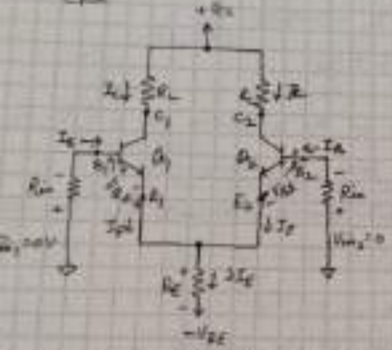
Since the transistors are identical, R_{in} of the signal sources are equal and small and the voltage drop across them can be taken as negligible. Since Q_1 transistors are matched and, the operating point obtained for one transistor is same for the other. The dc equivalent circuit for all the four configurations is same, therefore the dc analysis done below applies for all the configurations.

Redraw the circuit of Fig 2 by reducing the two input voltages to zero.

Fig 2



- Operating point I_{CQ}, V_{CEQ} for both transistors
- I_C, V_{CE} of Q_1 for one trans
- Voltage drop across R_{in} negligible
- $V_{BE} = 0.6V$ for Si, $= 0.2V$ for Ge
- $I_C \approx I_E$

Applying Kirchhoff's voltage law for BE circuit for transistor Q_1

$$-R_{in} I_B - V_{BE} - R_E(2I_E) + V_{EE} = 0 \qquad (1)$$

Put $I_B = I_E/\beta_{dc}$ in Eq (1) assuming $I_C = I_E$

$$-R_{in}\frac{I_E}{\beta_{dc}} - V_{BE} - 2R_E I_E + V_{EE} = 0$$

$$-I_E\left(\frac{R_{in}}{\beta_{dc}} + 2R_E\right) = -(V_{EE} - V_{BE})$$

- When we use only one input signal : Single input
- When the output is taken between two collectors : balanced output
- When the output is taken from one of the collectors w.r.t. ground : unbalanced output

In analyzing difference amplifier, r-parameters are used because they are

- simpler, more straight forward
- unlike h-parameters no need to manipulate h-parameters at operating points.
- easy to remember equations, etc.

Balanced Output :

The two collectors of the two transistors are at the same dc voltages w.r.t. the ground.

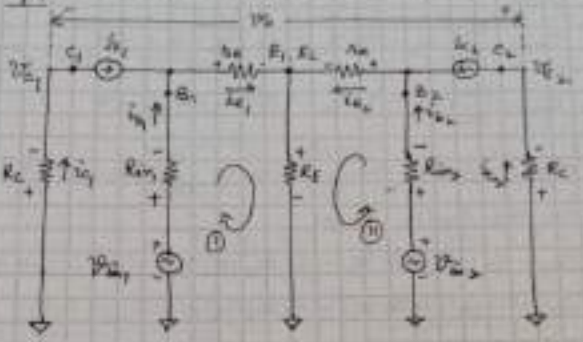
Unbalanced Output :

The collector at which the output is measured is at a definite dc voltage even when no input is given.

the dc voltage sources are shorted out, and transistors are replaced by their T-equivalent models based on r-parameters.

Equivalent circuit (AC) of Fig. 3

Fig. 4



Voltage Gain

Note: 1. Two identical common-emitter circuit with matched transistors, etc., therefore

$$I_{E_1} = I_{E_2} = I_E \text{ and}$$

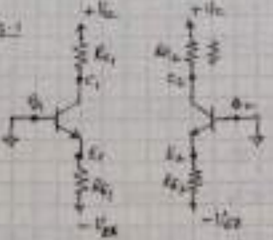
$$r_{e_1} = r_{e_2} = r_e$$

2. Because of the common-emitter configuration, the voltages at the collectors are shown to be 180° out of phase with that of v_{in_1} and v_{in_2}.

3. Collector C_2 is assumed to be more positive w.r.t. C_1 even though both are negative w.r.t. the ground.

Differential amplifier is the basic building block of operational amplifiers. Consider two identical emitter-biased transistor circuits.

