EXAMPLE 6.5

Objective: Determine the small-signal voltage gain, input resistance, and output resistance of the circuit shown in Figure 6.28.

Assume the transistor parameters are: $\beta = 100$, $V_{BE}(\text{on}) = 0.7$ V, and $V_A = 100$ V.

DC Solution: We first perform a dc analysis to find the Q-point values. We find that $I_{CQ} = 0.95$ mA and $V_{CEQ} = 6.31$ V, which shows that the transistor is biased in the forward-active mode.

AC Solution: The small-signal hybrid-π parameters for the equivalent circuit are

$$r_\pi = \frac{V_T \beta}{I_{CQ}} = \frac{(0.026)(100)}{(0.95)} = 2.74\ \text{k}\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.95}{0.026} = 36.5\ \text{mA/V}$$

and

$$r_o = \frac{V_A}{I_{CQ}} = \frac{100}{0.95} = 105\ \text{k}\Omega$$

Assuming that C_C acts as a short circuit, Figure 6.29 shows the small-signal equivalent circuit. The small-signal output voltage is

$$V_o = -(g_m V_\pi)(r_o \| R_C)$$

The dependent current $g_m V_\pi$ flows through the parallel combination of r_o and R_C, but in a direction that produces a negative output voltage. We can relate the control voltage V_π to the input voltage V_s by a voltage divider. We have

$$V_\pi = \left(\frac{R_1 \| R_2 \| r_\pi}{R_1 \| R_2 \| r_\pi + R_S}\right) \cdot V_s$$

We can then write the small-signal voltage gain as

$$A_v = \frac{V_o}{V_s} = -g_m \left(\frac{R_1 \| R_2 \| r_\pi}{R_1 \| R_2 \| r_\pi + R_S}\right)(r_o \| R_C)$$

or

$$A_v = -(36.5)\left(\frac{5.9 \| 2.74}{5.9 \| 2.74 + 0.5}\right)(105 \| 6) = -163$$

We can also calculate R_i, which is the resistance to the amplifier. From Figure 6.29, we see that

$$R_i = R_1 \| R_2 \| r_\pi = 5.9 \| 2.74 = 1.87\ \text{k}\Omega$$

The output resistance R_o is found by setting the independent source V_s equal to zero. In this case, there is no excitation to the input portion of the circuit so $V_\pi = 0$, which implies that $g_m V_\pi = 0$ (an open circuit). The output resistance looking back into the output terminals is then

$$R_o = r_o \| R_C = 105 \| 6 = 5.68\ \text{k}\Omega$$

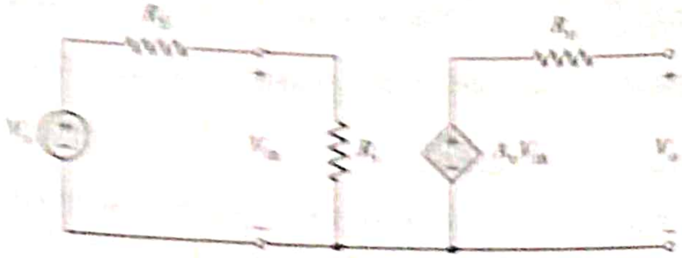


Figure 6.30 Two-port equivalent circuit for the amplifier in Example 6.5

Comment: In this circuit, the effective series resistance between the voltage source V_s and the base of the transistor is much less than that given in Example 6.1. For this reason, the magnitude of the voltage gain for the circuit given in Figure 6.28 is much larger than that found in Example 6.1.

Discussion: The two-port equivalent circuit along with the input signal source for the common-emitter amplifier analyzed in this example is shown in Figure 6.30. We can determine the effect of the source resistance R_S in conjunction with the amplifier input resistance R_i. Using a voltage-divider equation, we find the input voltage to the amplifier is

$$V_{in} = \left(\frac{R_i}{R_i + R_S}\right)V_s = \left(\frac{1.87}{1.87 + 0.5}\right)V_s = 0.789\, V_s$$

Because the input resistance to the amplifier is not very much greater than the signal source resistance, the actual input voltage to the amplifier is reduced to approximately 80 percent of the signal voltage. This is called a **loading effect.** The voltage V_{in} is a function of the amplifier connected to the source. In other amplifier designs, we will try to minimize the loading effect, or make $R_i \gg R_S$, which means that $V_{in} \cong V_s$.

