

# Electronics A

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November 10, 2022

## Abstract

In this lab we investigate four common circuits built around the operational amplifier LM741: An inverting amplifier, a non-inverting amplifier, a Schmitt trigger and an integrator. For the two amplifiers we investigate their amplification behavior depending on the resistor values. We conclude that these circuits behave as expected from theory, though for higher voltages, we see a slight deviation due to the operational limits of our op-amp. A frequency response analysis was performed for the inverting amplifier, for which we determined the cutoff frequency to be around 40 kHz, and for the integrator, who had a much lower cutoff frequency of around 10 Hz, due to the capacitor in the circuit. For the Schmitt trigger we again showed that the trigger frequency depends on the resistances as we would expect from theory and that the slight deviations stem from operating the op-amp at its limits.

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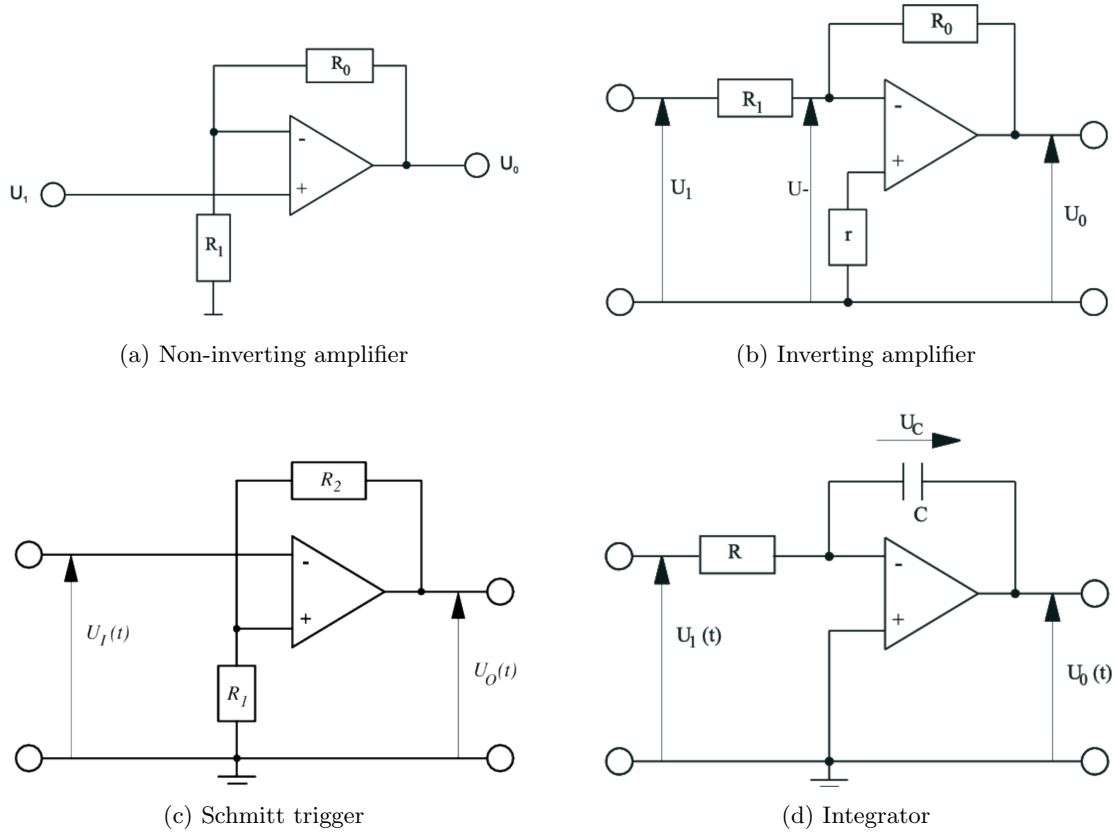
# 1 Introduction

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. An ideal op-amp has infinite voltage amplification, infinite input resistance, zero output resistance, no phase delay, a flat frequency response with infinite bandwidth and has no output if no signal is applied to the input.

The op-amp used in the experiments was the widely used LM741. It has a voltage amplification of about  $10^5$ . The input resistance is sufficiently large that the input currents can be neglected. The output resistance is about  $150\ \Omega$ . The frequency response is also not flat. As we will see in the following experiments, the amplification decreases with increasing frequency.

In this lab we investigated the amplification behavior and frequency response of inverting and non-inverting amplifier circuits, looked at a schmitt trigger and finally determined the frequency response of an integrator circuit.

## 2 Theory



	$U_0$ [V]	$U_{in}$ [V]	$R_0$ [k $\Omega$ ]	$R_1$ [k $\Omega$ ]	$R_2$ [k $\Omega$ ]	$r$ [k $\Omega$ ]	$R$ [k $\Omega$ ]	$C$ [ $\mu$ F]
a)	$15 \pm 1$	0.5-4.0	10-23	$7.12 \pm 0.05$				
b)	$15 \pm 1$	0.5-4.0	10-23	$7.12 \pm 0.05$		0		
b)	$15 \pm 1$	$1.15 \pm 0.05$	$22.94 \pm 0.05$	$7.13 \pm 0.05$		0		
c)	$15 \pm 1$	$4.8 \pm 0.025$		$9.96 \pm 0.05$	10-100			
d)	$15 \pm 1$	$0.65 \pm 0.025$					$49.7 \pm 0.05$	$0.1 \pm 0.05$

Figure 1: Diagrams of the investigated circuits along with a table of all component values used in the experiments.

