Unconnected operational amplifier (comparator)

Experiment Objectives

- Investigation of how the output voltage depends on the operational amplifier's input voltages
- Transformation of the sinusoidal signal into a square-wave voltage with adjustable duty cycle
- Observation of how the output voltage's duty cycle depends on phase shift of the input voltages

Basic Information

An operational amplifier (OpAmp, op amp, or op-amp) is a high-gain differential amplifier. It has an inverting (negative) and a non-inverting (positive) input. The voltage difference between these two inputs gets greatly amplified (≥ 10^5) at the output. OpAmps require a supply voltage U_V that is, for practical reasons, usually symmetric to the ground.

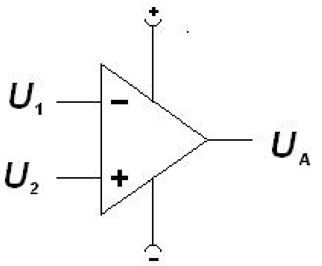

Illustration 1: Operational amplifier

The blank operational amplifier, with no feedback, functions as a "voltage comparator." Because of the large amplification, a small voltage difference at the inputs is enough to force the OpAmp output in its bound. So the output voltage U_A reaches roughly the positive or negative supply voltage U_V. (*Experiments a – c*)

An alternating voltage at one input that oscillates around the potential of the second input (switching point) results in a square-wave voltage at the output. This is independent of the input voltage's shape and amplitude. Changing the second input's potential can adjust the duty cycle of the square-wave voltage at the output. The duty cycle is the duration of the positive amplitude T_+ over the time of oscillation T:

Duty cycle: $\frac{T_+}{T}$

(*Experiment c*)

Even the smallest fluctuations of the input voltages at the switching point lead the output voltage to oscillate. A hysteresis resistor R_H is inserted to prevent this. The hysteresis resistor R_H is a resistor between the output and the positive input (positive feedback) that, along with the input resistor R_E, modifies the voltage and the positive input. The output signal thus does not change every time the voltage difference at the inputs crosses zero, but instead only when the hysteresis voltage U_H is crossed. The following applies:

$$U_H = \frac{R_E}{R_E + R_H} \cdot \Delta U_A$$

With an additional diode in the hysteresis path, the hysteresis resistance only becomes effective in one direction. (*Experiment d*)

If two alternating voltages with different phases are applied to the inputs, then the voltage difference also in turn produces a square-wave voltage at the output. The hysteresis resistor and a diode produce a duty cycle that depends on the phase shift. (*Experiment e*)

Apparatus

1 Plug-in board DIN A4	576 74
1 Set of 10 bridging plugs	501 48
1 STE Operational amplifier LM 741	578 85
1 STE Resistor 10 kΩ, 0.5 W	577 46
2 STE Resistors 33 kΩ, 0.5 W	577 61
1 STE Resistor 39 kΩ, 0.5 W	577 62
1 STE Resistor 100 kΩ, 0.5 W, 1 %	577 68
1 STE Resistor 470 kΩ, 0.5 W	577 74
2 STE Potentiometers 1 kΩ, 1 W	577 96
2 STE Capacitor 2.2 nF, 160 V, 2.5%	578 26
1 STE Capacitor 10 nF, 100 V, 20 %	578 28
1 STE Si-diode 1N 4007	578 51
1 DC power supply 0...+/- 15 V	521 45
1 Function generator S 12	522 621
1 Two-channel oscilloscope 303	575 211
2 Screened cables BNC/4 mm	575 24
8 Connection leads, Ø 1 mm², 50 cm, black	500 424

KEM/JN 1008

Setup and Procedure

Notes:

Especially with these experiments, it makes sense to vary the voltages, frequencies and signal shapes a little and to observe their effects.

Not all kinds of OpAmps can be used as comparators.

a) Investigation of the operational amplifier's two inputs

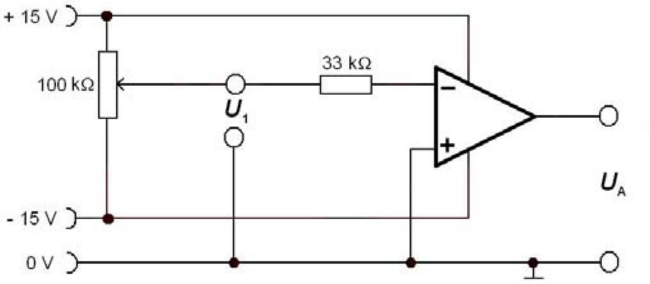

Illustration 2: Adjustable voltage U_1 at the negative input with protective resistor R_E = 33 kΩ

