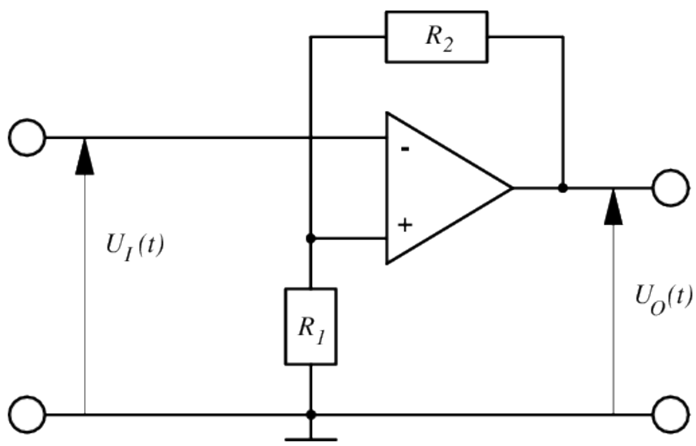


Figure 13: Schmitt trigger

When U_I is small, the output of the op-amp is at its maximal voltages U_m (a bit smaller than the supply voltage):

$$\begin{aligned} U_O &= +U_m \\ U_+ &= U_m \frac{R_1}{R_1 + R_2} = \text{threshold voltage} \end{aligned}$$

If the input voltage now rises over the threshold voltage, the output voltage drops to the minimal value $-U_m$ and thus the threshold voltage changes. This change causes the hysteresis, as visible in figure 14 and 15.

i.e., if $U_I > U_+$:

$$\begin{aligned} \longrightarrow U_O &= -U_m \\ U_+ &= -U_m \frac{R_1}{R_1 + R_2} \end{aligned}$$

$$\text{Hysteresis} = 2\,U_m \frac{R_1}{R_1 + R_2}$$

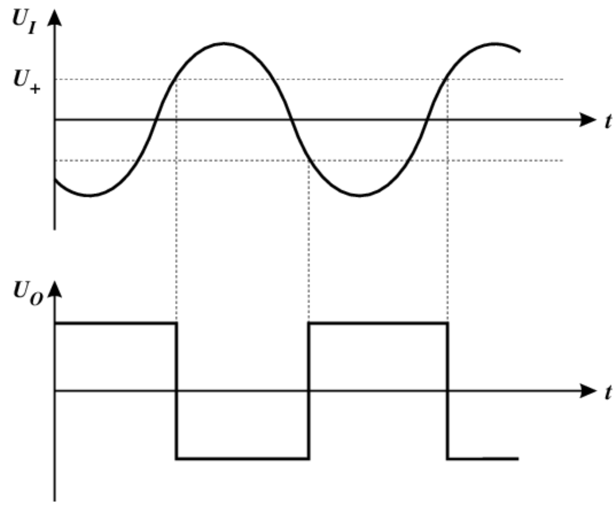


Figure 14: Input and output signal

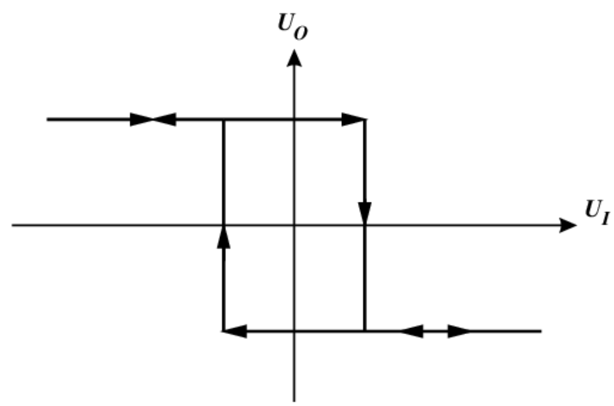


Figure 15: Behavior of the hysteresis of the Schmitt trigger

3.4 Solution of Differential Equations

These operational amplifiers can be combined as well. This example shows how, using analog electronics, a differential equation can be solved. To this end, integrators and summers are combined in a suitable way. It would be possible as well to build differentiators using operational amplifiers but these are less stable in operation.
An example of a differential equation of an oscillation is of the following form:

$$\ddot{x}(t) + 2\rho\,\dot{x}(t) + \omega_0^2 x(t) \; = \; -\omega_0^2 K(t)$$

with $-\omega_0^2 K(t)$ being from the external excitation. Integrating this differential equation twice results in

$$x(t) + 2\rho \int x(t)dt + \omega_0^2 \int\!\!\int x(t)dt^2 \; = \; -\omega_0^2 \int\!\!\int K(t)dt^2 \tag{4}$$

The corresponding analog computer circuit is shown in figure 16.

