Examination of the input amplifier stage in operational amplifier

1A

1. Introduction

In this exercise an input stage (e.g. differential amplifier) of the operational amplifier is examined. The measurement system allows to measure basic parameters of the differential amplifier made of bipolar transistors and allows changing the configuration of the differential pair. By means of switches, you can select one of the variants of the current source that biases the transistors, as well as the type of load of the transistors.

Before starting the exercise, please read the theory about the principles of operation of the differential amplifier (included in this manual).

2. Measurements

Perform measurements of the differential amplifier in the following configurations:

A. current source — resistor R_E, load — resistor R_C;
B. current source — resistor R_E, load — R'_C;
C. current source — transistor with resistor R_{E1}, load — resistor R_C;
D. current source — transistor with resistor R_{E2}, load — resistor R_C;

NOTE: Every time the configuration A-D is changed, the circuit must be balanced. To do this, depress the switch K1 and set the input voltage equal to 0 mV using potentiometer P1. For such a condition, set the same voltages at the collectors of transistors T_1 i T_2 using the potentiometer P3 marked "RESET".

For each configuration, A-D, take measurements of static characteristics when excited by:

1) differential input voltage (the switch K1 pressed),
2) common-mode input voltage (the switch K1 depressed).

In the first case, measure the voltages at the collectors of transistors T_1 and T_2 (V_{WY1}, V_{WY2}) as a function of the input differential voltage V_{WER} (the switch K1 pressed). In addition, for the same values of the input voltage measure the current I_E (the right gauge). The input voltage must be changed in the range [-150mV, +150mV], using the potentiometer P2. Value of the input voltage can be read from the left gauge, the reading multiply by 10 and the result is in mV.

In the second case (for common-mode input), measure the voltage at the collectors of transistors T_1 and T_2 (V_{WY1}, V_{WY2}) as a function of the input common-mode voltage V_{WES} (the switch K1 pressed). In addition, for the same values of the input voltage measure the current I_E. The input voltage must be changed in the range [-5V, +5V], using the potentiometer P2. Value of the input voltage can be read from the left gauge, the reading multiply by 2 and the result is in V.

Pressing the switch marked: R_E, R_{E1}, R_{E2}, R_C, R'_C, R_D will activate the selected configuration. To complete settings of a required configuration, press one of the switches: R_E, R_{E1}, R_{E2} (balck color) and one of the switches: R_C, R'_C, R_D (white color).

3. Results elaboration

1) The results of measurements of the differential amplifier in configurations: A, B, C and D to be presented in plots:

- V_{WYR}= f(V_{WER}) ie. a joint plot of V_{WYR} as a function of the differential input voltage V_{WER} for the four configurations: A, B, C and D.
- I_E= f(V_{WER}) ie. a joint plot of I_E as a function of the differential input voltage V_{WER} for the four configurations: A, B, C and D.
- I_E= f(V_{WES}) ie. a joint plot of I_E as a function of the common-mode input voltage V_{WES} for the four configurations: A, B, C and D.

2) Based on the results of measurements calculate: differential voltage gain K_r, common-mode voltage gain K_s, and value of CMRR coefficient.

3) Using the schematics of the amplifier in configuration A and B, calculate: the operation point of T_1 and T_2, value of current I_E, and the differential voltage gain K_r. Compare the measurement results with the calculated values for I_E and K_r.

Include your own conclusions and observations, compare amplifiers with one another, as well as comment on the compliance of theoretical calculation results with measurements.

4. Principle of operation and theory

A simplified schematic of a differential amplifier (without switches for configuration changes and potentiometers for input voltage regulation) is shown in Fig. 1.

The differential amplifier is composed of two symmetrical branches containing transistors T_1 and T_2.