### 2.1 Non-Inverting Amplifier

Figure (1a) shows the circuit diagram of a non-inverting amplifier. The amplification  $G = \frac{U_0}{U_1}$  is given by

$$G = \frac{R_0 + R_1}{R_1}. \quad (1)$$

### 2.2 Inverting Amplifier

Figure (1b) shows the circuit diagram of the inverting amplifier. Its amplification is given by

$$G = -\frac{R_0}{R_1}. \quad (2)$$

The output signal is inverted, which for a sinusoidal signal results in a phase shift of  $180^\circ$ . Further, note that the amplification does not depend on the resistance  $r$ . Usually circuits with op-amps

are built 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, but for these experiments we simply replaced  $r$  with a direct link.

### 2.3 Schmitt Trigger

The Schmitt trigger transforms any arbitrary input into a rectangular signal. If the input signal passes a certain input voltage  $U_+$  the output signal becomes "high" outputting a voltage  $U_m$ , which is slightly lower than the supply voltage of the op-amp. After that, once the input voltage drops below  $-U_+$ , the output becomes "low", outputting  $-U_m$ . Note the hysteresis effect that we have here.

Figure (1c) shows the circuit diagram of a Schmitt trigger. The threshold voltage  $U_+$  is given by

$$U_+ = -U_m \frac{R_1}{R_1 + R_2}. \quad (3)$$

### 2.4 Integrator

Figure (1d) shows the circuit diagram of the integrator. The current through the capacitor is given by  $I_c = \frac{dU_c}{dt}$ , and as  $U_0 = -U_c$  and  $I_c = I_R$  we get for the output voltage:

$$U_0(t) = \frac{1}{C} \left( - \int_0^t I_C(\tau) d\tau + Q_0 \right) = -\frac{1}{RC} \int_0^t U_1(\tau) d\tau + U_0(t=0). \quad (4)$$

So we see that the output is given by the inverted integral of the input. Further, this circuit acts like a low pass filter. At high input frequencies the capacitor acts like a short circuit and the output voltage drops towards zero.

### 3 Experiments & Results

#### 3.1 Non-Inverting Amplifier

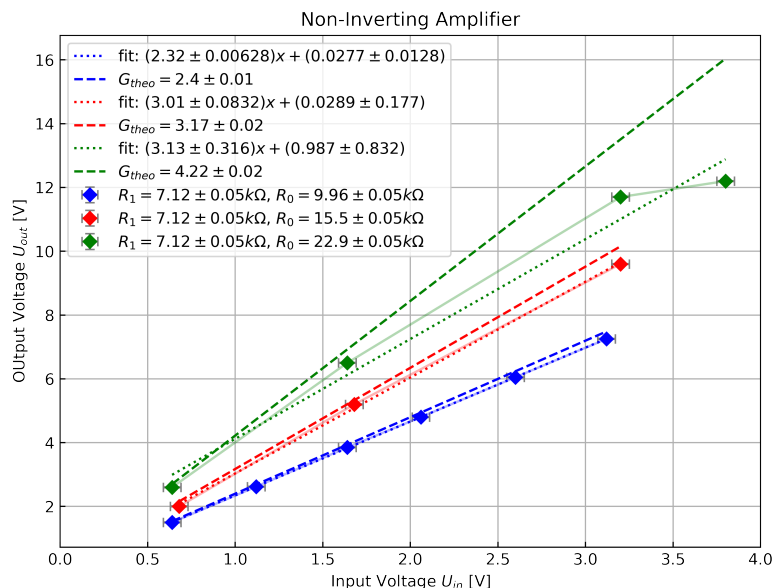


Figure 2: Output voltage  $U_{out}$  plotted against input voltage of the non-inverting amplifier circuit (shown in figure (1a)) for three different resistor combinations.

For the non-inverting amplifier (and all subsequent experiments), we held the supply voltage for the op-amp constant at  $(15 \pm 1)$  V. We tested three different resistor value combinations, which can be seen in table (1) with the corresponding theoretical and measured amplifications values  $G_{theo}$  and  $G_{meas}$ . For each amplification level we fed the circuit with sine signals at a frequency of  $(840.0 \pm 0.5)$  Hz and various (peak-to-peak) amplitudes  $A_{in}$ . The output amplitude  $A_{out}$  was then measured (also peak-to-peak). The plot in figure (2) shows the input and output voltages, which we simply took as  $U_{in,out} = \frac{1}{2}A_{in,out}$ .

$R_1$ [k $\Omega$ ]	$R_0$ [k $\Omega$ ]	$G_{theo}$ [-]	$G_{meas}$ [-]
$7.12 \pm 0.05$	$9.96 \pm 0.5$	$2.4 \pm 0.01$	$2.32 \pm 0.01$
$7.12 \pm 0.05$	$15.5 \pm 0.5$	$3.17 \pm 0.02$	$3.01 \pm 0.08$
$7.12 \pm 0.05$	$22.9 \pm 0.5$	$4.22 \pm 0.02$	$3.13 \pm 0.32$

Table 1: Resistor values used in the experiments on the non-inverting amplifier and the corresponding theoretical and measured amplifications.

## 3.2 Inverting Amplifier

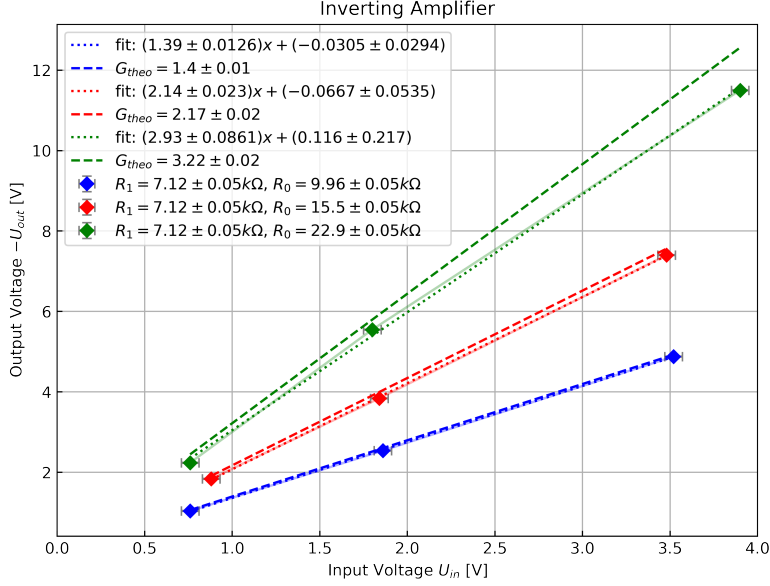


Figure 3: Negative output voltage  $U_{\text{out}}$  plotted against input voltage of the inverting amplifier circuit (shown in figure (1b)) for three different resistor combinations.

