Basic connections for operational amplifiers

1 Introduction

An operational amplifier (Fig 1) is a circuit whose output voltage depends on the two voltage values applied to its input as follows:

$$U_{out} = A_u \cdot (U_1 - U_2) \tag{1}$$

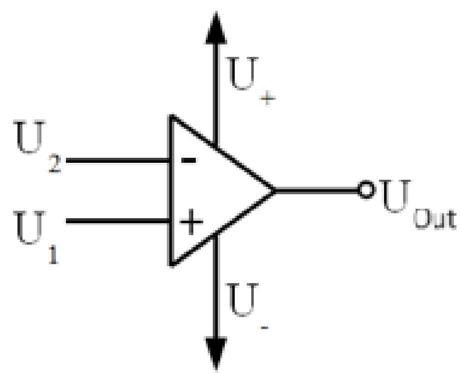

Figure 1: Symbol of the operational amplifier

For the amplifier, A_u is the voltage gain, U_1 is the voltage applied to the non-inverting (+) input of the amplifier, and U_2 is the voltage applied to the inverting (-) input of the amplifier. The important parameters of operational amplifiers are the input and output resistances. The input resistance indicates how much resistance the input of the amplifier loads the circuit before it, and the output resistance indicates how much the current load on the output changes the value of the output voltage. The DC equivalent circuit of the operational amplifier is shown in Figure 2.

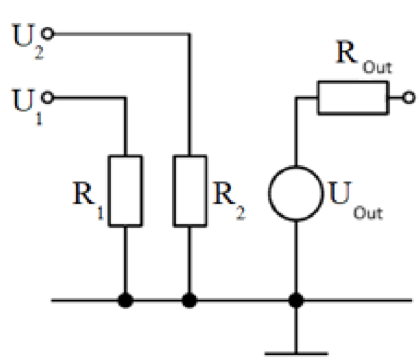

Figure 2: DC equivalent image of an operational amplifier

The input resistors are R_1 and R_2 and the output resistor is R_{out}. The output is an ideal voltage generator with a voltage of U_{out}. From equation (1) it can be seen that the voltage amplification between the output and the input side creates a connection.

2 Linear mode and saturation

The operational amplifier must be powered in order to function properly. Symmetrical supply voltages relative to 0V are usually used ($\pm$12V, $\pm$9V, or $\pm$5V), but in many cases, it is simpler and cheaper to use asymmetrical supplies (e.g. +5V and 0V). The data sheet of the amplifier indicates the possible supply voltage modes! In general, symmetrical supply is used, but if an amplifier also operates from an asymmetrical voltage, this is indicated separately (single supply mode). A general operational amplifier does not operate with asymmetrical supply (e.g. +9 V)! The supply voltage is not always indicated on the wiring diagrams! Of course, the output voltage can only vary within the supply voltages as limits. The operational amplifier also amplifies direct current. Its DC characteristics are, due to the aforementioned limitations, as shown in Fig 3.

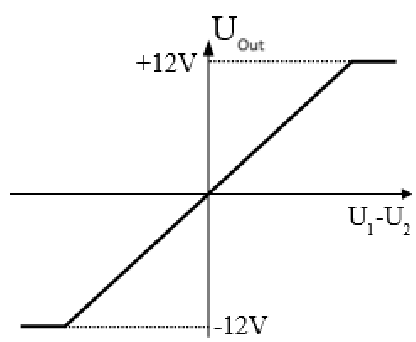

Figure 3: DC characteristics of the operational amplifier

The range where equation (1) holds is called the linear mode. Outside this range, the operational amplifier goes into saturation, its output voltage becoming independent of the input voltages. If the voltage gain (A_u) is large, the linear range is very small. For example, for the characteristic shown in Fig 3, if A_u=106, then |$(U_1 - U_2)$|<12μV, i.e. only an input voltage difference less than 12μV will give a signal at the output less than the supply voltage. The transfer function is therefore very steep.

3 Ideal operational amplifier

Today you can get very good quality operational amplifiers. Their parameters are close to ideal values, so we do not make a big mistake when calculating our circuits with them.