- Experiment setup according to Illustration 2. Potentiometer initially near the center position.
- Connect the oscilloscope to measure the voltages U_1 and U_A.
- Change the potentiometer's setting to vary the voltage U_1 and observe the voltages U_1 and U_A.
- Modify the experiment setup so that the adjustable voltage (U_2) is now applied through the protective resistor to the positive input and the negative input goes to the ground.
- Repeat the experiment.

b) Unconnected operational amplifier (voltage comparator)

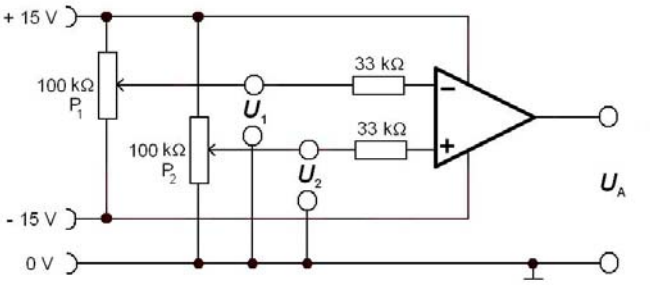

Illustration 3: Adjustable voltage U_1 at the negative input and adjustable voltage U_2 at the positive input

- Experiment setup according to Illustration 3. Connect the oscilloscope to measure the voltage U_1.
- Set the voltage U_1 = 5 V using the potentiometer P_1.
- Now connect the oscilloscope to measure the voltages U_2 and U_A.
- Change the potentiometer's setting P_2 to vary the voltage U_2 and observe the voltages U_2 and U_A.

c) Transformation of an alternating voltage into a square-wave voltage

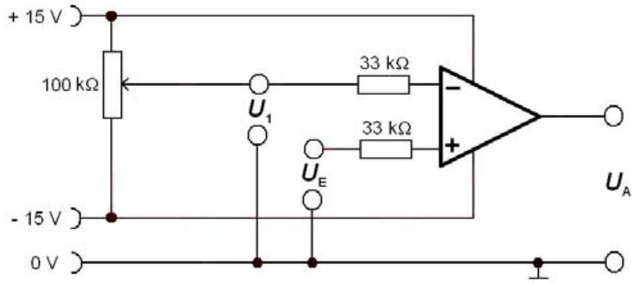

Illustration 4: Adjustable voltage U_1 at the negative input and adjustable alternating voltage U_E at the positive input

- Experiment setup according to Illustration 4. Potentiometer initially near the center position, i.e. $U_1 \approx 0$ V.
- Connect the function generator to U_E, choose delta voltage and set a frequency of $f \approx 500$ Hz.
- Connect the oscilloscope to measure the voltages U_E and U_A.
- Change the amplitude of the alternating voltage U_E on the function generator and observe the voltages U_E and U_A.
- Change the potentiometer's setting to vary the voltage U_1 and observe the voltages U_E and U_A.
- For different settings of U_1, observe in each case U_E at the same time as U_A, resp. U_1.

d) Comparator with hysteresis resistance

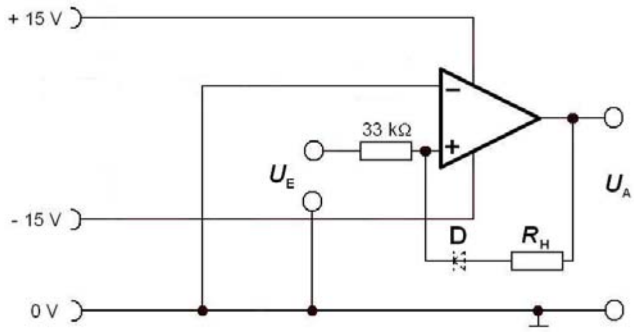

Illustration 5: Comparator with hysteresis resistance R_H

- Experiment setup according to Illustration 5. Initially, do not incorporate any hysteresis resistor R_H or any diode D.
- Connect the function generator to U_E, choose sinusoidal voltage and set a frequency of $f \approx 50$ Hz.
- Observe the input voltage U_E and output voltage U_A with the oscilloscope. Then represent $U_A = f(U_E)$ in XY mode.
- First insert a hysteresis resistor R_H = 470 kΩ, and then R_H = 100 kΩ. Observe $U_A = f(U_E)$ and also the hysteresis voltage U_H in each case. Instead of a diode, first use bridging plugs.
- Insert diode D, observing first $U_A = f(U_E)$ and then U_A and U_E.