The inverting amplifier circuit from figure (1b) was tested in the same way as the non-inverting circuit. The supply voltage was held constant at  $(15 \pm 1)$  V and the circuit was fed with a sinusoidal signal with a frequency of  $(840.0 \pm 0.5)$  Hz and various amplitudes. Measurements of the output amplitude were again taken for three different resistor combinations, which can be seen in table (2) along with the theoretical amplifications  $G_{\text{theo}}$  and the measured ones  $G_{\text{meas}}$ . Note that the plot in figure 3 shows the negative output voltage, as it is inverted. We once again set  $U_{\text{in,out}} = \frac{1}{2}A_{\text{in,out}}$ .

$R_1$ [k $\Omega$ ]	$R_0$ [k $\Omega$ ]	$G_{\text{theo}}$ [-]	$G_{\text{meas}}$ [-]
$7.12 \pm 0.05$	$9.96 \pm 0.5$	$1.40 \pm 0.01$	$1.39 \pm 0.01$
$7.12 \pm 0.05$	$15.5 \pm 0.5$	$2.17 \pm 0.02$	$2.14 \pm 0.02$
$7.12 \pm 0.05$	$22.9 \pm 0.5$	$3.22 \pm 0.02$	$2.93 \pm 0.09$

Table 2: Resistor values used in the experiments on the inverting amplifier and the corresponding theoretical and measured amplifications.

Further, we performed a frequency sweep of the inverting amplifier circuit to analyze its frequency response. With a supply voltage of  $(15 \pm 1)$  V and resistances  $R_1 = (7.13 \pm 0.05)$  k $\Omega$  and  $R_0 = (22.94 \pm 0.05)$  k $\Omega$  we fed the circuit with a sine signal of amplitude  $A_{\text{in}} = (2.3 \pm 0.1)$  V at frequencies ranging from  $10^3$  to  $10^5$  Hz. The plot in figure (4) shows the amplification for various frequencies.

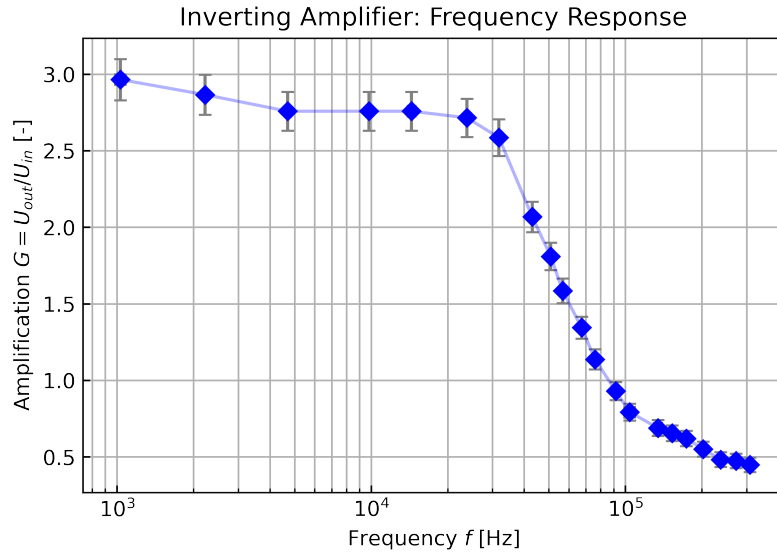


Figure 4: Amplification factor  $G$  for various input frequencies to the inverting amplifier circuit shown in figure (1b) with  $R_1 = (7.13 \pm 0.05) \text{ k}\Omega$  and  $R_0 = (22.94 \pm 0.05) \text{ k}\Omega$ .