The ideal operational amplifier is the device for which (using the notations in the previous diagrams):

- $A_u = \infty$
- $R_{in} = R_1 = R_2 = \infty\Omega$
- $R_{out} = 0\Omega$
- $U_{in} = 0V$
- $B = \infty Hz(bandwidth of the amplifier)$
- CMRR=∞ (CMRR=Common Mode Rejection Ratio. Meaning: $U_{out} = 0V$ even if $U_{in1} = U_{in2} = \infty V$)

- Slew Rate, the rate of change of the output voltage, in reality usually in the order of 5-10V/μs

The linear range of the amplifier is very narrow. This does not mean that these amplifiers cannot operate in linear mode, but that if the amplifier is operating in linear mode, $|U_1 - U_2|$ remains negligibly small. So in linear mode $U_1 = U_2$. This makes the calculation of such circuits very easy. The input resistance of the amplifier is infinitely large, i.e. its input current is zero. The output resistance of the amplifier is zero, the output voltage is equal to the voltage U_{Out}. This makes it easier to calculate some feedback circuits. Real operational amplifiers try to approximate the ideal, i.e. their DC gain is very high (millions of times), their input resistance is also high (sometimes thousands MΩ) and their output resistance is very low (some Ω).

4 Use of operational amplifiers

In practice, operational amplifiers are used in one of two basic connections. In both cases, the voltage gain of the amplifier is determined by the feedback between the output and the input. In amplifiers, feedback is applied to the negative input!

4.1 Inverting circuit

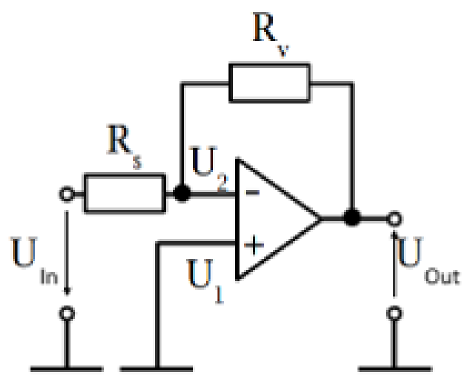

Figure 4: Inverting OPAMP

As the name of the circuit indicates, a positive voltage applied to the input results in a negative voltage at the output.

Since $U_1 - U_2 \approx 0$, U_2 can be considered a virtual ground point. The current flowing through R_s due to U_{in} cannot flow into the amplifier, so it flows through R_v to the output. The voltage across R_v is equal to the output voltage and since this voltage is reduced relative to the virtual ground (U_2), it will have a negative sign. In the case of a negative input voltage, the current will flow in the reverse direction, i.e. from the output towards the virtual earth point, and a positive output voltage will be measured. Knowing these, we can see that the gain is determined only by the ratio of the resistors (R_v and R_s).

For example:

$R_v = 22k\Omega, R_s = 2{,}2k\Omega, U_{in} = 1V$

Then the current flowing through R_v and R_s: I=454μA. $U_{Rv} = I \cdot R_v = 454\mu A \cdot 22k\Omega = 10V$ U_{Rv} is negative with respect to the virtual earth, so $U_{out} = -10V$. $A_{uv} = U_{out}/U_{in} = 10V/1V = 10$ The parameters of the circuit shown in Fig 4 (A_{uv} the feedback voltage amplification):

$$A_{uv} = -(\frac{R_v}{R_s}) \qquad R_{in} = R_s \qquad R_{out} \approx 0 \tag{2}$$

4.2 Non-inverting circuit

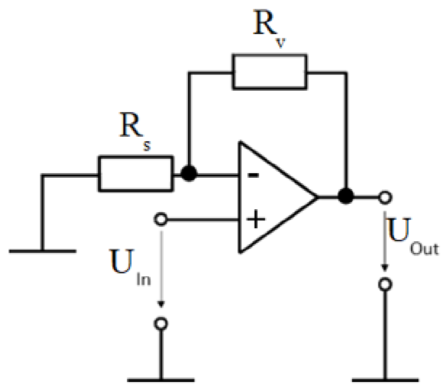

Figure 5: Non-inverting OPAMP

The parameters of the circuit shown in Fig 5:

$$A_{uv} = 1 + \frac{R_v}{R_s} \qquad R_{in} = \infty \qquad R_{out} \approx 0 \tag{3}$$

Compared to the inverting configuration, this amplifier has a high input impedance!