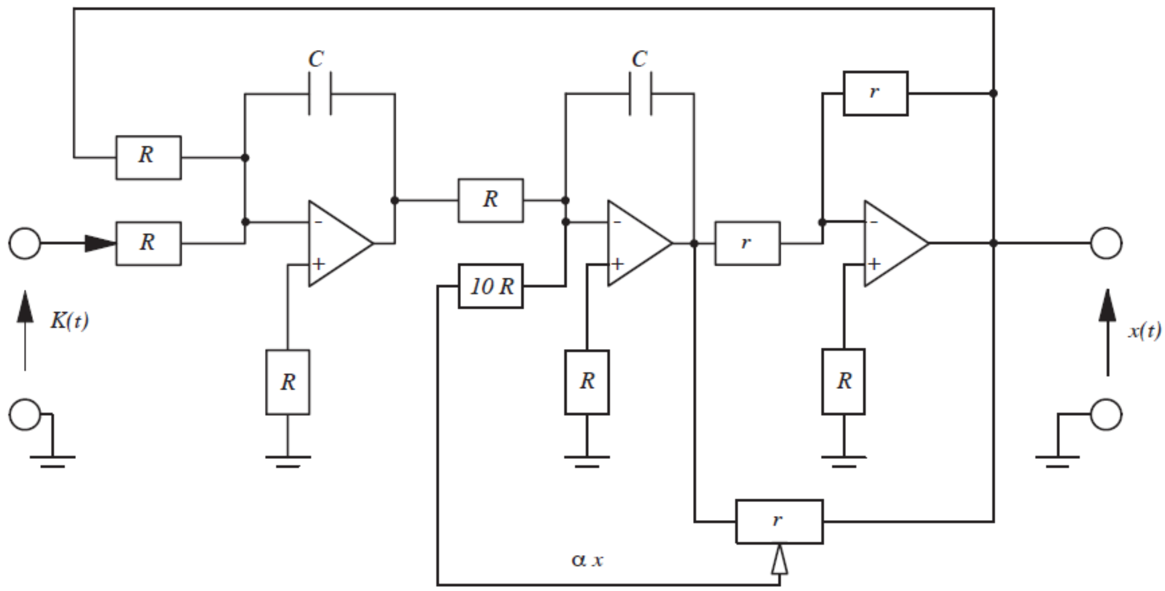


Figure 16: Analog computer for the oscillation differential equation. The values of the element are: C=1 μF, R=100 kΩ, r=10 kΩ.

Now let

$$T := RC$$

The first op-amp in figure 16 sums $x + K$ and builds the inverted amplified integral of the sum:

$$y_1(t) := -\frac{1}{T}\int x(t)dt - \frac{1}{T}\int K(t)dt$$

The second op-amp yields:

$$\begin{aligned} y_2(t) :&= -\frac{1}{T}\int y_1(t)dt - \frac{1}{T}\int K(t)dt \\ &= \frac{1}{T^2}\iint x(t)dt^2 + \frac{1}{T^2}\iint K(t)dt^2 - \frac{\alpha}{10T}\int x(t)dt \end{aligned}$$

A third op-amp is put as a voltage inverter in front of the output:

$$y_3(t) := -y_2(t) = x(t)$$

With this we get the following equation:

$$x(t) - \frac{\alpha}{10T}\int x(t)dt + \frac{1}{T^2}\iint x(t)dt^2 = -\frac{1}{T^2}\iint K(t)dt^2 \tag{5}$$

Comparison of equation 4 and 5 with each other yields

$$\begin{aligned} 2\rho &= -\frac{\alpha}{10T} \\ \omega_0^2 &= \frac{1}{T^2} \end{aligned}$$

where α can be varied between -1 and $+1$. The case $\alpha = 1$ corresponds to a negative damping (i.e. the amplitude increases after about 20 oscillations to $e-$times its original value) and $\alpha = -1$ corresponds to a positive damping (i.e. the amplitude falls). The factor α can be set with the potentiometer.
With this circuit can for example the transient oscillations as well as the resonance behavior be measured and recorded. With this circuit, one can for example measure and record both the transient oscillations and the resonance behavior.