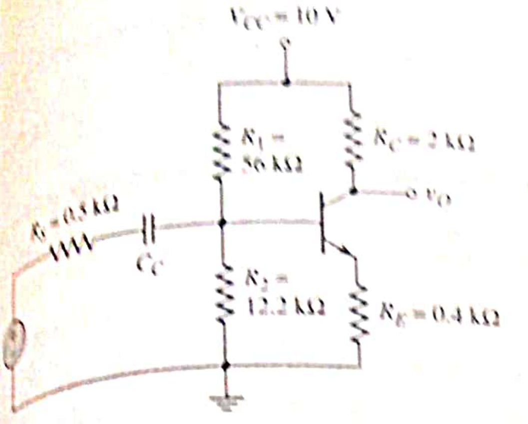
EXERCISE PROBLEM

Ex 6.5: The circuit parameters in Figure 6.28 are changed to $V_{CC} = 5$ V, $R_1 = 35.2\ \text{k}\Omega$, $R_2 = 5.83\ \text{k}\Omega$, $R_C = 10\ \text{k}\Omega$, and $R_S = 0$. Assume the transistor parameters are the same as listed in Example 6.5. Determine the quiescent collector current and collector-emitter voltage, and find the small-signal voltage gain. (Ans. $I_{CQ} = 0.21$ mA, $V_{CEQ} = 2.9$ V, $A_v = -79.1$)

6.4.2 Circuit with Emitter Resistor

For the circuit in Figure 6.28, the bias resistors R_1 and R_2 in conjunction with V_{CC} produce a base current of 9.5 μA and a collector current of 0.95 mA, when the B–E turn-on voltage is assumed to be 0.7 V. If the transistor in the circuit is replaced by a new one with slightly different parameters so that the B–E turn-on voltage is 0.6 V instead of 0.7 V, then the resulting base current is 26 μA, which is sufficient to drive the transistor into saturation. Therefore, the circuit shown in Figure 6.28 is not practical. An improved dc biasing design includes an emitter resistor.

In the last chapter, we found that the Q-point was stabilized against variations in β if an emitter resistor were included in the circuit, as shown in Figure 6.31. We will find a similar property for the ac signals, in that the voltage gain of a circuit with R_E will be less dependent on the transistor current gain β. Even though the emitter of this circuit is not at ground potential, this circuit is still referred to as a common-emitter circuit.



ure 6.31 An npn common-emitter circuit h an emitter resistor, a voltage-divider biasing uit, and a coupling capacitor

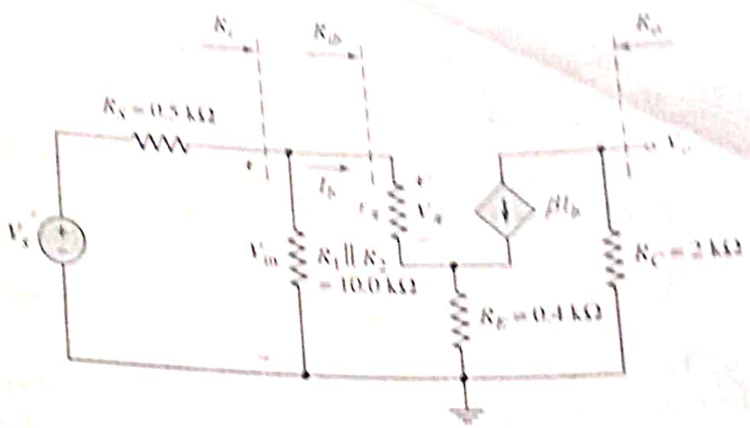


Figure 6.32 The small-signal equivalent circuit of the circuit shown in Figure 6.31