### 3.3 Schmitt Trigger

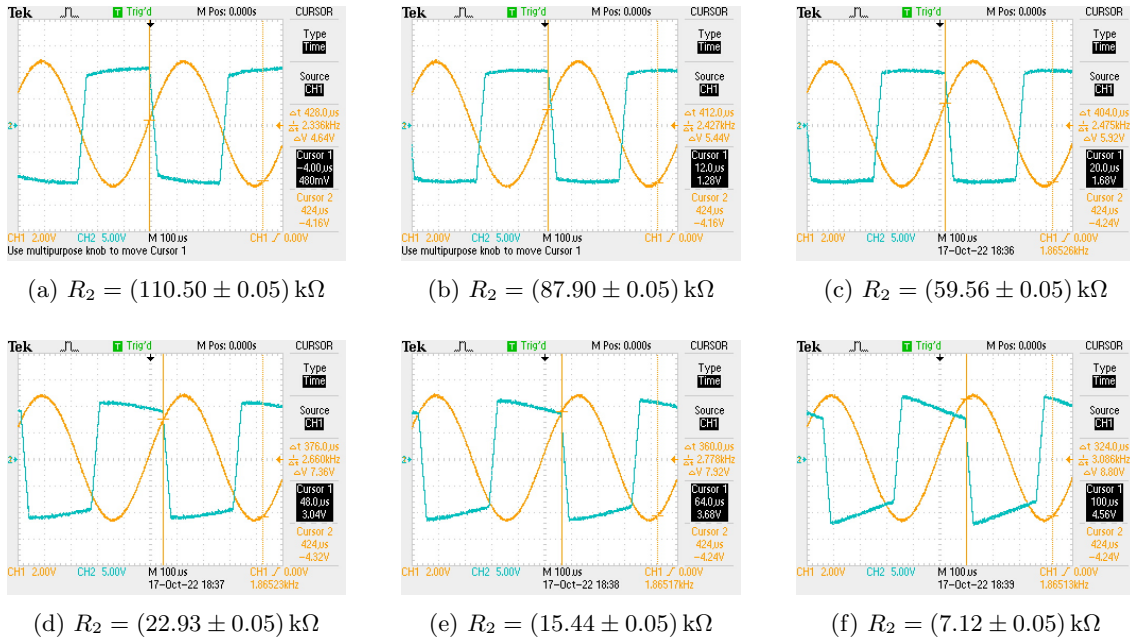


Figure 5: Oscilloscope readout of the Schmitt trigger circuit shown in figure (1c), with  $R_1 = (9.96 \pm 0.05) \text{ k}\Omega$ . In Yellow is the input sine wave with frequency  $(1.86 \pm 0.05) \text{ kHz}$  and amplitude  $(9.60 \pm 0.05) \text{ V}$ . The output square wave is shown in blue. Note the varying trigger voltage depending on  $R_2$ .

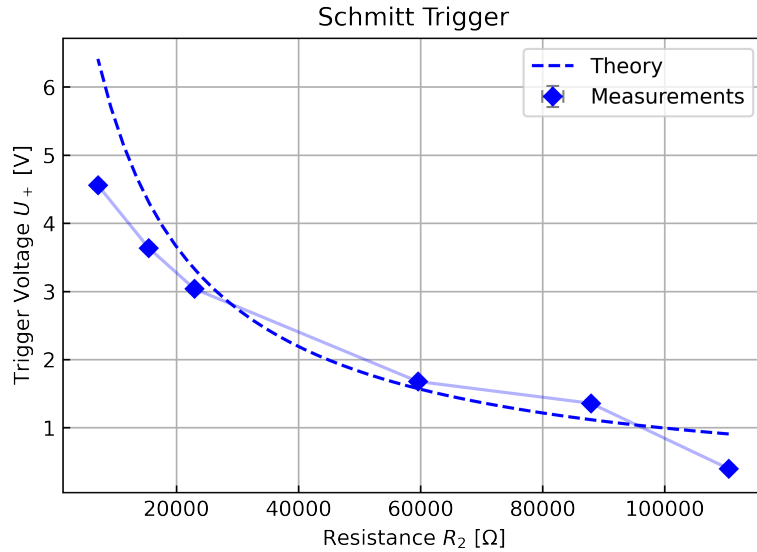
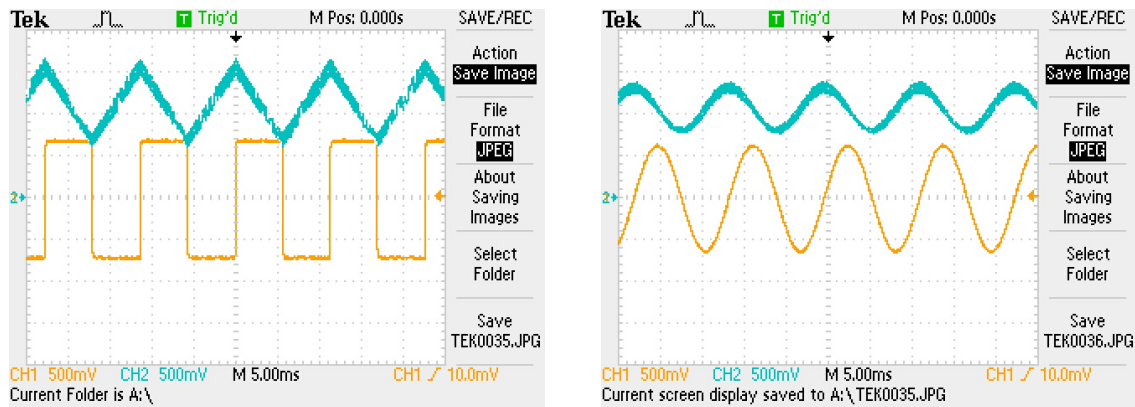


Figure 6: Measurements of the critical trigger voltage  $U_+$  for various resistances  $R_2$ . The circuit is shown in figure (1c).

For the Schmitt trigger circuit shown in figure (1c), we connected a sinusoidal signal with frequency  $(1.860 \pm 0.005)$  kHz and amplitude  $A_{in} = (9.60 \pm 0.05)$  V. The Schmitt trigger then output a square wave with the same frequency and a "high" state voltage of  $U_m = (11.0 \pm 0.5)$  V, which is as expected slightly below the supply voltage of the op-amp, at again  $(15 \pm 1)$  V. The trigger voltage  $U_+$ , at which the square wave switches from low to high and vice versa, depends on the resistors  $R_1$  and  $R_2$ .  $R_1$  was held constant at  $R_1 = (9.96 \pm 0.05)$  k $\Omega$ , whilst  $R_2$  was varied between 10 to 100 k $\Omega$ . Figure (6) shows the measured  $U_+$  for various resistances  $R_2$  along with the theoretical prediction.  $U_+$  was always taken to be the voltage of the input sine signal at the time of the start of the falling edge of the outputted square wave, as shown in figure (5).

### 3.4 Integrator



(a) Square wave input.

(b) Sine wave input.

Figure 7: Input- (yellow) and output- (blue) signals of the integrator circuit shown in figure (1d).