3.4.1 Transient Oscillations without External Excitation

The amplitude increases or decreases over time depending on the setting of α. These curves can be recorded with the x-y recorder or digital oscilloscope. For this one has to pay attention to determine and write down the set scales of the recorder as well as the parameter (α).

3.4.2 Transient Oscillations with External Excitation

For this part a sinusoidal signal is connected to the input of the oscillator. This external excitation should be close to the resonance frequency. The amplitude of the input signal should be written down.

3.4.3 The Resonance Behavior of the Harmonic Oscillator

For the measurements of the resonance curve (i.e. the output amplitude as a function of the frequency) it is recommended to use a much higher eigenfrequency of the oscillator, otherwise it will take long until the stationary state is reached and it would be thus much more complicated to read off the amplitudes. For this the capacitors C are exchanged with smaller ones.

4 References

1. U. Tieze, Ch. Schenk: *Halbleiter-Schaltungstechnik*
2. R.U. Redmer: *Schaltungen mit dem IC-741*
3. S.M. Sze: *Physics of Semiconductor Devices*
4. Burr-Brown: *Handbook of Operational Amplifier Applications*

5 Appendix: Data sheet of a 741

HARRIS SEMICONDUCTOR

CA741, CA741C, CA1458, CA1558, LM741, LM741C, LM1458

Single and Dual, High Gain Operational Amplifiers for Military, Industrial and Commercial Applications

November 1996

Features

- **Input Bias Current . . . . 500nA (Max)**
- **Input Offset Current. . . . . 200nA (Max)**

Applications

- **Comparator**
- **DC Amplifier**
- **Integrator or Differentiator**
- **Multivibrator**
- **Summing Amplifier**
- **Narrow Band or Band Pass Filter**

Ordering Information

PART NUMBER	TEMP. RANGE (^{o}C)	PACKAGE	PKG. NO.
CA0741E	-55 to 125	8 Ld PDIP	E8.3
CA0741CE	0 to 70	8 Ld PDIP	E8.3
CA1458E	0 to 70	8 Ld PDIP	E8.3
CA1558E	-55 to 125	8 Ld PDIP	E8.3
CA0741T	-55 to 125	8 Pin Metal Can	T8.C
CA0741CT	0 to 70	8 Pin Metal Can	T8.C
CA1458T	0 to 70	8 Pin Metal Can	T8.C
CA1558T	-55 to 125	8 Pin Metal Can	T8.C
LM741N	-55 to 125	8 Ld PDIP	E8.3
LM741CN	0 to 70	8 Ld PDIP	E8.3
LM741H	-55 to 125	8 Pin Metal Can	T8.C
LM741CH	0 to 70	8 Pin Metal Can	T8.C
LM1458N	0 to 70	8 Ld PDIP	E8.3

Description

The CA1458, CA1558 (dual types); CA741C, CA741 (single types); high-gain operational amplifiers for use in military, industrial, and commercial applications.

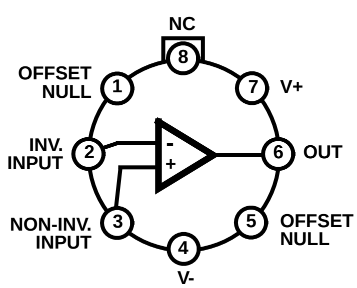
These monolithic silicon integrated circuit devices provide output short circuit protection and latch-free operation. These types also feature wide common mode and differential mode signal ranges and have low offset voltage nulling capability when used with an appropriately valued potentiometer. A 10kΩ potentiometer is used for offset nulling types CA741C, CA741 (see Figure 1). Types CA1458, CA1558 have no specific terminals for offset nulling. Each type consists of a differential input amplifier that effectively drives a gain and level shifting stage having a complementary emitter follower output.

The manufacturing process make it possible to produce IC operational amplifiers with low burst “popcorn” noise characteristics. The CA741 gives limit specifications for burst noise in the data bulletin, File Number 530. Contact your Sales Representative for information pertinent to other operational amplifier types that meet low burst noise specifications.

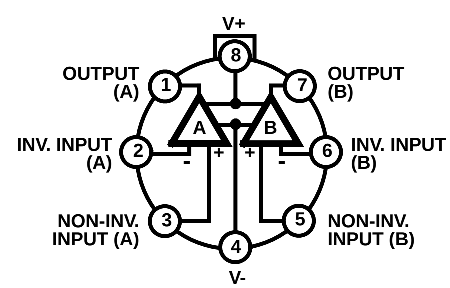
Technical Data on LM Branded types is identical to the corresponding CA Branded types.