Assuming that C_C acts as a short circuit, Figure 6.32 shows the small-signal hybrid-π equivalent circuit. s we have mentioned previously, to develop the small-signal equivalent circuit, start with the three termi- ls of the transistor. Sketch the hybrid-π equivalent circuit between the three terminals and then sketch in e remaining circuit elements around these three terminals. In this case, we are using the equivalent circuit th the current gain parameter β, and we are assuming that the Early voltage is infinite so the transistor out- t resistance r_o can be neglected (an open circuit). The ac output voltage is

$$V_o = -(\beta I_b) R_C \tag{6.53}$$

To find the small-signal voltage gain, it is worthwhile finding the input resistance first. The resistance R_{ib} the input resistance looking into the base of the transistor. We can write the following loop equation

$$V_{in} = I_b r_\pi + (I_b + \beta I_b) R_E \tag{6.54}$$

e input resistance R_{ib} is then defined as, and found to be,

$$R_{ib} = \frac{V_{in}}{I_b} = r_\pi + (1 + \beta) R_E \tag{6.55}$$

the common-emitter configuration that includes an emitter resistance, the small-signal input resistance oking into the base of the transistor is r_π plus the emitter resistance multiplied by the factor $(1 + \beta)$. This fect is called the **resistance reflection rule.** We will use this result throughout the text without further de- ation.

The input resistance to the amplifier is now

$$R_i = R_1 \| R_2 \| R_{ib} \tag{6.56}$$

e can again relate V_{in} to V_s through a voltage-divider equation as

$$V_{in} = \left(\frac{R_i}{R_i + R_S} \right) \cdot V_s \tag{6.57}$$

mbining Equations (6.53), (6.55), and (6.57), we find the small-signal voltage gain is

$$A_v = \frac{V_o}{V_s} = \frac{-(\beta I_b) R_C}{V_s} = -\beta R_C \left(\frac{V_{in}}{R_{ib}} \right) \cdot \left(\frac{1}{V_s} \right) \tag{6.58(a)}$$

or

$$A_v = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E}\left(\frac{R_i}{R_i + R_S}\right) \tag{6.58(b)}$$

From this equation, we see that if $R_i \gg R_S$ and if $(1+\beta)R_E \gg r_\pi$, then the small-signal voltage gain is approximately

$$A_v \cong \frac{-\beta R_C}{(1+\beta)R_E} \cong \frac{-R_C}{R_E} \tag{6.59}$$

Equations (6.58(b)) and (6.59) show that the voltage gain is less dependent on the current gain β than in the previous example, which means that there is a smaller change in voltage gain when the transistor current gain changes. The circuit designer now has more control in the design of the voltage gain, but this advantage is at the expense of a smaller gain.

In Chapter 5, we discussed the variation in the Q-point with variations or tolerances in resistor values. Since the voltage gain is a function of resistor values, it is also a function of the tolerances in those values. This must be considered in a circuit design.

EXAMPLE 6.6

Objective: Determine the small-signal voltage gain and input resistance of a common-emitter circuit with an emitter resistor.

For the circuit in Figure 6.31, the transistor parameters are: $\beta = 100$, $V_{BE}(\text{on}) = 0.7$ V, and $V_A = \infty$.

DC Solution: From a dc analysis of the circuit, we can determine that $I_{CQ} = 2.16$ mA and $V_{CEQ} = 4.81$ V, which shows that the transistor is biased in the forward-active mode.

AC Solution: The small-signal hybrid-π parameters are determined to be

$$r_\pi = \frac{V_T\beta}{I_{CQ}} = \frac{(0.026)(100)}{(2.16)} = 1.20\,\text{k}\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{2.16}{0.026} = 83.1\text{ mA/V}$$

and

$$r_o = \frac{V_A}{I_{CQ}} = \infty$$

The input resistance to the base can be determined as

$$R_{ib} = r_\pi + (1+\beta)R_E = 1.20 + (101)(0.4) = 41.6\,\text{k}\Omega$$

and the input resistance to the amplifier is now found to be

$$R_i = R_1 \| R_2 \| R_{ib} = 10 \| 41.6 = 8.06\,\text{k}\Omega$$

Using the exact expression for the voltage gain, we find

$$A_v = \frac{-(100)(2)}{1.20 + (101)(0.4)}\left(\frac{8.06}{8.06 + 0.5}\right) = -4.53$$

If we use the approximation given by Equation (6.59), we obtain

$$A_v = \frac{-R_C}{R_E} = \frac{-2}{0.4} = -5.0$$

Comment: The magnitude of the small-signal voltage gain is substantially reduced when an emitter resistor is included. Also, Equation (6.59) gives a good first approximation for the gain, which means that it can be used in the initial design of a common-emitter circuit with an emitter resistor.