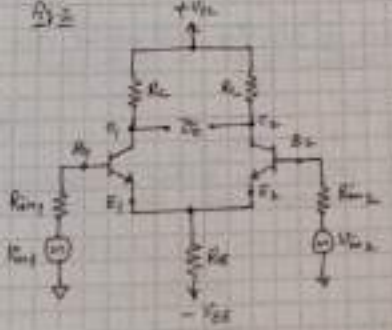
Fig. 1



- The transistors have same characteristics
- $R_{C_1} = R_{C_2}$, $R_{E_1} = R_{E_2}$
- $|V_{CC}| = |V_{EE}|$ and are measured w.r.t. ground.

Reconnect the above circuit with $R_C = R_{C_1} = R_{C_2}$ & $R_E = R_{E_1} \| R_{E_2}$ and common supply voltages as shown below:

Fig. 2



- Differential amplifier amplifies difference between input signals V_{in_1} & V_{in_2}
- V_o is the output voltage
- R_{in_1} and R_{in_2} are internal resistances of the signal sources and are equal, R_{in}
- This circuit is Dual Input balanced output Dif Amp

FOUR Configurations of Differential (Difference) Amplifiers are:

1. Dual-input, balanced output
2. Dual-input, unbalanced output
3. Single-input, balanced output
4. Single-input, unbalanced output

$$I_E = \frac{V_{EE} - V_{BE}}{2R_E} \qquad \left| \; 2R_E \gg \frac{R_{in}}{\beta_{dc}} \right| \quad \text{—(3)}$$

It is clear that I_E is set up by R_E and is not dependent upon R_C.

For V_{CE}, assuming voltage across R_i to be negligible, the emitter E_1 is at $-V_{BE}$ as $I_C \approx I_E$. Considering base-collector circuit, the collector C_1 is at voltage

$$V_C = V_{CC} - R_C I_C$$

And
$$V_{CE} = V_C - V_E$$
$$= V_{CC} - R_C I_C - (-V_{BE})$$
$$V_{CE} = V_{CC} - R_C I_C + V_{BE} \qquad \text{—(4)}$$

The operating point for the transistor Q_1 is (I_E, V_{CE}), the I_C and V_{CE} are given by equations (2) to (4).

Thus operating point for any or both the transistors is written as

$$I_{CQ} = I_E$$
$$V_{CEQ} = V_{CE}$$

$$i_{e_2} = \frac{\begin{vmatrix} \cdots & v_{in_1} \\ R_E & v_{in_2} \end{vmatrix}}{\begin{vmatrix} r_e+R_E & R_E \\ R_E & r_e+R_E \end{vmatrix}}$$

$$= \frac{(r_e+R_E)v_{in_2} - R_E v_{in_1}}{[(r_e+R_E)^2 - R_E^2]} \longrightarrow r_e(r_e+2R_E)$$

The output voltage is

$$v_o = v_{c_2} - v_{c_1}$$

$$= -R_C i_{c_2} - (-R_C i_{c_1})$$

$$= R_C i_{c_1} - R_C i_{c_2}$$

$$= R_C(i_{e_1} - i_{e_2}) \qquad \text{since } i_c \cong i_e$$

Putting (11) & (12) in (14),

$$v_o = R_C\left[\frac{(r_e+R_E)v_{in_1} - R_E v_{in_2}}{(r_e+R_E)^2 - R_E^2} - \frac{(r_e+R_E)v_{in_2} - R_E v_{in_1}}{(r_e+R_E)^2 - R_E^2}\right]$$

$$= R_C\left[\frac{(r_e+R_E)(v_{in_1} - v_{in_2}) + R_E(v_{in_1} - v_{in_2})}{(r_e+R_E)^2 - R_E^2}\right]$$

$$= R_C\left[\frac{(r_e+2R_E)(v_{in_1} - v_{in_2})}{(r_e+R_E)^2 - R_E^2}\right]$$

$$= R_C\left[\frac{(r_e+2R_E)(v_{in_1} - v_{in_2})}{r_e^2 + \cancel{R_E^2} + 2r_eR_E - \cancel{R_E^2}}\right]$$

$$= R_C\left[\frac{\cancel{(r_e+2R_E)}(v_{in_1} - v_{in_2})}{r_e\cancel{(r_e+2R_E)}}\right]$$

$$v_{in_2} - R_{in_2} i_{b_2} - i_{e_2} r_e - R_E(i_{e_1} + i_{e_2}) = 0 \tag{6}$$