Pinouts

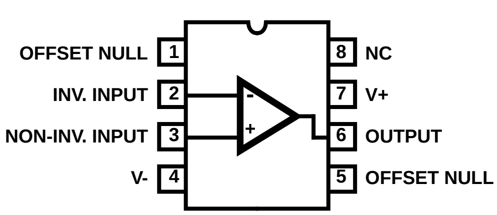
CA741, CA741C, LM741, LM741C (CAN)
TOP VIEW



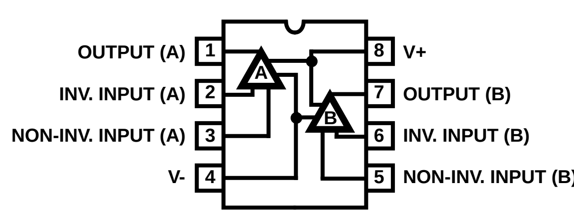
CA1458, CA1558 (METAL CAN)
TOP VIEW



CA741, CA741C, LM741, LM741C (PDIP)
TOP VIEW



CA1458, CA1558, LM1458 (PDIP)
TOP VIEW



Absolute Maximum Ratings

Supply Voltage
- CA741C, CA1458, LM741C, LM1458 (Note 1) 36V
- CA741, CA1558, LM741 (Note 1) 44V

Differential Input Voltage 30V
Input Voltage . . . . $\pm V_{SUPPLY}$
Offset Terminal to V- Terminal Voltage (CA741C, CA741) . . . ±0.5V
Output Short Circuit Duration . . . . Indefinite

Thermal Information

Thermal Resistance (Typical, Note 3)	θ_{JA} ($^oC/W$)	θ_{JC} ($^oC/W$)
PDIP Package	130	N/A
Can Package	155	67

Maximum Junction Temperature (Can Package) . . . . 175^{o}C
Maximum Junction Temperature (Plastic Package) . . . . 150^{o}C
Maximum Storage Temperature Range . . . . -65^{o}C to 150^{o}C
Maximum Lead Temperature (Soldering 10s) . . . . 300^{o}C

Operating Conditions

Temperature Range
- CA741, CA1558, LM741 . . . . -55^{o}C to 125^{o}C
- CA741C, CA1458, LM741C, LM1458 (Note 2) . . . . . 0^{o}C to 70^{o}C

CAUTION: Stresses above those listed in "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress only rating and operation of the device at these or any other conditions above those indicated in the operational sections of this specification is not implied.

NOTES:
1. Values apply for each section of the dual amplifiers.
2. All types in any package style can be operated over the temperature range of -55^{o}C to 125^{o}C, although the published limits for certain electrical specification apply only over the temperature range of 0^{o}C to 70^{o}C.
3. θ_{JA} is measured with the component mounted on an evaluation PC board in free air.

Electrical Specifications

Typical Values Intended Only for Design Guidance, V_{SUPPLY} = ±15V

PARAMETER	SYMBOL	TEST CONDITIONS	TYPICAL VALUE (ALL TYPES)	UNITS
Input Capacitance	C_I		1.4	pF
Offset Voltage Adjustment Range			±15	mV
Output Resistance	R_O		75	Ω
Output Short Circuit Current			25	mA
Transient Response: Rise Time	t_r	Unity Gain, V_I = 20mV, R_L = 2kΩ, $C_L \leq$ 100pF	0.3	µs
Transient Response: Overshoot	O.S.		5.0	%
Slew Rate (Closed Loop)	SR	$R_L \geq$ 2kΩ	0.5	V/µs

Electrical Specifications

For Equipment Design, V_{SUPPLY} = ±15V

PARAMETER	TEST CONDITIONS	TEMP (^{o}C)	(NOTE 4) CA741, CA1558, LM741 MIN	TYP	MAX	(NOTE 4) CA741C, CA1458, LM741C, LM1458 MIN	TYP	MAX	UNITS
Input Offset Voltage	$R_S \leq$ 10kΩ	25	-	1	5	-	2	6	mV
		Full	-	1	6	-	-	7.5	mV
Input Common Mode Voltage Range		25	-	-	-	±12V	±13V	-	V
		Full	±12V	±13V	-	-	-	-	V
Common Mode Rejection Ratio	$R_S \leq$ 10kΩ	25	-	-	-	70	90	-	dB
		Full	70	90	-	-	-	-	dB
Power Supply Rejection Ratio	$R_S \leq$ 10kΩ	25	-	-	-	-	30	150	µV/V
		Full	-	30	150	-	-	-	µV/V
Input Resistance		25	0.3	2	-	0.3	2	-	MΩ