Discussion: The amplifier gain is nearly independent of changes in the current gain parameter β. This fact is shown in the following calculations:

β	A_v
50	−4.41
100	−4.53
150	−4.57

In addition to gaining an advantage in stability by including an emitter resistance, we also gain an advantage in the loading effect. We see that, for $\beta = 100$, the input voltage to the amplifier is

$$V_{in} = \left(\frac{R_i}{R_i + R_S}\right) \cdot V_s = (0.942)V_s$$

We see that V_{in} is much closer in value to V_s than in the previous example. There is less loading effect because the input resistance to the base of the transistor is higher when an emitter resistor is included.

The same equivalent circuit as shown in Figure 6.30 applies to this example also. The difference in the two examples is the values of input resistance and gain parameter.

EXERCISE PROBLEM

Ex 6.6: For the circuit in Figure 6.33, let $R_E = 0.6\,\text{k}\Omega$, $R_C = 5.6\,\text{k}\Omega$, $\beta = 120$, $V_{BE}(\text{on}) = 0.7$ V, $R_1 = 250\,\text{k}\Omega$, and $R_2 = 75\,\text{k}\Omega$. (a) For $V_A = \infty$, determine the small-signal voltage gain A_v. (b) Determine the input resistance looking into the base of the transistor. (Ans. (a) $A_v = -8.27$, (b) $R_{ib} = 80.1\,\text{k}\Omega$)

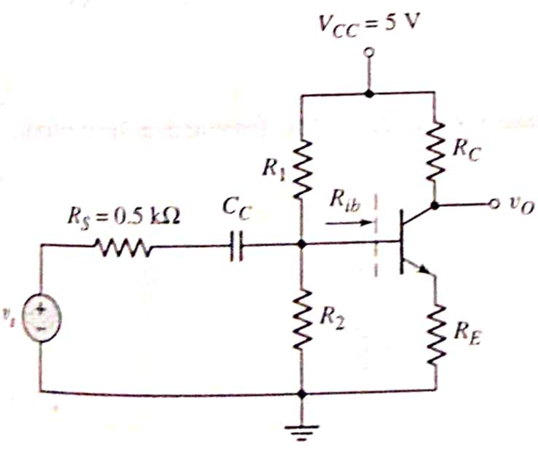


Figure 6.33 Figure for Exercise Ex6.6

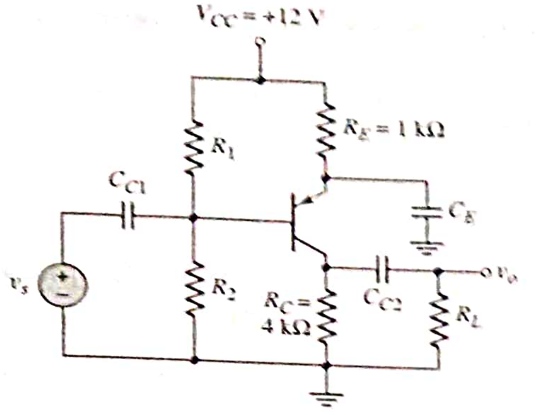


Figure 6.51 Figure for Exercise Ex6.12

Test Your Understanding

TYU 6.8 For the circuit in Figure 6.33, use the parameters given in Exercise Ex6.6. If the total instantaneous current must always be greater than 0.1 mA and the total instantaneous C–E voltage must be in the range $0.5 \le v_{CE} \le 5$ V, determine the maximum symmetrical swing in the output voltage. (Ans. 3.82 V peak-to-peak)

TYU 6.9 For the circuit in Figure 6.40, assume the transistor parameters are: $\beta = 100$, $V_{BE}(\text{on}) = 0.7$ V, and $V_A = \infty$. Determine a new value of R_E that will achieve a maximum symmetrical swing in the output voltage, for $i_C > 0$ and $0.7 \le v_{CE} \le 19.5$ V. What is the maximum symmetrical swing that can be achieved? (Ans. $R_E = 16.4$ kΩ, 10.6 V peak-to-peak)

6.6 COMMON-COLLECTOR (EMITTER-FOLLOWER) AMPLIFIER

Objective: • Analyze the emitter-follower amplifier and become familiar with the general characteristics of this circuit.