4.3 Adder circuit

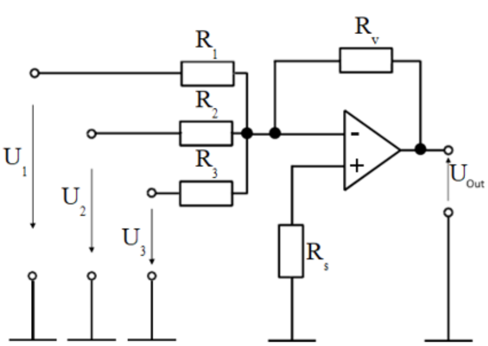

Figure 6: Adder circuit

$$U_{out} = -\frac{R_v}{R}(U_1 + U_2 + U_3),$$
where $R = R_1 = R_2 = ... = R_X$

In the circuit shown in Fig 6, the input voltages establish currents through their associated resistors, while the output voltage appears across the feedback resistor. If the input resistors are equal in value, the adder weights all voltages equally. If the resistor values differ ($R_1 \neq R_2 \neq R_3 \neq R_X$), the circuit functions as a weighted adder, where each input voltage contributes to the output in inverse proportion to its corresponding resistor. Write the node (KCL) equation at the common node of $R_1, R_2, R_3,$ and R_v:

$$\frac{U_1}{R_1} + \frac{U_2}{R_2} + \frac{U_3}{R_3} + \frac{U_{out}}{R_v} = 0 \tag{4}$$

(we neglect the current flowing into the amplifier, since for an ideal amplifier $R_{in} = \infty$)

From equation (4), solving for the output voltage, we see that U_{out} is proportional to the sum of the input voltages.

$$U_{out} = -(\frac{R_v}{R_1} \cdot U_1 + \frac{R_v}{R_2} \cdot U_2 + \frac{R_v}{R_3} \cdot U_3) \tag{5}$$

Thus, we can create an "analog computer" that calculates the linear combination (weighted sum) of three voltages.

4.4 Subtractor circuit

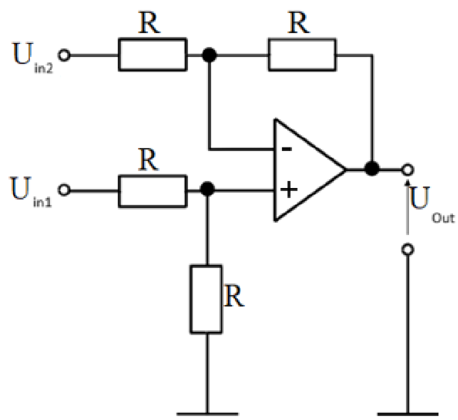

Figure 7: Subtractor circuit

$$U_{out} = U_{in1} - U_{in2}$$

A subtractor circuit can, for example, be built using both inputs of the operational amplifier. Such a configuration is shown in Fig 7.

4.5 Voltage followers (buffer amplifiers)

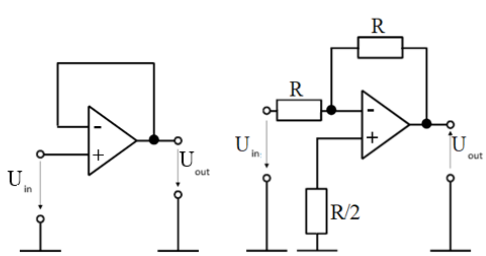

Figure 8: Non-inverting and inverting voltage followers

In Fig 8, the configurations of non-inverting and inverting unity-gain (A=1) followers are shown. Due to their high input impedance, they do not load the driving stage, while at the same time providing voltage-source drive for the load.

4.6 Differentiator circuit

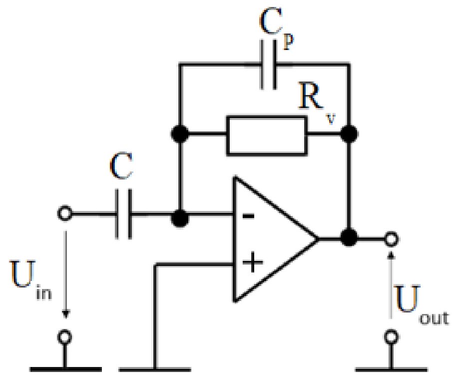

Figure 9: Differentiator circuit

With a differentiator circuit (Fig 9), an output voltage proportional to the rate of change of the input voltage can be produced. The input voltage charges and discharges a capacitor, and the resulting current through the capacitor is converted into a voltage. Since the inverting input is considered a virtual ground, the current flowing into and out of the capacitor passes through resistor R_v from the output toward the virtual ground. The voltage across R_v is the output voltage, which is proportional to the rate of change of U_{in}. For a positive, linear change in the input voltage, a constant negative voltage appears at the output of the operational amplifier. The voltage inversion results from the fact that the input signal is applied to the inverting input of the amplifier, thus forming an inverting amplifier.