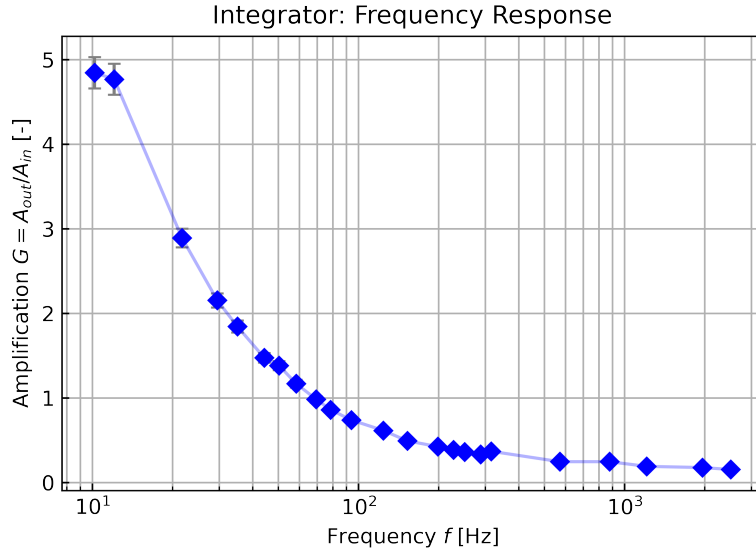


Figure 8: Frequency response of the integrator circuit shown in figure (1d). The component values used are  $R = (49.70 \pm 0.05) \text{ k}\Omega$  and  $C = (0.10 \pm 0.05) \mu\text{F}$ .

Finally, we looked at the integrator circuit shown in figure (1d). As we can see in figure (7), the circuit nicely integrates (and inverts) the inputs. The resistor and capacitance values were  $R = (49.70 \pm 0.05) \text{ k}\Omega$  and  $C = (0.10 \pm 0.05) \mu\text{F}$ . The supply voltage to the op-amp was once again  $(15 \pm 1) \text{ V}$ . Here we again performed a frequency response analysis by feeding the circuit a sine wave with an amplitude of  $(1.30 \pm 0.05) \text{ V}$  and looking at the amplification factor at different frequencies. These results are shown in figure (8).

## 4 Discussion

### 4.1 Non-Inverting Amplifier

From the graph in figure (2) and from the theoretical and measured values of  $G$  in table (1), we see that the theory fits our measurements rather accurately. For higher input voltages though, we do see a slight decline in output voltage from what the theory predicts. This is most prominent for the measurements with  $R_2 = (22.0 \pm 0.5) \text{ k}\Omega$  (green in figure (2)). Figure (9) shows the reason why. For higher input and output voltages, the op-amp reaches its limits and starts to cut off the output signal. This effect is minimized with a higher supply voltage, but the op-amp is also only rated to operate at a maximum of 15 V to 19 V.

### 4.2 Inverting Amplifier

For the inverting amplifier we can draw very much the same conclusions as for the non-inverting amplifier. The theoretical and measured values for  $G$  (shown in table (2)) fit very accurately. We again see a slight decline in output voltage for higher input voltages, due to the same reason as before. Though, here the effect is less prominent as the total amplification of the inverting amplifier is smaller and therefore we have smaller output voltages.

From the frequency response plot in figure (4), we can see that we have a cutoff frequency of about 40 kHz. After that we see linear decline (in the semilog plot) up to an amplification of about 0.75, after which the frequency response flattens out towards 0.

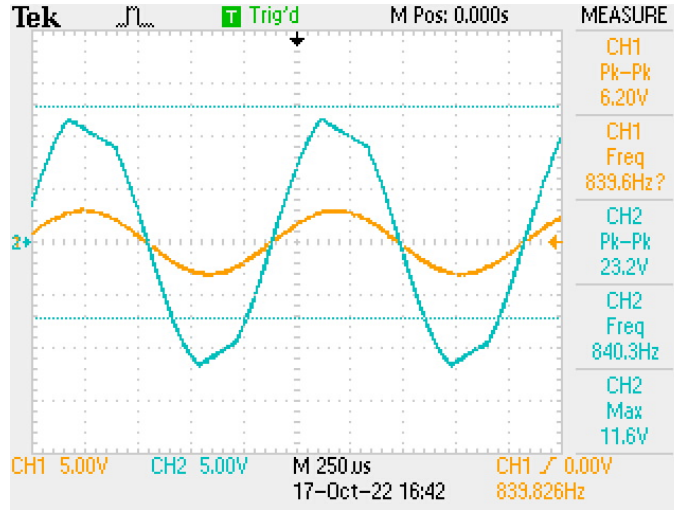


Figure 9: Input- (yellow) and output- (blue) signals of the non-inverting amplifier (figure (1a)) for  $R_1 = (7.12 \pm 0.05) \text{ k}\Omega$ ,  $R_2 = (22.9 \pm 0.5) \text{ k}\Omega$  and  $A_{in} = (6.4 \pm 0.1) \text{ V}$ . Note the cut off on the output signal.

### 4.3 Schmitt Trigger

The measurements on the Schmitt Trigger also coincided rather nicely with the theory. We can see in figure (5), that for lower resistor values for  $R_2$ , the outputted square wave got more and more slewed, which is probably the main reason for these measurements to be the furthest off the theoretical values.

### 4.4 Integrator

In figure (7) we can see that the integrator works very nicely with the chosen resistance, capacitance and input amplitude. Note though, that these results were very sensitive to these values. Figure (10) shows how the integrated square signal looked like for a slightly different resistor value. We can see that the capacitor is fully charged before the signal drops again, which causes a brief impurity in the outputted triangle signal.