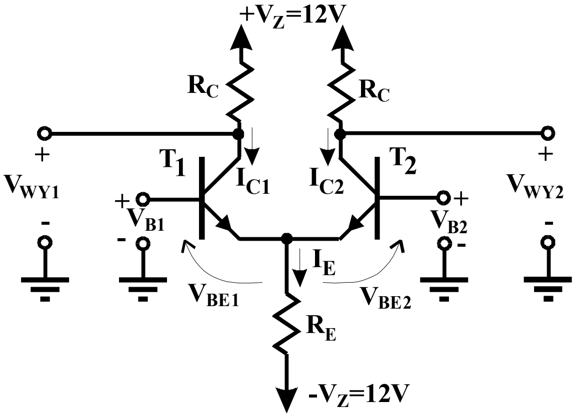


Fig. 1. Simplified schematic of a differential amplifier.

Principle of operation of the amplifier is as follow. If the base voltage V_{B1} of transistor T_1 is increased to positive value, and the base voltage of transistor T_2 is $V_{B2}=0$, then the collector current I_{C1} of transistor T_1 increases. At the same time the collector current I_{C2} of transistor T_2 decreases. The situation reverses when the voltage polarity is opposite. In the amplifier the sum of transistors' emitter currents is always equal to the current I_E, which flows through the resistor R_E, thus:

$$I_{E1} + I_{E2} = I_E \tag{1}$$

If the resistance R_E is sufficiently large, the current I_E is independent of voltages at the bases of transistors T_1 and T_2. Therefore, it is preferred to use a current source instead of a resistor R_E. Using the Kirchhoff's current low one can formulate the following equations:

$$V_{BE1} = V_{B1} - V_E$$
$$V_{BE2} = V_{B2} - V_E \qquad (2)$$

Afrer removing V_E from (2), it is achieved:

$$V_{WER} = V_{B1} - V_{B2} = V_{BE1} - V_{BE2} \qquad (3)$$

The voltage V_{WER} is called a differential input voltage. It is seen from (3) that the differential input voltage V_{WER} is independent of R_E. Therefore the differential voltage gain K_r is also independent of R_E.
The schematic of the amplifier with unsimetrical input voltage is presented in Fig. 2.

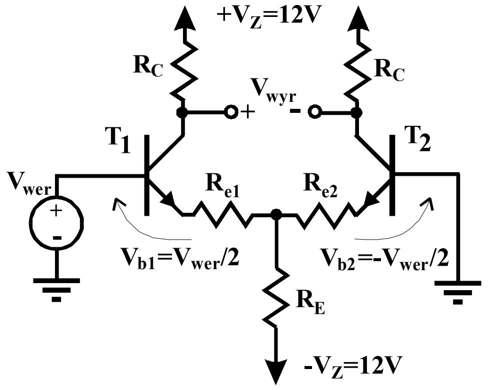


Fig. 2. Differential amplifier with unsimetrical input and symmetrucal output.

In circuit, shown in Fig. 2, the transistor T_1 works in an emitter follower configuration. The signal from T_1 emitter is passed to transistor T_2, which works in a common base configuration. For sufficiently large resistance R_E, instantaneous changes in emitter currents of both transistors are equal and opposite. Hence voltages controling both transistors are almost identical (for a perfect current source instead of R_E, and identical transistors T_1 and T_2). Each of these voltages is half of the input voltage V_{wer}. Therefore, a differential amplifier has a feature of automatic rebalancing of the input voltage controlling both transistors. As a result, the gain of each branch of the amplifier is equal to half the gain of the entire circuit.

4.1. The region of linear operation of the differential amplifier

Fig. 3 shows typical static characteristics of a differential amplifier. It can be seen that there is a range of relatively linear operation. The transfer characteristics of the transistors are linear in the vicinity of a quiescent point of the amplifier, ie. midpoint corresponding to a situation where $.V_{B1} = V_{B2}$. The region of linear operation of the amplifier corresponds to the difference of the input voltages of approximately 50 mV. This range is thus very small. If the linear range needs to be expanded, this can be achieved, including additional resistors R_{e1} and R_{e2} between the emitters of the transistors and the connection point of the resistor R_E (as shown in Fig. 2). The additional resistors introduce a negative feedback that extends a range of linearity of equivalent transconductance g^*_m of the amplifier. The influence of the resistances $R_e = R_{e1} = R_{e2}$ on the linear range is shown in Fig. 4.