The current flowing through the capacitor is:

$$I = \frac{dQ(t)}{dt} = \frac{dCu_c(t)}{dt} = C \cdot \frac{dU_c(t)}{dt}$$

where $U_C(t)$ is the voltage across the capacitor, and $U_C(t) = U_{in}(t)$.

Based on the node equation written at the inverting input:

$$I + \frac{U_{out}}{R_v} = 0 \rightarrow U_{out}(t) = -CR_v \frac{dU_{in}(t)}{dt}$$

In addition to analog computers, differentiator circuits are also used in control engineering, for example, in situations where the rate of change of a process variable must not exceed a certain limit (e.g., the rate of temperature increase in a boiler due to thermal expansion). In such cases, the DC output voltage is connected to a comparator, which activates an alarm or initiates intervention when the preset maximum level is reached.

The circuit will accurately perform differentiation if the time constant $\tau = R_v C$ is much smaller than the period of the signal to be differentiated: $\tau \ll T$, i.e., $f \ll 1/\tau$. In this case, however, the output signal amplitude is also very small. A larger amplitude output can be obtained with the same circuit, but then the differentiation will be less accurate.

4.7 Integrator circuit

Sometimes we need exactly the opposite circuit function of the one described earlier: we want the output signal to be proportional to the magnitude and duration of the input signal measured from 0 V. For this, an integrator circuit must be used. Compared to the previous configuration, it is sufficient to exchange the positions of the capacitor and the resistor—this yields an integrator.

U_2 is a virtual ground, so if the input voltage is 0 V, the output will not be exactly 0 V but will remain at a constant voltage. If a positive, constant voltage is applied to the input, the current flowing into U_2 is forced through

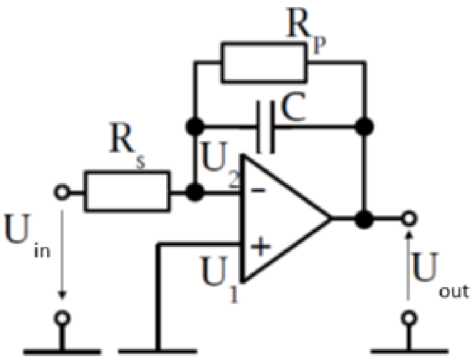

Figure 10: Integrator circuit

the capacitor, accumulating an increasing charge in it. As a result, the output voltage will continuously decrease, because the same amount of charge accumulates on the output side plate of the capacitor, which must be supplied by an increasing current flowing into the capacitor from U_{out}. Similarly, a negative input signal results in a linearly increasing positive output voltage. The rate of change of the output signal will be proportional to the input voltage.

Let i be the current flowing through the capacitor; then, based on the node equation written at U_2:

$$\frac{U_{in}}{R_s} + i = 0$$

For the ideal amplifier, $R_{in} = \infty$, therefore no current flows into it. If the ideal amplifier operates in the linear mode, then $U_2 - U_1 = 0$ V, and thus in this configuration $U_2 = 0$ V.

$$i = \frac{dQ}{dt} = C\frac{dU_c}{dt} \rightarrow C\frac{dU_c}{dt} = -\frac{U_{in}}{R_s}$$

The voltage across the capacitor is:

$$U_c(t) = U_{out}(t) = -\frac{1}{R_s C}\int_0^t U_{in} dt$$

A typical application area of the integrator circuit in nuclear technology is the measurement of irradiation level or dose based on the signals of a proportional detector. As we know, an absorbed radiation dose is the time integral of the pulses resulting from the detector's converted counts.

The same dose can be produced either over a long time with low-intensity radiation or over a short time with high-intensity radiation. In these two cases, the slope of the output voltage will differ, but in the end, the voltage level will be the same. The integrator therefore takes into account both the intensity and the duration of the input signal and generates the output signal accordingly.