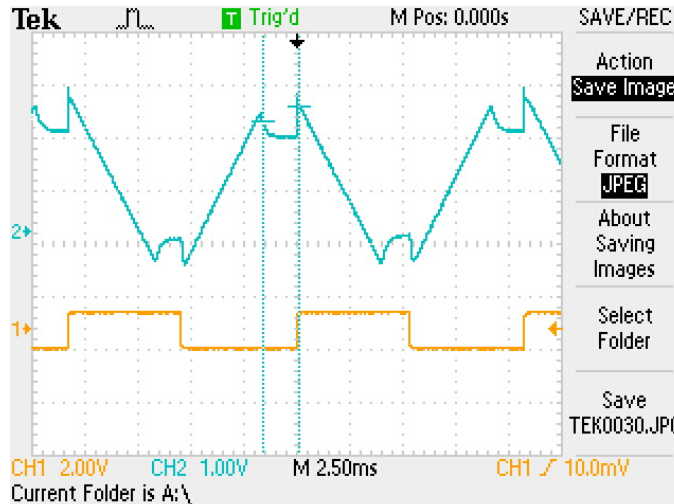


Figure 10: Input- (yellow) and output- (blue) signals of the integrator circuit (figure (1d)) for slightly different resistor values from what was used in figure (7).

Further, in the frequency response plot in figure (8) we see that the cutoff happens at a much lower frequency than with the inverting amplifier (figure (4)). The reason for this is the capacitor, whose behavior is also highly frequency dependent. Therefore we see a cutoff frequency of about 10 Hz and afterwards a less rapid decline compared to the frequency sweep of the inverting amplifier.

## 5 Conclusion

In conclusion we measured various aspects of four different circuits for which op-amps are often used for: An inverting amplifier, a non-inverting amplifier, a Schmitt trigger and an integrator. For all of them the measurements very much behaved according to our theory. Most deviations were due to the operational limits of the op-amp, in our case the LM741. If these circuits had to be run at or beyond these limits, one could look for other op-amps which were designed to be operated in the desired range.

## References

- [1] Dr. Joseba Alonso & Myriam Schönenberger (1998, rev. 2013) *Manual Electronics A (Operational Amplifier)*, ETH Zurich.

## Appendix: Data sheet of a 741

## 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 (°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.

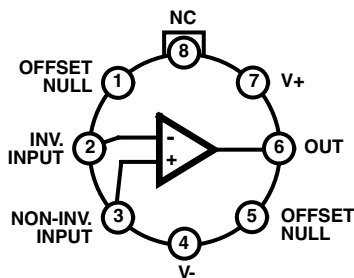
These monolithic silicon integrated circuit devices provide output short circuit protection and latch-free operation. These types also feature wide common mode and differential mode signal ranges and have low offset voltage nulling capability when used with an appropriately valued potentiometer. A 10kΩ 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.

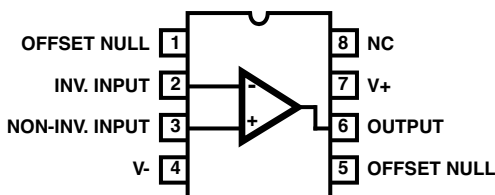
Technical Data on LM Branded types is identical to the corresponding CA Branded types.

### Pinouts

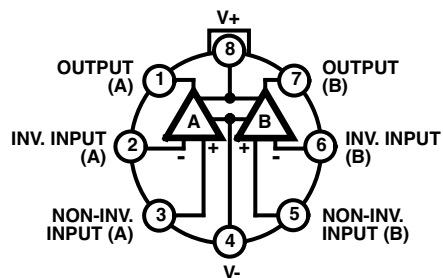
CA741, CA741C, LM741, LM741C (CAN)  
TOP VIEW



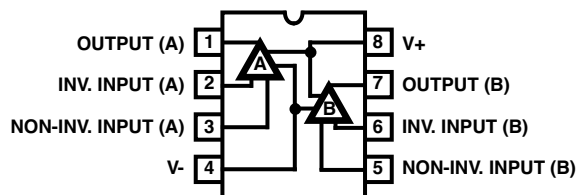
CA741, CA741C, LM741, LM741C (PDIP)  
TOP VIEW



CA1458, CA1558 (METAL CAN)  
TOP VIEW



CA1458, CA1558, LM1458 (PDIP)  
TOP VIEW



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

## 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)	$\pm 0.5V$
Output Short Circuit Duration	Indefinite

## Thermal Information

Thermal Resistance (Typical, Note 3)	$\theta_{JA}$ (°C/W)	$\theta_{JC}$ (°C/W)
PDIP Package	130	N/A
Can Package	155	67
Maximum Junction Temperature (Can Package)	175°C	
Maximum Junction Temperature (Plastic Package)	150°C	
Maximum Storage Temperature Range	-65°C to 150°C	
Maximum Lead Temperature (Soldering 10s)	300°C	

## Operating Conditions

Temperature Range	
CA741, CA1558, LM741	-55°C to 125°C
CA741C, CA1458, LM741C, LM1458 (Note 2)	0°C to 70°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:

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

## Electrical Specifications Typical Values Intended Only for Design Guidance, $V_{SUPPLY} = \pm 15V$

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

## Electrical Specifications For Equipment Design, $V_{SUPPLY} = \pm 15V$

PARAMETER	TEST CONDITIONS	TEMP (°C)	(NOTE 4) CA741, CA1558, LM741			(NOTE 4) CA741C, CA1458, LM741C, LM1458			UNIT S
			MIN	TYP	MAX	MIN	TYP	MAX	
Input Offset Voltage	$R_S \leq 10k\Omega$	25	-	1	5	-	2	6	mV
		Full	-	1	6	-	-	7.5	mV
Input Common Mode Voltage Range		25	-	-	-	$\pm 12V$	$\pm 13V$	-	V
		Full	$\pm 12V$	$\pm 13V$	-	-	-	-	V
Common Mode Rejection Ratio	$R_S \leq 10k\Omega$	25	-	-	-	70	90	-	dB
		Full	70	90	-	-	-	-	dB
Power Supply Rejection Ratio	$R_S \leq 10k\Omega$	25	-	-	-	-	30	150	$\mu V/V$
		Full	-	30	150	-	-	-	$\mu V/V$
Input Resistance		25	0.3	2	-	0.3	2	-	M $\Omega$