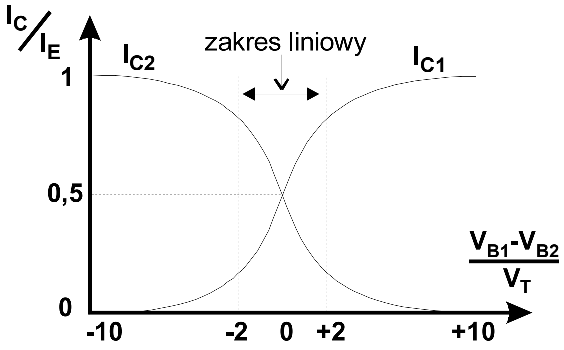


Fig. 3 Static characteristics of a differential amplifier.

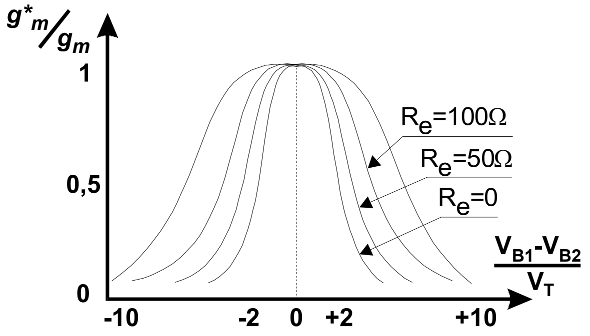


Fig. 4 The influence of the resistances Re=Re1=Re2 on the linear range of the amplifier transconductance g^*_m.

Under assumption that $R_e = R_{e1} = R_{e2}$, the equivalent transconductance g^*_m of the amplifier, working with unsimetrical output, can be calculated from:

$$g^*_m = \frac{g_m}{2\left(1 + R_e g_m\right)} \qquad (4)$$

where $g_m = I_C / V_T$, $V_T = 25{,}8mV$.

4.2. The role of resistor R_E in a differential amplifier

For equal in amplitude and in-phase input voltages V_{B1} and V_{B2} (common-mode), or for similar changes of transistors parameters (eg. caused by changes of ambient temperature) there is a strong negative feedback on a common resistance R_E. This feedback is the stronger the higher is the resistance R_E. On the other hand, when the amplifier is excited by a differential voltage, changes in currents of both transistors are opposite and reduce at the resistance R_E. Therefore in this case the resistance does not affect the output voltage of the amplifier. Consequently, the gain for a differential voltage is much greater than for a common-mode one. The differentaial gain depends only on resistance R_C and R_e, whereas the common-mode gain depends on resistance R_C, R_e and R_E, namely:

$$K_r = \frac{\Delta V_{WYR}}{\Delta V_{WER}} = -2 R_C g^*_m \qquad (5)$$

$$K_s = \frac{\Delta V_{WY1}}{\Delta V_{WES}} = -\frac{R_C g_m}{1 + \left(2R_E + R_e\right) g_m} \qquad (6)$$

The equation (5) was derived based on equation (4), which defines the transconductance for a whole differential amplifier (the gain is equal to the product of the transconductance g^*_m and the load resistance R_C).

4.3. Common-mode operation of a differential amplifier

The common-mode operation of a differential amplifier is when both input voltages are equal $V_{B1} = V_{B2}$. In this case the voltages controlling the transistors will be reduced by the amount of a drop voltage across the resistor R_E. Therefore, the gain for a common mode voltages is strongly dependent on resistance R_E. From equation (6) it can be seen that the greater the resistance R_E is, the smaller the gain K_S is.

In practice, all the disturbance signals are common mode, eg. thermal drift that alters the operating points of transistors T_1 and T_2. On the other hand differential signal carries useful information. It can be concluded that an ideal differential amplifier should have zero common mode gain.