The second type of transistor amplifier to be considered is the **common-collector circuit.** An example of this circuit configuration is shown in Figure 6.52. As seen in the figure, the output signal is taken off of the emitter with respect to ground and the collector is connected directly to V_{CC}. Since V_{CC} is at signal ground in the ac equivalent circuit, we have the name common-collector. The more common name for this circuit is **emitter follower.** The reason for this name will become apparent as we proceed through the analysis.

6.6.1 Small-Signal Voltage Gain

The dc analysis of the circuit is exactly the same as we have already seen, so we will concentrate on the small-signal analysis. The hybrid-π model of the bipolar transistor can also be used in the small-signal analysis of this circuit. Assuming the coupling capacitor C_C acts as a short circuit, Figure 6.53 shows the small-signal

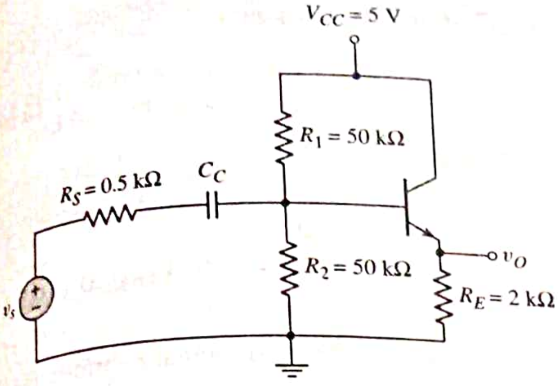


Figure 6.52 Emitter-follower circuit. Output signal is at the emitter terminal with respect to ground.

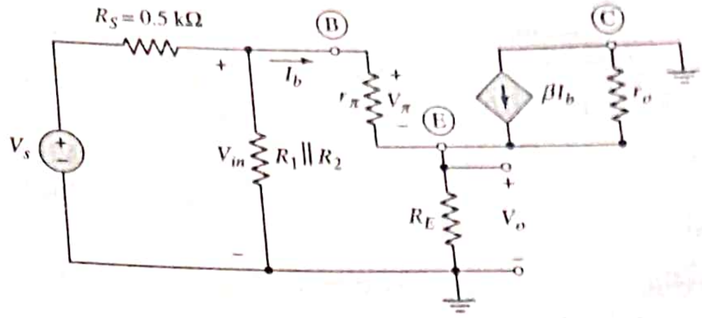


Figure 6.53 Small-signal equivalent circuit of the emitter-follower

equivalent circuit of the circuit shown in Figure 6.52. The collector terminal is at signal ground and the transistor output resistance r_o is in parallel with the dependent current source.

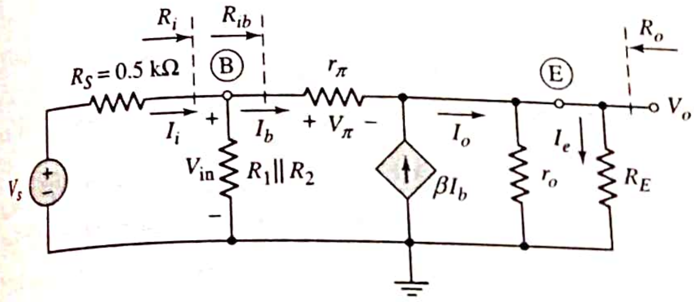


Figure 6.54 Small-signal equivalent circuit of the emitter-follower with all signal grounds connected together

Figure 6.54 shows the equivalent circuit rearranged so that all signal grounds are at the same point. We see that

$$I_o = (1 + \beta)I_b \tag{6.64}$$

so the output voltage can be written as

$$V_o = I_b(1 + \beta)(r_o \| R_E) \tag{6.65}$$

Writing a KVL equation around the base-emitter loop, we obtain

$$V_{in} = I_b[r_\pi + (1 + \beta)(r_o \| R_E)] \tag{6.66(a)}$$

or

$$R_{ib} = \frac{V_{in}}{I_b} = r_\pi + (1 + \beta)(r_o \| R_E) \tag{6.66(b)}$$

We can also write

$$V_{in} = \left(\frac{R_i}{R_i + R_S}\right) \cdot V_s \tag{6.67}$$

where $R_i = R_1 \| R_2 \| R_{ib}$.

