5 (1. Halbtag) | Operationsverstärker

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Contents

1 Introduction

This experiment deals with the opamp and its funcitonality in different circuits. The opamp can be used as a non–inverting or inverting amplifier, adder, differential amplifier, current source, monoflop, to logarithmize or exponentiate and to differentiate or integrate a signal. It is also possible to build a SCHMITT–trigger or an astable multivibrator. In this experiment the opamp will serve as a non–inverting amplifier, adder, current source, integrator and differential amplifier.

2 Theory

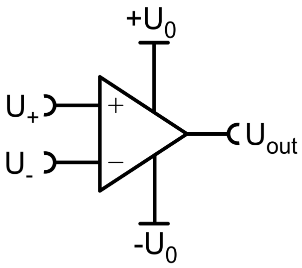

Figure 1: Schematic of an opamp; Abb. 5/6.1[1]

The most important properties of opamps are

– With stable negative feedback, the opamp regulates the output voltage such that $U_+ = U_-$.

– There is close to no input current $I_+ = I_- \approx 0$.

Important features of real opamps to keep in mind

– The maximum output voltage can't be higher than the maximum supply voltage.

– Due to internal constrains, the opamp has a finit slew rate, meaning that it can't change a signal at infinite speed.

– The open–loop gain decreases with rising frequency. The bandwidth is the cutoff frequency at which $\nu = \frac{1}{\sqrt{2}}$.

– For $U_+ = U_- = 0$ one would assume that $U_{\text{out}} = 0$. In real world opamps this is not the case. The output voltage goes to zero at a certain difference between U_+ and U_-. This difference is component specific.

– The output voltage should not change if both input voltages increae at the same rate. This is not the case in the real world. The common mode rejection ratio is the ratio between the differential gain and common mode gain.

The opamp can be utilised as a non–inverting amplifier with an ideal open–loop gain of infinity. Here $U_- = k \cdot U_{\text{out}}$ and $U_+ = U_{\text{in}}$. The gain is

$$\nu = \frac{U_{\text{out}}}{U_{\text{in}}} = \frac{1}{k} = 1 + \frac{Z_2}{Z_1}. \tag{2.1}$$

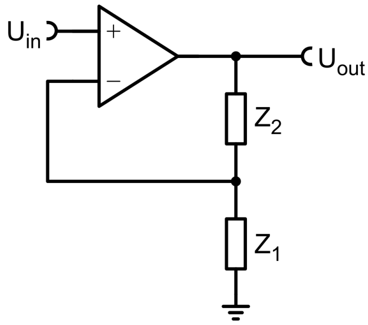

Figure 2: Non–inverting amplifier; Abb. 5/6.4[1]

The opamp can also be used as an adder. As discussed in preliminary task F the output voltage is an addition of input voltages

$$U_{\text{out}} = c_i U_i \qquad c_i = -\frac{R_0}{R_i}. \tag{2.2}$$

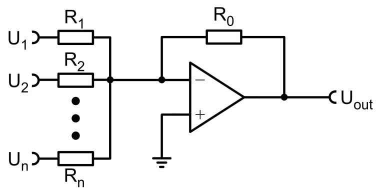

Figure 3: Adder; Abb. 5/6.6[1]

The opamp can also integrate signals by charging a capacitor to sum up the input signal

$$U_{\text{out}}(t) = -\frac{1}{R_1 C} \int_{t_0}^{t} U_{\text{in}}(t')\, \mathrm{d}t'. \tag{2.3}$$

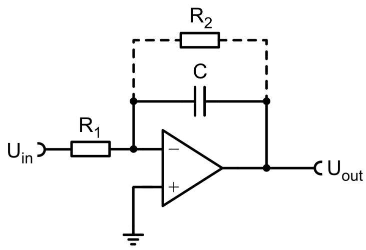

Figure 4: Integrator; Abb. 5/6.11[1]

At last the opamp is used in a circuit to function as a differential amplifier. As discussed in preliminary task G, the output voltage is an amplification of the difference of the input voltages

$$U_{\text{out}} = \frac{R_2}{R_1}\left(U_2 - U_1\right). \tag{2.4}$$

Here $\frac{R_2}{R_1}$ is the gain.

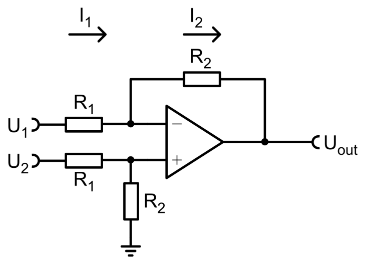

Figure 5: Differential amplifier; Abb. 5/6.7[1]

When using the opamp as an inverting amplifier, the current flowing through the negative feedback circuit does not depend on Z_2 but only on U_{in} and Z_1. Thus one can construct a current source for the resistance Z_2 which can be controlled via the input voltage.