Substituting in these equations

$$i_{b_1} = \frac{i_{e_1}}{\beta_{ac}} \quad \text{and} \quad i_{b_2} = \frac{i_{e_2}}{\beta_{ac}}$$

we get

$$v_{in_1} - \frac{R_{in_1}}{\beta_{ac}} i_{e_1} - r_e i_{e_1} - R_E(i_{e_1} + i_{e_2}) = 0$$

$$v_{in_2} - \frac{R_{in_2}}{\beta_{ac}} i_{e_2} - r_e i_{e_2} - R_E(i_{e_1} + i_{e_2}) = 0$$

Neglect second term because $\frac{R_{in_1}}{\beta_{ac}}$ and $\frac{R_{in_2}}{\beta_{ac}}$ are very small. We get

$$v_{in_1} - r_e i_{e_1} - R_E i_{e_1} - R_E i_{e_2} = 0$$

$$v_{in_2} - r_e i_{e_2} - R_E i_{e_1} - R_E i_{e_2} = 0$$

Rearranging, we get

$$(r_e + R_E) i_{e_1} + R_E i_{e_2} = v_{in_1} \tag{7}$$

$$R_E i_{e_1} + (r_e + R_E) i_{e_2} = v_{in_2} \tag{8}$$

Using Cramer's rule to solve equations (7) and (8) simultaneously for i_{e_1} and i_{e_2}:

$$i_{e_1} = \frac{\begin{vmatrix} v_{in_1} & R_E \\ v_{in_2} & r_e + R_E \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}} \tag{9}$$

$$= \frac{(r_e + R_E) v_{in_1} - R_E v_{in_2}}{(r_e + R_E)^2 - R_E^2} \tag{10}$$

resistance measured at either input terminal with other terminal grounded. With R_{s1} and R_{s2} neglected as they are very small, the differential input resistances are

$$R_{i1} = \left|\frac{v_{in1}}{i_{b1}}\right|_{v_{in2}=0} = \left|\frac{v_{in1}}{i_{E1}/\beta_{ac}}\right|_{v_{in2}=0} \quad (19)$$

$$R_{i2} = \left|\frac{v_{in2}}{i_{b2}}\right|_{v_{in1}=0} = \left|\frac{v_{in2}}{i_{E2}/\beta_{ac}}\right|_{v_{in1}=0} \quad (20)$$

Substituting the value of i_{E1} from eq (14) in eq (19), we get

$$R_{i1} = \frac{\beta_{ac}\, v_{in1}}{\dfrac{(r_e + R_E)\, v_{in1} - R_E(0)}{(r_e + R_E)^2 - R_E^2}} \longrightarrow r_e^2 + \cancel{R_E^2} + 2 r_e R_E - \cancel{R_E^2}$$

$$= \frac{\beta_{ac}\, v_{in1}}{\dfrac{(r_e + R_E)\, v_{in1}}{r_e^2 + 2 r_e R_E}} \longrightarrow r_e(r_e + 2R_E)$$

$$= \frac{\beta_{ac}\, \cancel{v_{in1}}\, r_e (r_e + 2R_E)}{(r_e + R_E)\, \cancel{v_{in1}}}$$

Generally $R_E \gg r_e$, therefore r_e can be neglected in the bracketed terms:

$$R_{i1} = \frac{\beta_{ac}\, r_e \cdot 2\cancel{R_E}}{\cancel{R_E}}$$

$$R_{i1} = 2\beta_{ac}\, r_e \quad (21)$$

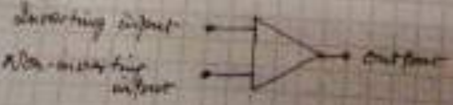
OPERATIONAL AMPLIFIER (Block diagram) OP-AMP

It is a direct coupled high gain amplifier consisting of one or more differential amplifiers followed by a level translator and a push-pull or push-pull complementary symmetry pair. It is a single chip IC.

Versatile device, used for initially for mathematical operations hence its name operational amplifier. Apart from mathematical operations, op-amps are used in amplifiers, oscillators, filters, comparators, regulators and other circuits. Block diagram:

Input stage establishes the input resistance of the op-amp. The output stage, a push-pull complementary-symmetry amplifier, increases the output voltage swing and raises the current supplying capability of the op-amp. Output stage provides low output resistance.

