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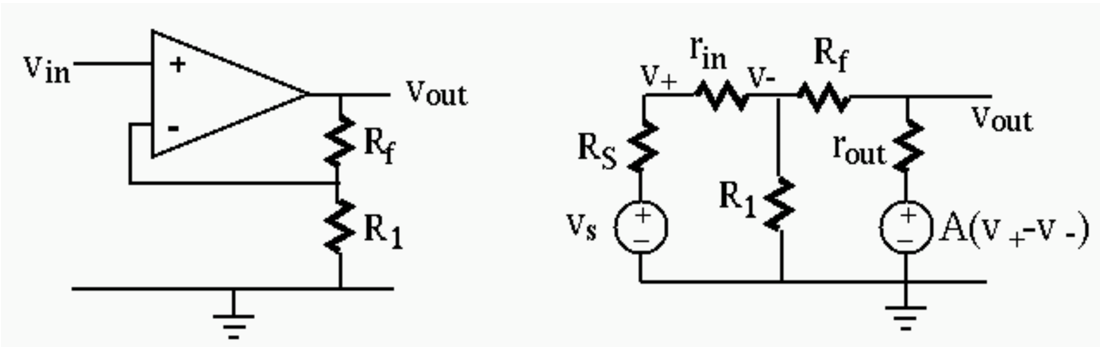

Find the three parameters of this non-inverting amplifier: open-circuit voltage gain A_{oc}, input resistance R_{in} and output resistance R_{out}.

- **Voltage gain:**
  - First, assume $r_{out}=0$. Connect an ideal voltage source v_s (with $R_s=0$) to the positive input so that $v^+=v_s$, and denote the voltage across r_{in} by $v_{in}=v^+-v^-$, i.e., $v^-=v_s-v_{in}$. Applying KCL to the node of v^-, we get

$$\frac{-v_{in}}{r_{in}}+\frac{v_s-v_{in}}{R_1}+\frac{v_s-v_{in}-Av_{in}}{R_f}=0$$

Solving this for v_{in}, we get:

$$v_{in}=v_s\frac{r_{in}(R_f+R_1)}{R_1R_f+r_{in}R_f+r_{in}R_1(A+1)}$$

The open-circuit voltage gain is:

$$A_{oc}=\frac{v_{out}}{v_s}\approx\frac{Av_{in}}{v_s}=\frac{Ar_{in}(R_f+R_1)}{R_1R_f+r_{in}R_f+r_{in}R_1(A+1)}$$

As $A >> 1$ and r_{in} is usually very large, we have

$$A_{oc} \approx \frac{R_1 + R_f}{R_1}$$

- Second, assume $r_{in} \to \infty$ but $r_{out} \neq 0$, we have

$$v_{out} = A(v^+ - v^-)\frac{R_f + R_1}{r_{out} + R_f + R_1} = A(v^+ - v^-)\frac{R_f + R_1}{r_{out} + R_f + R_1} = A(v_s - v_{out}\frac{R_1}{R_1 + R_f})\frac{R_f + R_1}{r_{out} + R_f + R_1}$$

  Solving for v_{out} we get

$$v_{out} = v_s \frac{A(R_f + R_1)}{r_{out} + R_f + (A+1)R_1}$$

  and

$$A_{oc} = \frac{v_{out}}{v_s} = \frac{A(R_1 + R_f)}{r_{out} + R_f + (A+1)R_1} \approx \frac{A(R_1 + R_f)}{AR_1} = \frac{R_1 + R_f}{R_1}$$

  The approximation is due to $A >> 1$ and $r_{out} << R_f + R_1$, i.e., $(R_f + R_1)(r_{out} + R_f + R_1) \approx 1$.

- If we could assume both $r_{in} \to \infty$ and $r_{out} = 0$, we can apply KCL to the v^- node to get

$$\frac{v^-}{R_1} + \frac{v^- - v_{out}}{R_f} = 0, \quad \text{or} \quad v_{out} = \frac{R_1 + R_f}{R_1} v^-$$

  But as $v^- \approx v^+ = v_s$, we get the same result for A_{oc}.

In particular, when $R_f = 0$, $A_{oc} = 1$ and the circut becomes the voltage follower.

- **Input resistance:** We let $v^+ = v_s$ (with $R_s = 0$) and assume the input current is i_{in}, then we have $v^+ - v^- = r_{in} i_{in}$, i.e., $v^- = v^+ - r_{in} i_{in} = v_s - r_{in} i_{in}$. Applying KCL to the node of v^- we get:

$$i_{in} - \frac{v_s - r_{in} i_{in}}{R_1} - \frac{v_s - r_{in} i_{in} - A r_{in} i_{in}}{R_f + r_{out}} = 0$$

Solving this we get:

$$R_{in} = \frac{v_s}{i_{in}} = \frac{[(A+1)R_1 + R_f + r_{out}] r_{in} + (R_f + r_{out}) R_1}{R_1 + R_f + r_{out}} = \frac{(A+1)R_1 + R_f + r_{out}}{R_1 + R_f + r_{out}} r_{in} + R_1 || (R_f + r_{out})$$

The same result can be obtained if we use loop current method. As $A >> 1$ and $r_{out} \approx 0$, we get

$$R_{in} \approx \frac{(A+1)R_1 + R_f}{R_1 + R_f} r_{in} + R_1 || R_f \approx A r_{in} + R_1 || R_f$$

Moreover, when $R_f = 0$, $R_{in} \approx A r_{in}$ as in the voltage follower case.

- **Output resistance:** To simplify the analysis we still assume $r_{in} = \infty$. First, as shown above, the open-circuit output voltage is

$$v_{oc} = \frac{A(R_f + R_1)}{r_{out} + R_f + (A+1)R_1} v_s$$

Second, we find the short-circuit current, i.e., output port is shorted with $v_{out} = 0$, we have $v^- = v_{out} R_1 / (R_1 + R_f) = 0$, and $v_{in} = v^+ - v^- = v_s$,

$$i_{sc} = \frac{A(v^+ - v^-)}{r_{out}} = \frac{Av_{in}}{r_{out}} = \frac{Av_s}{r_{out}}$$

Now the output resistance can be obtained as:

$$R_{out} = \frac{v_{oc}}{i_{sc}} = \frac{A(R_f + R_1)v_s}{r_{out} + R_f + (A+1)R_1} \frac{r_{out}}{Av_s} = \frac{(R_1 + R_f)r_{out}}{r_{out} + R_f + (A+1)R_1} \approx \frac{r_{out}}{A} \frac{R_1 + R_f}{R_1}$$

The approximation is due to $A >> 1$. In particular, when $R_f = 0$, $R_{out} = r_{out}/A$, as in the voltage follower case.

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