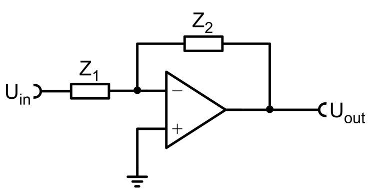

Figure 6: Inverting amplifier; Abb. 5/6.5[1]

The astable multivibrator uses the SCHMITT–trigger to construct a signal from an ideal wave form, see preliminary task K.

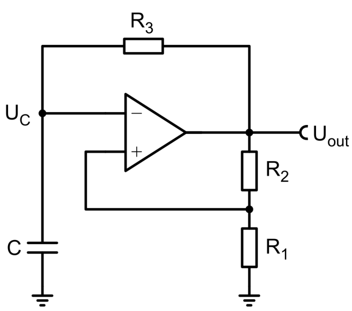

Figure 7: Astable multivibrator; Abb. 5/6.15[1]

3 Preliminary Tasks

3.1 A

The equation hold

$$\frac{1}{\nu} = \frac{1}{\nu_0} + k \qquad \nu = \frac{1}{\frac{1}{\nu_0} + k}. \tag{3.1}$$

For $k = 0.1$, $\nu_0 = 10^4$ and $\nu_0 = 10^5$

$$\nu_1 \approx 9.990 \qquad \nu_2 \approx 9.999. \tag{3.2}$$

The approximation $\nu = \frac{1}{k}$ results in

$$\nu_{\text{Näh}} = 10. \tag{3.3}$$

The deviation of ν_1 and ν_2 from $\nu_{\text{Näh}}$ lie at 0.001% and 0.0001% respectively.

3.2 B

It hold

$$U_x = U_{\text{in}} - kU_{\text{out}} \tag{3.4}$$
$$\Leftrightarrow \qquad = U_{\text{in}} - kv_0 U_x$$
$$\Leftrightarrow \qquad = \frac{U_{\text{in}}}{1 + v_0 k}. \tag{3.5}$$

For $k = 0.1$, $v_0 = 10^5$ and $U_{\text{in}} = 1\,\text{V}$

$$U_x \approx 0.0001\,\text{V}. \tag{3.6}$$

3.3 C

Let there be a common mode signal with $\Delta U_+ = \Delta U_- = +\Delta U_{\text{in}}$. then

$$\Delta U_+ = \Delta U_E + \Delta U_1 \quad \Delta U_- = \Delta U_E + \Delta U_1. \tag{3.7}$$

from this follows $\Delta U_{\text{in}} = \Delta U_E + \Delta U_1$. The output voltage is

$$\Delta U_{\text{out}} = R_C \cdot \Delta I_C. \tag{3.8}$$

At point 1,

$$I_1 = 2I_E. \tag{3.9}$$

Therefore

$$\begin{aligned}\Delta U_{\text{in}} &= R_E \cdot \Delta I_E + R_1 \cdot 2\Delta I_E \\ &= \Delta I_E \left(R_E + 2R_1\right) \approx \Delta I_E \cdot 2R_1.\end{aligned} \tag{3.10}$$

At the node U_{out} applies

$$\Delta I_E = \Delta I_C \Rightarrow \Delta U_{\text{out}} = R_C \cdot \Delta I_E. \tag{3.11}$$

The amplification results in

$$v_{CM} = \frac{\Delta U_{\text{out}}}{\Delta U_{\text{in}}} = \frac{R_C}{2R_1}. \tag{3.12}$$

The common mode suppression is

$$10\log\left(\frac{R_E}{R_1}\right) = 10\log\left(\frac{1\,\text{k}\Omega}{100\,\text{k}\Omega}\right) = -20\,\text{dB}. \tag{3.13}$$

3.4 D

The frequency dependence of the impedance of a capacitor is

$$Z_1 = \frac{1}{\text{i}\omega C} = \frac{1}{\text{i}2\pi f C} \tag{3.14}$$

$$|Z_1| = \left|\frac{1}{\text{i}\omega C}\right| = \frac{1}{2\pi f C}. \tag{3.15}$$

The gain as a function of frequency is

$$v(f) = 1 + \frac{Z_2}{|Z_1|} = 1 + R2\pi f C. \tag{3.16}$$

The limits are

$$\lim_{f\to 0}\left[1 + R2\pi f C\right] = 1 \quad \lim_{f\to\infty}\left[1 + R2\pi f C\right] = \infty. \tag{3.17}$$

For $|Z_1| = R$ it has to hold that

$$\frac{1}{2\pi f C} = R \Leftrightarrow f = \frac{1}{2\pi R C}. \tag{3.18}$$

With concrete values $Z_1 = R = 100\,\text{k}\Omega$ and $Z_1 = C = 100\,\text{nF}$, the frequency is

$$f = \frac{1}{2\pi R C} \approx 15.92\,\text{Hz} \Rightarrow v(f) \approx 2. \tag{3.19}$$