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

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

PARAMETER	TEST CONDITIONS	TEMP (°C)	(NOTE 4) CA741, CA1558, LM741			(NOTE 4) CA741C, CA1458, LM741C, LM1458			UNIT S
			MIN	TYP	MAX	MIN	TYP	MAX	
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	$R_L \geq 2k\Omega, V_O = \pm 10V$	25	50,000	200,000	-	20,000	200,000	-	V/V
		Full	25,000	-	-	15,000	-	-	-
Output Voltage Swing	$R_L \geq 10k\Omega$	25	-	-	-	$\pm 12V$	$\pm 14V$	-	V
		Full	$\pm 12V$	$\pm 14V$	-	-	-	-	-
	$R_L \geq 2k\Omega$	25	-	-	-	$\pm 10V$	$\pm 13V$	-	V
		Full	$\pm 10V$	$\pm 13V$	-	$\pm 10V$	$\pm 13V$	-	-
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**

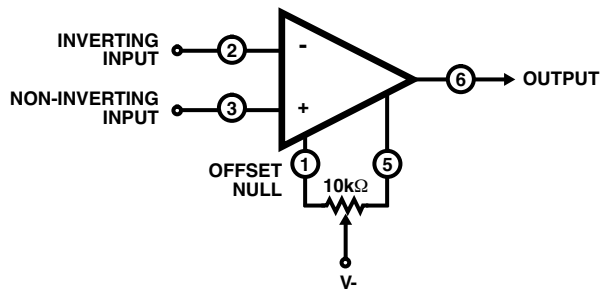


FIGURE 1. OFFSET VOLTAGE NULL CIRCUIT FOR CA741C, CA741, LM741C, AND LM741

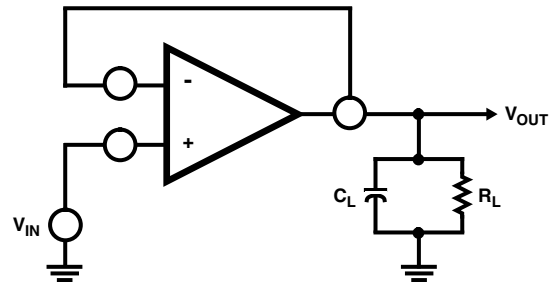
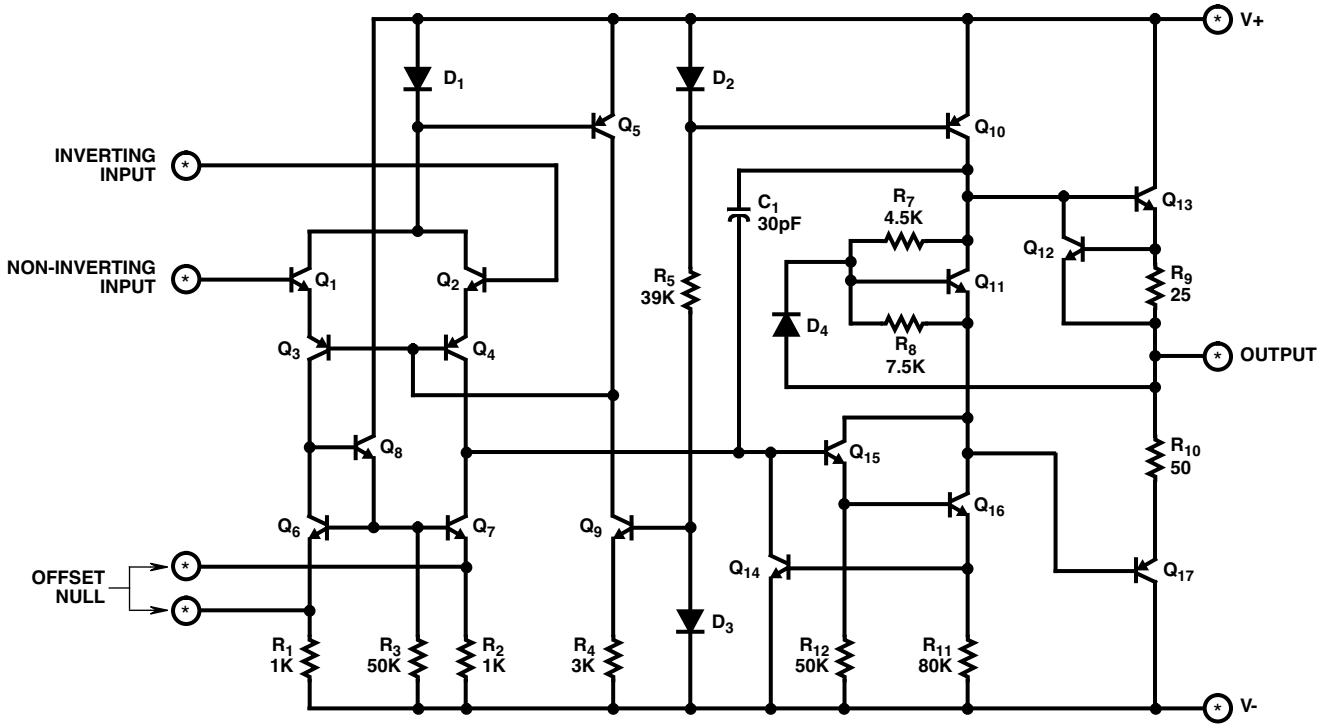