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e) Comparator as phase comparator

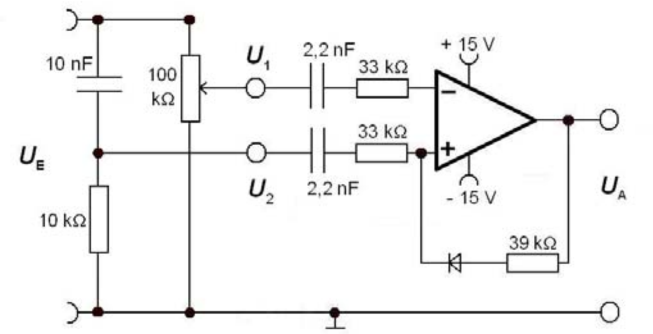


Illustration 6: Comparator as phase comparator

Note:

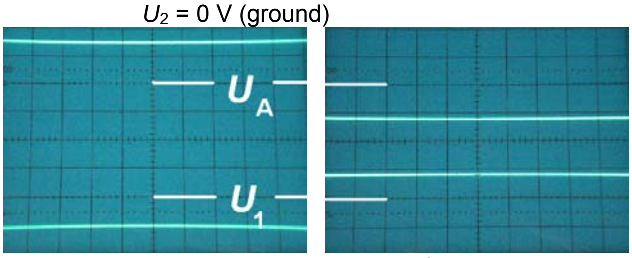
Both capacitors 2.2 nF here serve the DC decoupling. Connecting capacitors to an OpAmp's inputs without providing for a bleeder resistor for the bias current is actually not common. But the bipolar OpAmp LM 741 used here can function.

- Experiment setup according to Illustration 6.
- Choose sinusoidal voltage on the function generator, set the amplitude $U_{E,S}$ = 4 V and frequency $f \approx$ 5.5 kHz so that the oscilloscope just needs 9 fields (div). (Like that the phase shift $\Delta\varphi$ can easily be read in °.)
- Observe the input voltages U_1 and U_2 with the oscilloscope and determine the phase shift.
- Observe the input voltage U_1 and output voltage U_A with the oscilloscope. Determine the duty cycle.
- Repeat the experiment with the frequencies f = 1 kHz and f = 500 Hz.

Observations and Measurement Examples

a) Investigation of the operational amplifier's two inputs

Illustration 7: Adjustable voltage U_1 at the negative input and U_2 = 0 V (ground)



(top)	U_A	10 V/div	DC
(bottom)	U_1	1 V/div	DC
Sweep:		1 msec/div	

- If U_1 is negative (< 0 V), then $U_A \approx + U_V$.
- If U_1 is positive (> 0 V), then $U_A \approx - U_V$.
- At U_1 = 0 V, U_A jumps from $+U_V$ to $-U_V$.
- The negative input is inverting.

No illustration: Adjustable voltage U_2 at the positive input and U_1 = 0 V (ground)

- If U_2 is negative (< 0 V), then $U_A \approx - U_V$.
- If U_2 is positive (> 0 V), then $U_A \approx + U_V$.
- At U_1 = 0 V, U_A jumps from $-U_V$ to $+U_V$.
- The positive input is non-inverting.

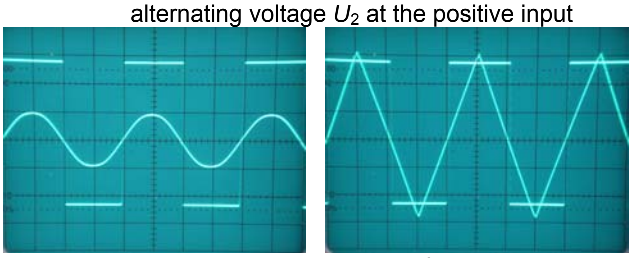
b) Unconnected operational amplifier (voltage comparator)

No illustration: Adjustable voltage U_1 at the negative input and adjustable voltage U_2 at the positive input

- If $U_1 < U_2$, i.e. $U_1 - U_2 < 0$ V, then $U_A \approx - U_V$.
- If $U_1 > U_2$, i.e. $U_1 - U_2 > 0$ V, then $U_A \approx + U_V$.
- At $U_1 = U_2$, U_A jumps from $-U_V$ to $+U_V$.
- The voltage difference $U_1 - U_2$ determines the output voltage U_A. The operational amplifier functions as a comparator.

c) Transformation of an alternating voltage into a square-wave voltage

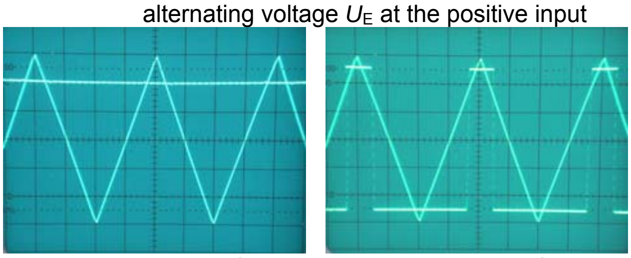
Illustration 8: $U_1 \approx 0$ V at the negative input and adjustable alternating voltage U_2 at the positive input



	U_E	2 V/div	DC
	U_A	5 V/div	DC
Sweep:		0.5 msec/div	

- An alternating voltage produces a square-wave voltage of the same frequency at the output.
- Whenever the input voltage crosses zero, the square-wave voltage switches signs.
- This is independent of the input voltage's amplitude or shape.