Electrical Specifications For Equipment Design, V_{SUPPLY} = ±15V **(Continued)**

PARAMETER	TEST CONDITIONS	TEMP (°C)	(NOTE 4) CA741, CA1558, LM741 MIN	TYP	MAX	(NOTE 4) CA741C, CA1458, LM741C, LM1458 MIN	TYP	MAX	UNITS
Input Bias Current		25	-	80	500	-	80	500	nA
		Full	-	-	-	-	-	800	nA
		-55	-	300	1500	-	-	-	nA
		125	-	30	500	-	-	-	nA
Input Offset Current		25	-	20	200	-	20	200	nA
		Full	-	-	-	-	-	300	nA
		-55	-	85	500	-	-	-	nA
		125	-	7	200	-	-	-	nA
Large Signal Voltage Gain	$R_L \geq 2k\Omega$, $V_O = \pm10V$	25	50,000	200,000	-	20,000	200,000	-	V/V
		Full	25,000	-	-	15,000	-	-	V/V
Output Voltage Swing	$R_L \geq 10k\Omega$	25	-	-	-	±12V	±14V	-	V
		Full	±12V	±14V	-	-	-	-	
	$R_L \geq 2k\Omega$	25	-	-	-	±10V	±13V	-	V
		Full	±10V	±13V	-	±10V	±13V	-	
Supply Current		25	-	1.7	2.8	-	1.7	2.8	mA
		-55	-	2	3.3	-	-	-	mA
		125	-	1.5	2.5	-	-	-	mA
Device Power Dissipation		25	-	50	85	-	50	85	mW
		-55	-	60	100	-	-	-	mW
		125	-	45	75	-	-	-	mW

NOTE:

4. Values apply for each section of the dual amplifiers.

Test Circuits

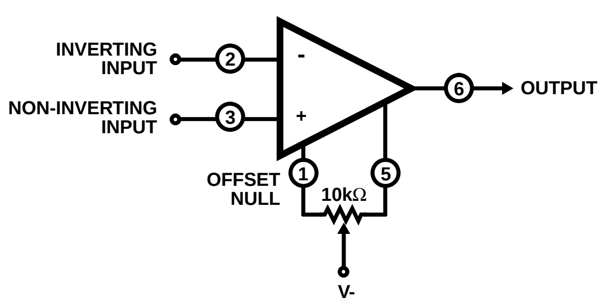


FIGURE 1. OFFSET VOLTAGE NULL CIRCUIT FOR CA741C, CA741, LM741C, AND LM741

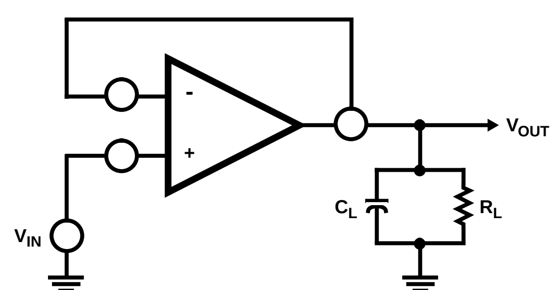
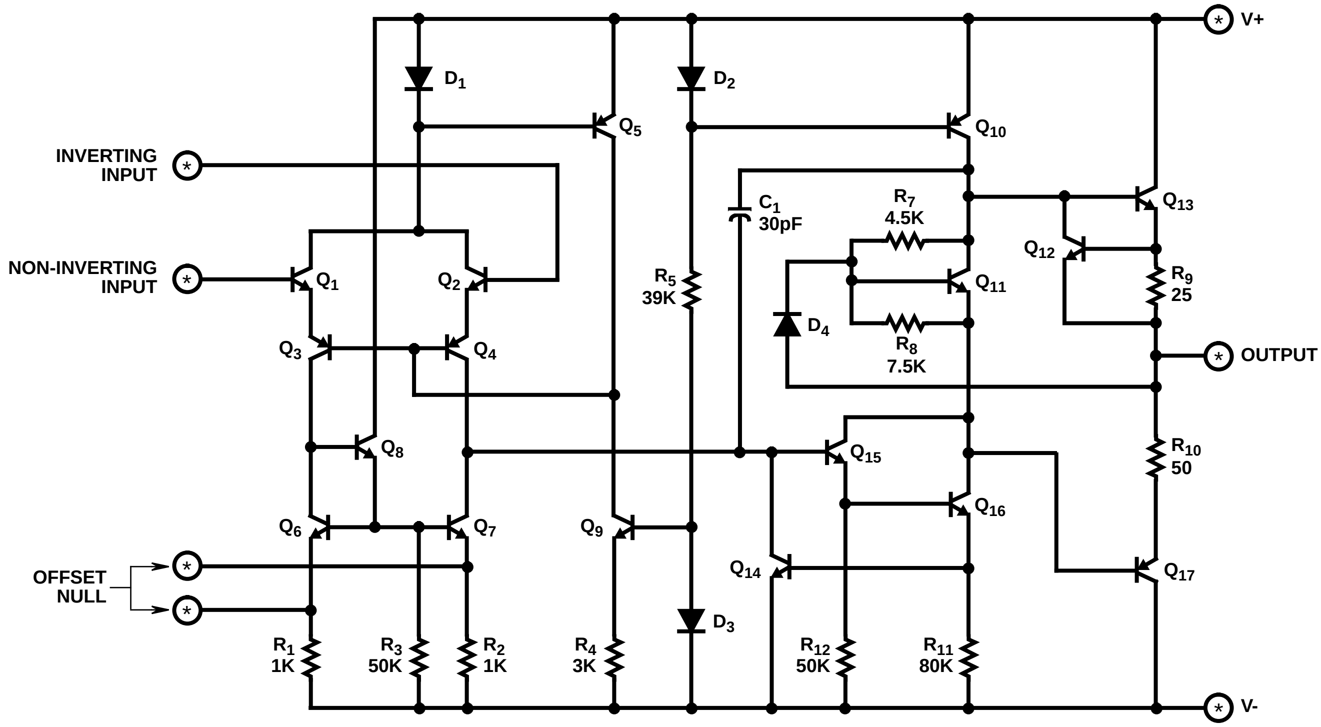


FIGURE 2. TRANSIENT RESPONSE TEST CIRCUIT FOR ALL TYPES

Schematic Diagram (Notes 5, 6)

CA741C, CA741, LM741C, LM741 AND FOR EACH AMPLIFIER OF THE CA1458, CA1558, AND LM1458



NOTES:

5. See Pinouts for Terminal Numbers of Respective Types.
6. All Resistance Values are in Ohms.

Typical Performance Curves

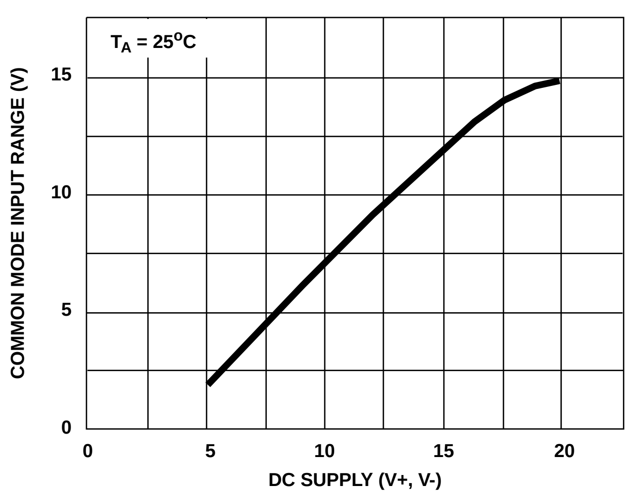


FIGURE 3. COMMON MODE INPUT VOLTAGE RANGE vs SUPPLY VOLTAGE FOR ALL TYPES

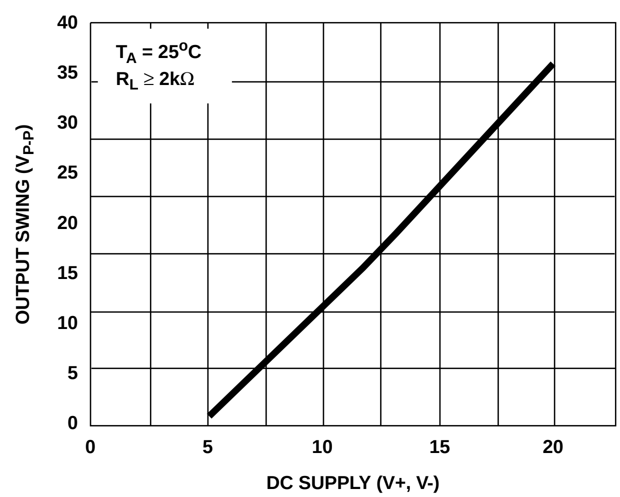


FIGURE 4. OUTPUT VOLTAGE vs SUPPLY VOLTAGE FOR ALL TYPES

Typical Performance Curves (Continued)

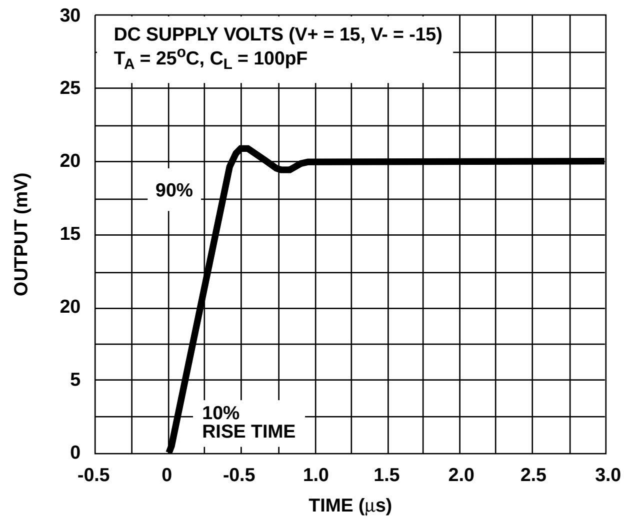
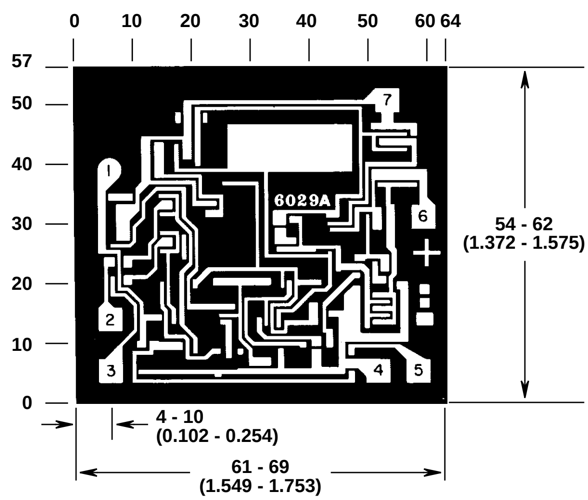


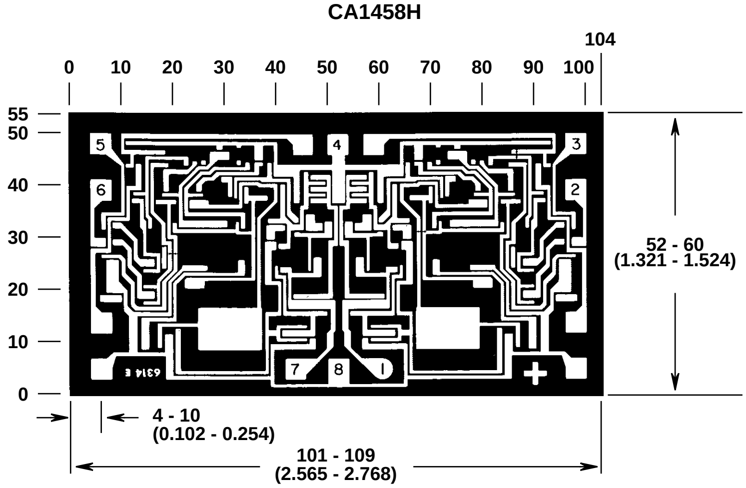
FIGURE 5. TRANSIENT RESPONSE FOR CA741C AND CA741

Metallization Mask Layout

CA741CH



CA1458H



NOTE: Dimensions in parentheses are in millimeters and are derived from the basic inch dimensions as indicated. Grid graduations are in mils (10^{-3} inch).