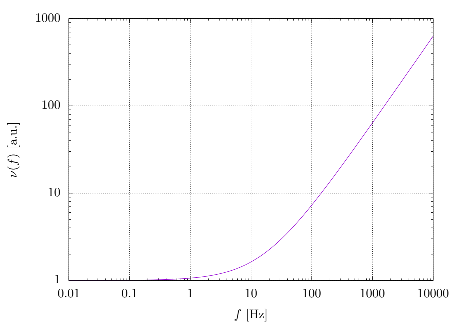

Figure 8: Time dependend amplification of a non–invertible amplifier as a BODE–plot

3.5 E

Let

$$v = \frac{U_{\text{out}}}{U_{\text{in}}} = -\frac{Z_2}{Z_1}. \tag{3.20}$$

The minus sign results from the negative feedback. Because of the golden rule $U_- = U_+ = 0\,\text{V}$, the negative feedback has a different sign compared to the input signal.

The input impedance is very high and the output impedance very low.

3.6 F

The first KIRCHHOFF's law states (EINSTEIN notation)

$$\sum_i I_i = -I_{\text{out}} \tag{3.21}$$

$$\Leftrightarrow \quad \frac{U_i}{R_i} = -\frac{U_{\text{out}}}{R_0} \tag{3.22}$$

$$\Leftrightarrow \quad -\frac{R_0}{R_i}U_i = U_{\text{out}} \tag{3.23}$$

$$\Leftrightarrow \quad c_i U_i = U_{\text{out}}. \tag{3.24}$$

3.7 G

$$U_+ = U_2\frac{R_2}{R_1 + R_2} \quad |\text{voltage divider} \tag{3.25}$$

$$U_- = U_+ \quad |\text{golden rule} \tag{3.26}$$

$$I_1 = \frac{U_1 - U_-}{R_1} \quad |\text{OHM's law} \tag{3.27}$$

$$I_2 = I_1 \quad |\text{golden rule} \tag{3.28}$$

$$I_2 = \frac{U_- U_{\text{out}}}{R_2} \quad |\text{OHM's law.} \tag{3.29}$$

The final result $U_{\text{out}} = \frac{R_2}{R_1}(U_2 - U_1)$ can be calculated using the above relations.

3.8 H

A constant negative input voltage provides a continuous charge to the capacitor, resulting in a steadily rising output voltage. One could also argue that for a constant input voltage the integral will increase linearly.

3.9 I

For an inverting amplifier $\nu = -\frac{Z_2}{Z_1}$. With $Z_1 = R$ and $Z_2 = \frac{1}{\text{i}\omega C}$

$$\nu = -\frac{1}{\text{i}\omega C R}. \tag{3.30}$$

The phase relation between the output– and inputsignal is then

$$\tan \Phi = \frac{\Im(\nu)}{\Re(\nu)} = \lim_{\alpha \to 0} \frac{-\frac{1}{\omega CR}}{\alpha} = -\infty. \tag{3.31}$$

Thus $\Phi = -\frac{\pi}{2}$.

3.10 J

The AD711 opamp has a slew rate of $s = 20\,\mathrm{V\,\mu s^{-1}}$. The peak to peak voltage lies at $U_{pp} = 28\,\mathrm{V}$. This means that the AD711 needs

$$t = \frac{U_{pp}}{s} = 1.4\,\mathrm{\mu s} \tag{3.32}$$

to get from $-14\,\mathrm{V}$ to $14\,\mathrm{V}$. The switching frequency is therefore

$$\tfrac{1}{t} = 0.714\,\mathrm{\mu s^{-1}}. \tag{3.33}$$

3.11 K

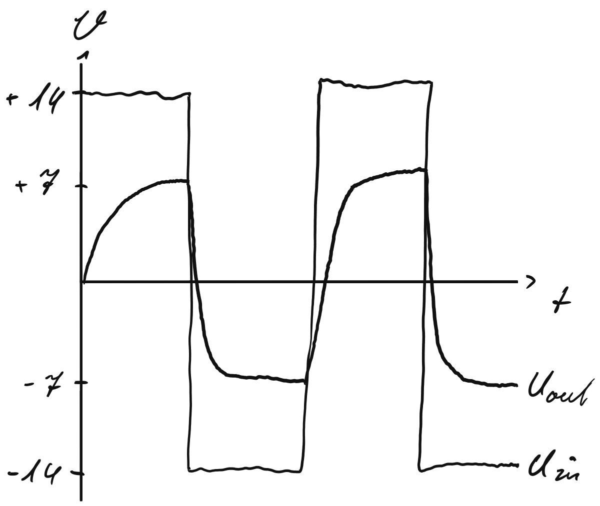

Figure 9: Astable multivibrator, voltage curve

The ideal signal is a square–wave with $U_{\max,\min} \pm 14\,\mathrm{V}$. Due to the slew rate of the opamp, the signal need time to rise to $\pm 7V$. The output voltage can be modeled with an exponential function.