Illustration 9: Adjustable voltage U_1 at the negative input and alternating voltage U_E at the positive input



U_E 2 V/div DC — U_E 2 V/div DC
U_1 2 V/div DC — U_A 5 V/div DC
Sweep: 0.5 msec/div

- If $U_E < U_1$, then $U_A \approx - U_V$.
- If $U_E > U_1$, then $U_A \approx + U_V$.
- Varying the voltage U_1 changes the duty cycle of the square-wave voltage at the output.

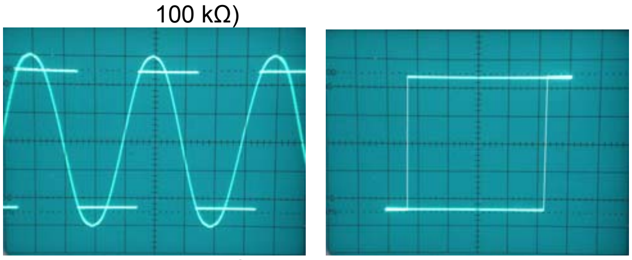
d) Comparator with hysteresis

Illustration 10: Comparator without hysteresis resistance

U_E 2 V/div DC — XY representation
U_A 5 V/div DC
Sweep: 5 msec/div

- The output voltage U_A changes its sign exactly when the input voltage U_E crosses zero.
- No hysteresis can be observed in the XY representation. U_E is plotted on the x-axis and U_A on the y-axis.

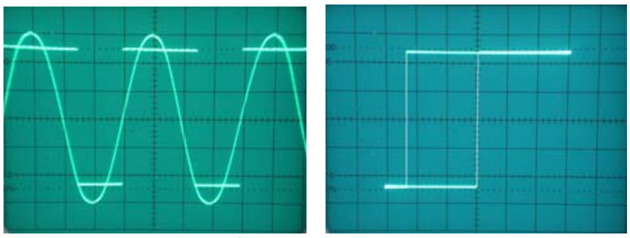
Illustration 11: Comparator with hysteresis resistance (R_H = 100 kΩ)



U_E 2 V/div DC — XY representation
U_A 5 V/div DC
Sweep: 5 msec/div

- When using a hysteresis resistance, the output voltage U_A changes its sign every time the input voltage U_E crosses the hysteresis voltage U_H.
- A hysteresis can be observed in the XY representation.
- The smaller the hysteresis resistance R_H (in relation to R_E), the greater the hysteresis voltage U_H.

Illustration 12: Comparator with hysteresis resistance R_H = 100 kΩ and diode

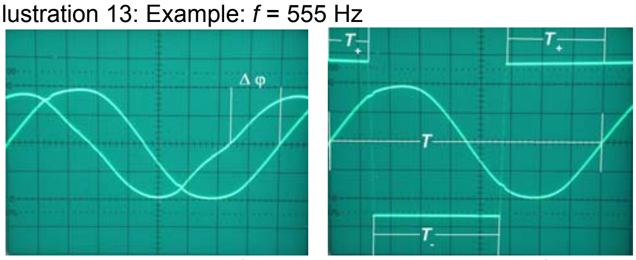


U_E 2 V/div DC — XY representation
U_A 5 V/div DC
Sweep: 5 msec/div

- The output voltage U_A changes its sign from - to + when an increasing input voltage U_E crosses zero.
- The output voltage U_A changes its sign from + to - when a decreasing input voltage U_E crosses the hysteresis voltage U_H.
  (conversely for an inverted diode)
- The diode cancels the hysteresis on one side.

e) Comparator as phase comparator

Illustration 13: Example: f = 555 Hz



U_1 1 V/div DC — U_1 1 V/div DC
U_2 1 V/div DC — U_A 5 V/div DC
Sweep: 0.2 msec/div

Period	Frequency	Phase shift	Duration of the positive amplitude	Duty cycle
$\frac{T}{\text{ms}}$	$\frac{f}{\text{Hz}}$	$\frac{\Delta\varphi}{°}$	$\frac{T_+}{\text{ms}}$	$\frac{T_+}{T}$
0.18	5555	24	0.07	0.39
0.9	1111	56	0.4	0.44
1.8	555	72	1.0	0.56
4.5	222	88	3.2	0.71

- The smaller the frequency f, the greater the phase shift $\Delta\varphi$.
- Because of the asymmetric hysteresis from the diode, the duty cycle changes with the phase shift of the input voltages U_I and U_2.
- The greater the phase shift, the greater also the duty cycle.

Note:

With a sequential circuit, this output voltage's duty cycle could produce a control voltage, which is analogous to a measurement for the phase shift.