SYMBOL



where $v_{id} = v_{in_1} - v_{in_2}$

= difference in two input signals

The voltage-gain of dual input, balanced output differential amplifier is

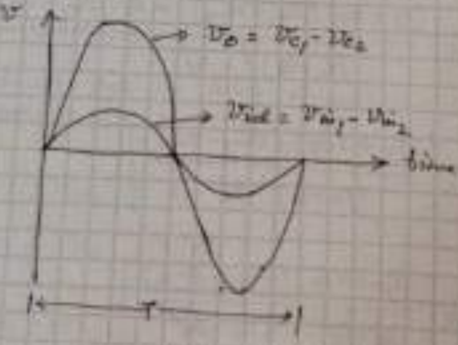
$$A_d = \frac{v_o}{v_{id}} = \frac{R_C}{r_e} \qquad (18)$$

Thus a differential amplifier amplifies the difference between two input signals.

- This equation is identical to that for voltage-gain for common-emitter amplifier, and
- is independent of R_E.

Input and output waveforms of dual-input, balanced-output difference amplifier is as shown in Fig. 5

Fig 5.



$$R_{i2} = \frac{R_{ac}\, v_{in2}}{\dfrac{(r_e+R_E)\, v_{in2} - R_E(0)}{(r_e+R_E)^2 - R_E^2}}$$

$$R_{i2} = \frac{R_{ac}\, v_{in2}\, r_e (r_e + 2R_E)}{(r_e+R_E)\, v_{in2}}$$

$$= \frac{R_{ac}\, r_e \cdot 2\cancel{R_E}}{\cancel{R_E}} \qquad \Big|\; R_E \gg r_e$$

$$R_{i2} = 2R_{ac}\, r_e \qquad \text{—(22)}$$

From eqs. (21) and (22), we conclude that

$$R_{i1} = R_{i2} \qquad (23)$$

Output resistance

By definition, the output resistance is the equivalent resistance measured at either collector w.r.t. ground.

From fig. 4, it is clear that

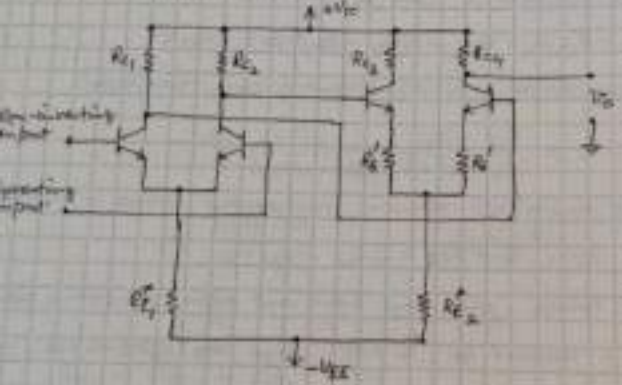
$$R_{o1} = R_{o2} = R_C \qquad (24)$$

Inverting & Non-inverting inputs

From fig 2 and eq. (15), it is clear that v_{in1}, if acting alone, decides the output polarity. If v_{in1} is +ve, v_0 is +ve and if v_{in1} is -ve, v_0 is -ve. Therefore v_{in1} is called non-inverting input and base B_1 is called the non-inverting input terminal.

Similarly if v_{in2} is acting alone, the polarity of the v_0 is opposite to that of v_{in2}. That is, if v_{in2} is +ve, v_0 is -ve and if v_{in2} is -ve, v_0 is +ve. Therefore v_{in2} is called inverting input and base B_2 is called inverting input terminal.

seen as follows. Two stages. First stage is a dual-input, balanced-output differential amplifier. Second stage is another differential amplifier driven by the output of the first stage. A single ended ~~or~~ unbalanced output is taken from the second stage. Transistor arrays CA3086 (or LM3146) offer electrical and thermal matching, compactness and ease of handling.



$$v_o = -R_C \frac{\quad}{r_e(r_e + 2R_E)}$$

$$= R_C \frac{R_E v_{in_1} - R_E v_{in_2}}{2 r_e R_E} \qquad \because R_E \gg r_e$$

$$= R_C \frac{R_E (v_{in_1} - v_{in_2})}{2 r_e R_E}$$

$$= \frac{R_C}{2r_e}(v_{in_1} - v_{in_2}) = \frac{R_C}{2r_e} v_{id}$$

$$A_d = \frac{v_o}{v_{id}} = \frac{R_C}{2r_e} \qquad (28)$$

Comparing this eq.(28) with eq.(18), we conclude that the voltage gain of dual-input unbalanced output difference amplifier is half of that of dual-input balanced output difference amplifier.