FIGURE 2. TRANSIENT RESPONSE TEST CIRCUIT FOR ALL TYPES

**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**

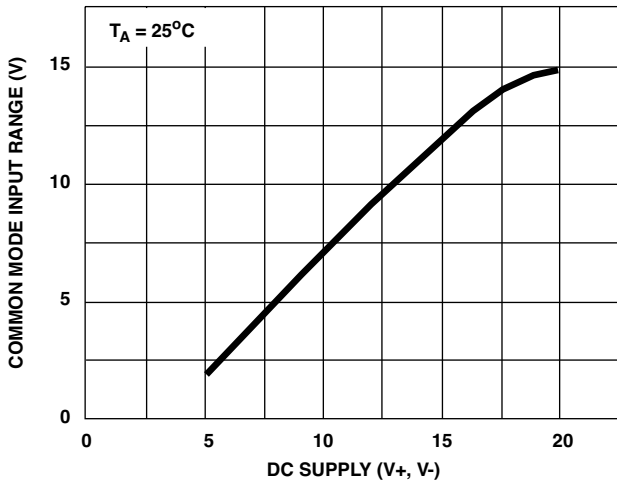


FIGURE 3. COMMON MODE INPUT VOLTAGE RANGE vs SUPPLY VOLTAGE FOR ALL TYPES

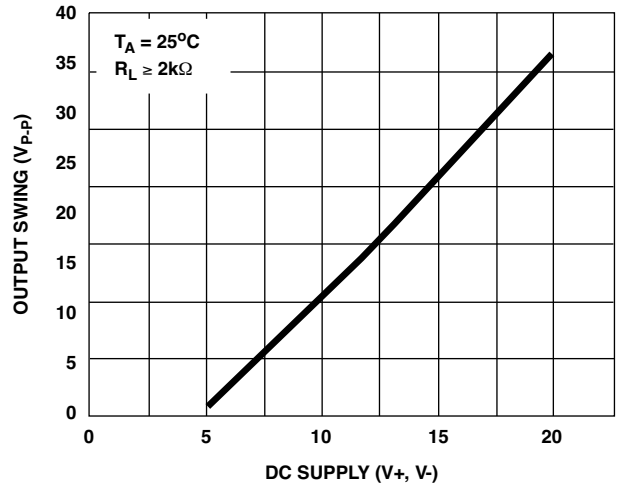


FIGURE 4. OUTPUT VOLTAGE vs SUPPLY VOLTAGE FOR ALL TYPES

Typical Performance Curves (Continued)

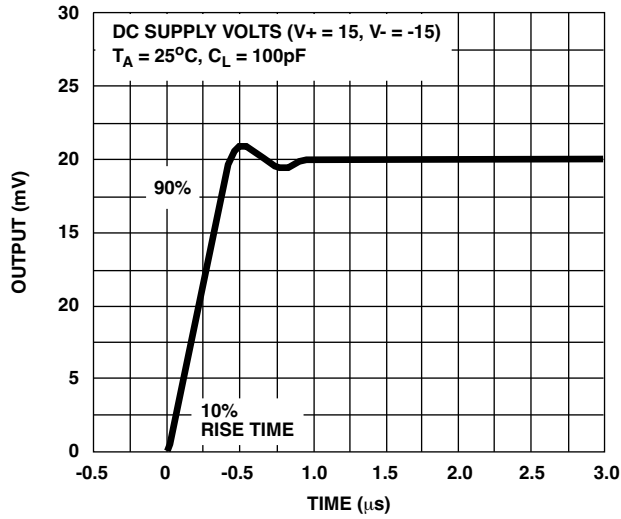
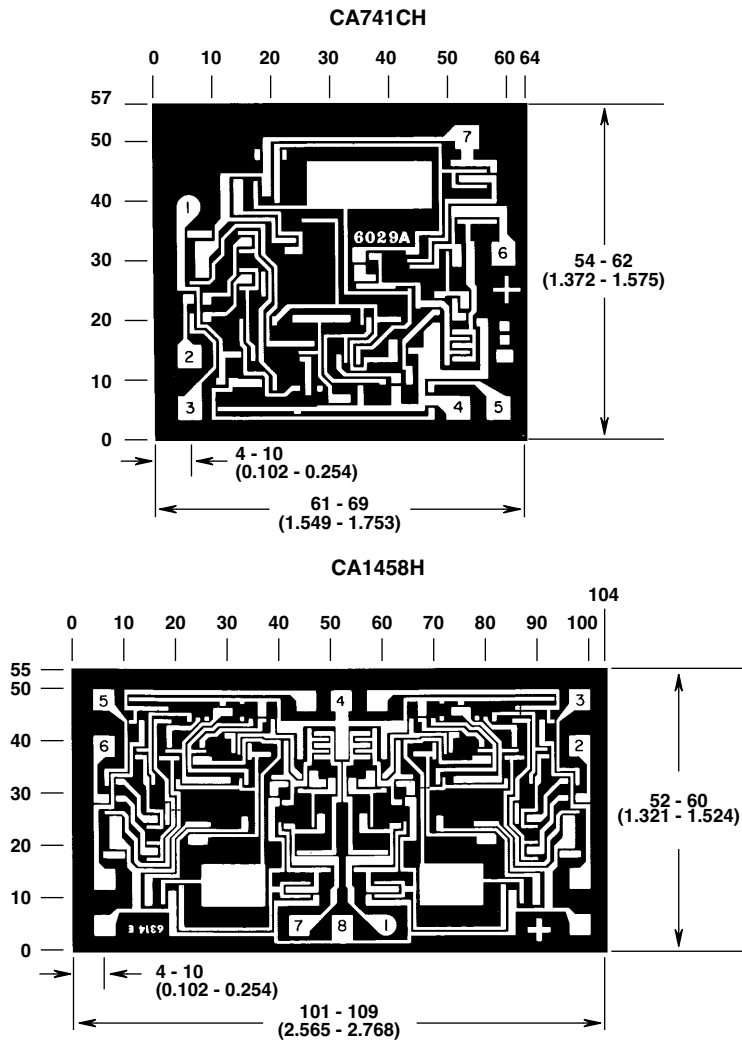


FIGURE 5. TRANSIENT RESPONSE FOR CA741C AND CA741

Metallization Mask Layout



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).