4.4. Calculation of operation points of the transistors

The operation points of the transistors can be calculated. based on the schematic in Fig. 2. In the quiescent state of the amplifier (the absence of the input voltage V_{wer} = 0) the following equations are valid:

$$\begin{aligned} V_{BE1} + I_E R_E + I_{C1} R_{e1} &= V_z \\ I_{C1} &= I_E / 2 \end{aligned} \tag{7}$$

hence:

$$\begin{aligned} I_E &= \frac{V_z - V_{BE}}{R_E + R_{e1}/2}; \quad I_{C1} = I_{C2} = I_E / 2 \\ V_{C1} &= V_{C2} = V_z - R_C I_E / 2 \end{aligned} \tag{8}$$

The calculation of I_E for a configuration with a current source using the transistor T_3, can be performed as follow (refer to Fig. 5):

$$V_{B3} = -\frac{R_7}{R_7 + R_8} V_z; \qquad I_E \cong I_{E3} = \frac{V_z + V_{B3} - V_{BE}}{R_{E1}} \tag{9}$$

assume V_{BE} = 0,65 V.

4.5. Common-mode rejection ratio — CMRR

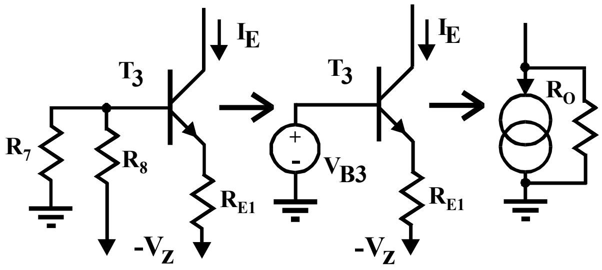
In pursuit to perfection, the differential amplifiers are designed in such a way to get the smallest common-mode gain. The parameter that characterizes the relationship between the useful differential gain to the disadvantageous common-mode gain is called CMRR (*Common Mode Rejection Ratio*):

$$CMRR = \frac{K_r}{K_{rs}} = \frac{\Delta V_{WYR} / \Delta V_{WER}}{\Delta V_{WYR} / \Delta V_{WES}} = \frac{\Delta V_{WES}}{\Delta V_{WER}} \tag{7}$$

In practice, it is more convenient to determine CMRR using the rightmost component of equation (7). This definition says, that CMRR is a ratio of the common-mode input voltage to the differential input voltage, which generates the same differential output voltage at the output. If the differential amplifier is perfectly simmetric, CMRR is equal to infinity. In a real circuit, however, CMRR value is limited and increases with increasing of the resistance R_E. Therefore, in order to obtain the best CMRR, it is required that the resistance R_E has the largest possible value. It is also necessary that the two transistors have identical parameters, in particular the current gain factor β.

4.6. Current source biasing emitters of an amplifier

As stated, it is possible to achieve good characteristics of the differential amplifier provided that resistance R_E is high. Increasing the value of this resistor is in practice limited by the supply voltage. It is possible, however, the application of a current source in place of the resistor. The simplest current source can be realized as a single transistor in the configuration shown in Fig. 5.



`Fig. 5. An example of a current source implemented using a single transistor.`

A typical value of the output resistance R_O of the source shown in Fig. 5 is equal to a few dozen MΩ.

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5. Parameters of the components used in the circuit

R_1=110Ω
R_2=110Ω
R_3=8,2kΩ
R_4=8,2kΩ
R_{E2}=6,36kΩ
R_{5DO}=5,18kΩ
P_2=10kΩ

R_5=820Ω
R_6=820Ω
R_7=2kΩ
R_8=910Ω
R_P=490Ω
P_1=2,2kΩ
P_3”ZER”**=470Ω**

R_C=12kΩ
R'_C=2kΩ
R_E=12kΩ
R_{E1}=3,13kΩ
R_W=4,9kΩ

R_{e1}= R_{e2}= P_3”ZER”/2

Literature:

[1] Z. J. Staszak, J. Glinianowicz, D. Czarnecki “Materiały pomocnicze do przedmiotu Układy Elektroniczne Liniowe”.
[2] A. Guziński, “Liniowe elektroniczne układy analogowe” WNT 1992.
[3] S. Soclof, “Zastosowania analogowych układów scalonych”, WKŁ 1991.