Since the input resistance doesn't depend how the output is taken, therefore from eqs. (19), (20) and (23),

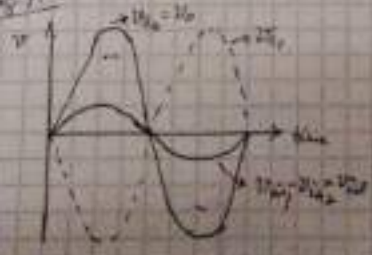
$$R_{i_1} = R_{i_2} = 2\beta_{ac} r_e \qquad (29)$$

The output resistance is the resistance measured at C_2,

$$R_o = R_C \qquad (30)$$

The output-input waveforms are shown in Fig. 7

Fig. 7:

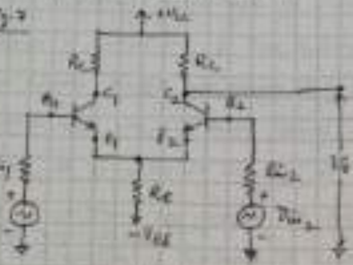


In this case dc voltage or error is also present at the output terminal. To reduce this undesired dc voltage to zero, this amplifier is followed by a level translator.

3. Dual-Input Unbalanced Output case

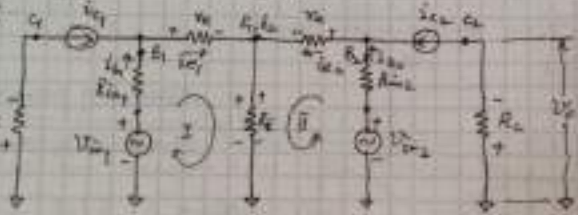
The differential amplifier of fig.2 is redrawn with output taken from the collector C_2 only

Fig.7



AC equivalent circuit of Fig.7 is redrawn with output taken from collector C_2 only

Fig.8



Since the above two circuits are same as that Fig. (a) and (b), except that the output is taken only from collector C_2, the Kirchhoff's voltage equations for loops I and II are same eqs. (5) & (6). Therefore, i_{e_1} and i_{e_2} equations are also same as eqs. (10) and (11).

The output voltage v_o is

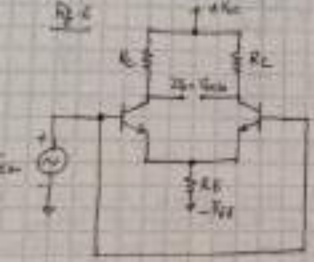
$$v_o = v_{c_2} = -R_C \, i_{c_2}$$

$$= -R_C \, i_{e_2} \qquad i_{c_2} = i_{e_2} \qquad (27)$$

Substituting for i_{e_2} from eq (11) in eq (27), we get

The ability to suppress undesired disturbances, pick-ups, noise that might be amplified along with the desired signal is an important characteristic of dual-input, balanced output differential amplifier. When matched pair of transistors is used in the difference amplifier, the undesired signals would appear as common to both the inputs, and therefore net output would be essentially zero. The effective rejection of the common-mode signal depends upon the degree of matching of transistors. When the same signal is applied to both the inputs of the differential amplifier, the differential amplifier is said to be working in common-mode configuration. The CMRR is defined as the ability to reject common-mode signal.

Fig 6



$$\text{CMRR} = \frac{\text{differential gain, } A_d}{\text{common-mode gain, } A_{cm}} \qquad (25)$$

where

$$A_{cm} = \frac{V_{ocm}}{V_{cm}} \qquad (26)$$

V_{cm} is common to both the terminals.