Our circuit will perform accurate integration if the time constant $\tau = R_v C$ is much greater than the period of the signal to be integrated, i.e., $\tau \gg T$, or $f \ll 1/\tau$. In this case, however, the output signal amplitude will also be very small. A larger amplitude output can be obtained with the same circuit, but then the integration will be less accurate.

4.8 Miller effect

The gain of operational amplifiers decreases at high frequencies. The explanation for this is that in the internal circuits and wiring of the IC, the effect of stray capacitances increases with frequency. If these capacitances are located between the input and output of an amplifier circuit, their effect is multiplied. To illustrate this, let us examine Fig 11,

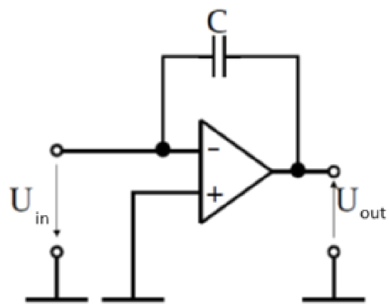

Figure 11: Illustration of Miller capacitance

but now let us not assume infinite gain (since we want to determine how the gain influences the apparent value of the capacitor)!

$$i_c = C\frac{d(U_{out} - U_{in})}{dt}$$
$$U_{out} = -AU_{in}$$

Substituting the latter:

$$i_c = C\frac{d}{dt}(-AU_{in} - U_{in}) = -C(1 + A)\frac{dU_{in}}{dt}$$

We can see that a capacitance connected between the inverting input and the output of the amplifier behaves, from the viewpoint of the input, as if it had a capacitance of $(1 + A)C$. If A is very large, then even small stray capacitances can cause significant effects. This is called the Miller effect.

5 Exercises

The supply voltage must be symmetric ±5 V with respect to the virtual ground (virtual GND). The virtual ground must also be connected to the circuit!

- M1: Build an inverting configuration (Figure 4) with a μA741 operational amplifier! $R_v = 470$ kΩ, $R_s = 100$ kΩ. The input signal is DC 100 mV, which you should increase in 100 mV steps until the amplifier output goes into saturation. Determine the gain based on the measured data and verify it by calculation as well!
- M2: Examine the operation of the summing amplifier (Fig 7)! $R_1 = R_2 = R_s = R_v = 1$ kΩ. It is sufficient to sum two voltages ($U_{in1} = U_{in2}$); i.e., the two inputs may be tied together. Perform the measurement for input voltages of 100 mV, 500 mV, and 1 V.
- M3: Prove by measurement that the gain of the non-inverting voltage follower (Fig 8) is $A_u = 1$! Using a function generator, apply a 1 kHz sinusoidal signal to the input of the circuit with a peak-to-peak value (Vpp) of 100 mV. Determine the upper cutoff frequency of the follower. The measurement is acceptable if the waveform is not distorted and only its amplitude decreases to $1/\sqrt{2}$ of the maximum value!
- M4: Examine the operation of the differentiator circuit using 1 kHz, 100 mV sine, square, and triangle inputs (Fig 9)! Let $C = 10$ nF, $R_v = 100$ kΩ, $C_P = 100$ pF! What is the role of C_P? Try the circuit both with and without C_P, and describe your observations! Display the input signal on the oscilloscope as well, and examine the output signal as a function of it. Include images of the observed waveforms in the report.
- M5: Examine the operation of the integrator circuit using 1 kHz, 100 mV sine, square, and triangle inputs (Fig 10)! Let $C = 10$ nF, $R_s = 100$ kΩ, $R_P = 10$ MΩ. What is the role of R_P? Try the circuit both with and without R_P, and describe your observations! Display the input signal on the oscilloscope as well, and examine the output signal as a function of it. Include images of the observed waveforms in the report.

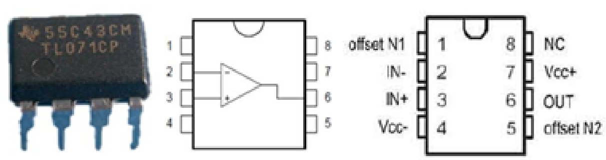

Figure 12: Pin configuration of TL071 and μA741

Please include in the report a detailed list of all measuring instruments, generators, cables, and components used, specifying their types, model numbers, quantities, and values whenever available on the devices. Ensure that the photo sizes are optimized so that the report does not exceed 10 MB in total.

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