4 Analysis

4.1 Non–inverting amplifier

The non–inverting amplifier is built with a gain of $\nu = 11$ (i.e. $R_1 = 1\,\mathrm{k}\Omega$ and $R_2 = 10\,\mathrm{k}\Omega$). A signal of $U_{pp} = 1\,\mathrm{V}$ is applied to the circuit and the gain is observed for different frequencies.

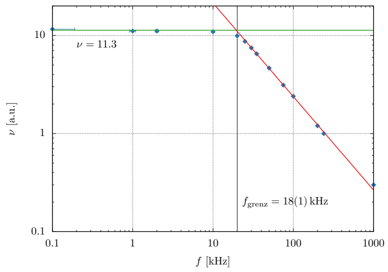

Figure 10: BODE–plot of a non–inverting amplifier with $\nu = 11$

As one can see, up to $f_{\mathrm{grenz}} \approx 18(1)\,\mathrm{kHz}$ the gain stays the same (at $\nu \approx 11.3$). After f_{grenz} the gain decreases exponentially and is 1 at $f_T = 240\,\mathrm{kHz}$.

frequency f [kHz]	gain ν [a.u.]
0.30	1000
1.00	240
1.20	200
2.40	100
3.12	75
4.65	50
6.50	35
7.48	30
8.69	25
9.92	20
10.9	10
11.1	2
11.1	1
11.6	0.1
11.5	0.01

Table 1: Values for BODE–plot

Because the opamp model LM301AP is not listed in the protocoll and has no onilne documentation it is not possible to compare the measured transit frequency to the exact value.

Now the gain is set to $\nu = 101$ by using $R_2 = 470\,\mathrm{k}\Omega$ and $R_1 = 4.7\,\mathrm{k}\Omega$. The signal has a peak to peak voltage of $100\,\mathrm{mV}$.

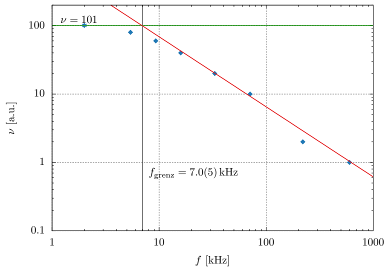

Figure 11: BODE–plot for different gain

The cutoff frequency lies at $f_{\mathrm{grenz}} = 7.0(5)\,\mathrm{kHz}$; the transit frequency lies at $f_T = 600\,\mathrm{kHz}$. For $\nu = 2$ the frequency lies at $f_2 = 220\,\mathrm{kHz}$. Due to the heavy negative feedback, the amplification decreases linear (in the loglog plot).

For $\nu = 101$ a square–wave signal with frequency of $f = 1\,\mathrm{kHz}$ and $U_{pp} = 20\,\mathrm{V}$ is set.

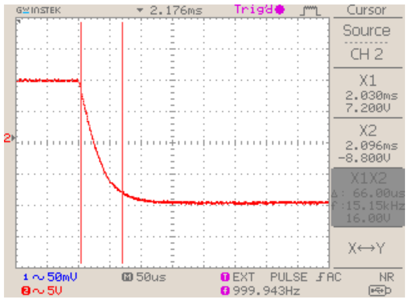

Figure 12: Slew rate for said square–wave

The slew rate is the time it takes the oscillograph to raise a signal from 10% to 90%. From the cursors on the oszillogramm, one can see the time difference to be $\Delta = 66\,\mu\mathrm{s}$.

When increasing the frequency, the slew rate stays the same, because the slew rate is an intrinsic property of the oscillograph and should not change if any outside parameters change. The amplitude decreases as the frequency increases because the plateaus of constant voltage shorten. If the frequency is high enough, the signal will change polarity too fast for the circuit to be complete saturated. There are no differences to the sine signal. The slew rate is also not relevant for the sine signal, because it does not switch sign instantly.

Now a gain of $\nu = 11$ (with $R_1 = 10\,\mathrm{k}\Omega$ and $R_2 = 100\,\mathrm{k}\Omega$) is set and a capacitor with $C = 0.1\,\mu\mathrm{F}$ is connected in series with R_1. Due to different unkown reasons, like a loose connection in a cable, nothing seemed to have changend, when connecting the capacitor. Our expectation was that the capacitor and resistor would behave like a high–pass, meaning that signals with high frequencies would rather run through the capacitor into ground than the opamp, resulting in high frequency signals not being amplified.

List of Figures

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Source

[1] Fabian Hügging. *Elektronik–Praktikum Versuchsanleitung*. Universität Bonn, kurs b edition, 2024.