Ideally $A_{cm} = 0$, i.e. $V_{ocm} = 0$. Thus, ideally, CMRR $= \infty$.
The differential amplifiers with higher CMRR should be used, since it is better able to reject common-mode signals.

$v_{in_2} = 20\text{ mV}$ pp at 1 kHz

$$v_o = \frac{R_C}{r_e}\left(v_{in_1} - v_{in_2}\right)$$

$$= 86.96\,(50\text{ mV} - 20\text{ mV})$$

$$= 2.61\text{ V pp}$$

Maximum peak-to-peak variation

$$V_{R_C} = I_C R_C$$

$$= 0.988\text{ mA} \times 2.2\text{ k}\Omega$$

$$= 2.17\text{ V} < V_{CE} = 8.54\text{ V}$$

Maximum change in voltage at collector is

± 2.17 or 4.34 V pp

In Dual-input, balanced output case

Maximum change is $2 \times 4.34 = 8.68\text{ V pp}$

In Dual-input, unbalanced output case

Maximum change is 4.34 V pp

$R_{C_1} = R_{C_2} = 2.2\,k\Omega$,

$+V_{CC} = +10V$, $-V_{EE} = -10V$, $\beta_{ac} = \beta_{dc} = 100$, $V_{BE} = 0.715V$

For dual-input, balanced output differential amplifier.

Find (i) I_{CQ}, V_{CEQ}, (ii) A_d, and (iii) R_i & R_o

(i) $$I_{CQ} = I_E = \frac{V_{EE} - V_{BE}}{2R_E + R_{in}/\beta_{dc}} = \frac{10 - 0.715}{9400 + 100/100} = 0.988\ mA$$

$$V_{CEQ} = V_{CC} + V_{BE} - R_C I_{CQ}$$

$$= 10 + 0.715 - (2.2k)(0.988)\ mA$$

$$= 8.54\ V$$

(ii) AC emitter resistance

$$r_e = \frac{25\,mV}{I_E\,mA} = \frac{25\,mV}{0.988\,mA} = 25.3\,\Omega$$

When the dc current is changed the base ... ac resistance is closely approximated by $r_{ac} = V_T/I$, where V_T is thermal voltage $= kT/q$ and I is dc current in amperes. At $T = 300K$, V_T is $0.026V$, so at room temp. $r_D = \frac{0.026}{I}\,\Omega$. And $r_D = \frac{25\,mV}{I(mA)}$ — Boyer

Voltage gain $$A_d = \frac{V_o}{V_{id}} = \frac{R_C}{r_e}$$

$$= \frac{2200}{25.3} = 86.96$$

(iii) $$R_{i_1} = R_{i_2} = 2\beta_{ac} r_e = 2 \times 100 \times 25.3 = 5060$$

$$= 5.06\,k\Omega$$

$$R_{o_1} = R_{o_2} = 2.2\,k\Omega$$

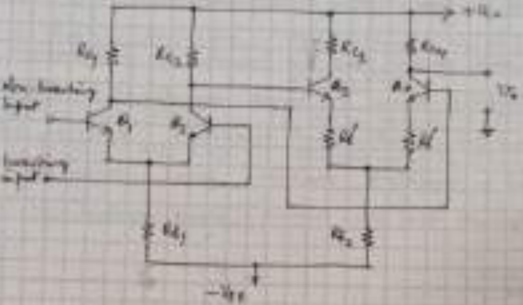
For dual-input unbalanced output case

$$A_d = \frac{R_C}{2r_e} = \frac{2200}{2 \times 25.3} = 43.48\,\Omega$$

For single-input balanced output gain is same as that in case of dual-input balanced output.

CASCADED DIFFERENTIAL AMPLIFIER

Two stages used. First stage dual-input balanced output stage and second is unbalanced output stage. Direct coupling



LEVEL TRANSLATOR

Because of direct coupling, dc level at the emitters rises from stage to stage. This increase in dc level tends to shift the operating point of the succeeding stages. Therefore, it limits the output voltage swing and may even distort the output signal.

A final stage is included which brings down the dc level at the second stage to zero volt dc. Such a stage is known as level translator which is shown in the figure. Proper selection of R_1 and R_2 produces 0 V at the junction of R_1 and R_2.