Combining Equations (6.65), (6.66(b)), and (6.67), the small-signal voltage gain is

$$A_v = \frac{V_o}{V_s} = \frac{(1+\beta)(r_o \| R_E)}{r_\pi + (1+\beta)(r_o \| R_E)} \cdot \left(\frac{R_i}{R_i + R_S}\right) \tag{6.68}$$

EXAMPLE 6.13

Objective: Calculate the small-signal voltage gain of an emitter-follower circuit.

For the circuit shown in Figure 6.52, assume the transistor parameters are: $\beta = 100$, $V_{BE}(\text{on}) = 0.7$ V, and $V_A = 80$ V.

Solution: The dc analysis shows that $I_{CQ} = 0.793$ mA and $V_{CEQ} = 3.4$ V. The small-signal hybrid-π parameters are determined to be

$$r_\pi = \frac{V_T \beta}{I_{CQ}} = \frac{(0.026)(100)}{0.793} = 3.28\ \text{k}\Omega$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{0.793}{0.026} = 30.5\ \text{mA/V}$$

and

$$r_o = \frac{V_A}{I_{CQ}} = \frac{80}{0.793} \cong 100\ \text{k}\Omega$$

We may note that

$$R_{ib} = 3.28 + (101)(100 \| 2) = 201\ \text{k}\Omega$$

and

$$R_i = 50 \| 50 \| 201 = 22.2\ \text{k}\Omega$$

The small-signal voltage gain is then

$$A_v = \frac{(101)(100 \| 2)}{3.28 + (101)(100 \| 2)} \cdot \left(\frac{22.2}{22.2 + 0.5}\right)$$

or

$$A_v = +0.962$$

Comment: The magnitude of the voltage gain is slightly less than 1. An examination of Equation (6.68) shows that this is always true. Also, the voltage gain is positive, which means that the output signal voltage at the emitter is in phase with the input signal voltage. The reason for the terminology emitter-follower is now clear. The output voltage at the emitter is essentially equal to the input voltage.

At first glance, a transistor amplifier with a voltage gain essentially of 1 may not seem to be of much value. However, the input and output resistance characteristics make this circuit extremely useful in many applications, as we will show in the next section.

EXERCISE PROBLEM

Ex 6.13: For the circuit shown in Figure 6.52, let $V_{CC} = 5$ V, $\beta = 120$, $V_A = 100$ V, $R_E = 1$ kΩ, $V_{BE}(\text{on}) = 0.7$ V, $R_1 = 25$ kΩ, and $R_2 = 50$ kΩ. (a) Determine the small-signal voltage gain $A_v = V_o/V_s$. (b) Find the input resistance looking into the base of the transistor. (Ans. (a) $A_v = 0.956$ (b) $R_{ib} = 120$ kΩ)

COMPUTER ANALYSIS EXERCISE

PS6.4: Perform a PSpice simulation on the circuit in Figure 6.52. (a) Determine the small-signal voltage gain and (b) find the effective resistance seen by the signal source v_s.

6.6.2 Input and Output Impedance

Input Resistance

The input impedance, or small-signal input resistance for low-frequency signals, of the emitter-follower is determined in the same manner as for the common-emitter circuit. For the circuit in Figure 6.52, the input resistance looking into the base is denoted R_{ib} and is indicated in the small-signal equivalent circuit shown in Figure 6.54.

The input resistance R_{ib} was given by Equation (6.66(b)) as

$$R_{ib} = r_\pi + (1+\beta)(r_o \| R_E)$$

Since the emitter current is $(1+\beta)$ times the base current, the effective impedance in the emitter is multiplied by $(1+\beta)$. We saw this same effect when an emitter resistor was included in a common-emitter circuit. This multiplication by $(1+\beta)$ is again called the **resistance reflection rule.** The input resistance at the base is r_π plus the effective resistance in the emitter multiplied by the $(1+\beta)$ factor. This resistance reflection rule will be used extensively throughout the remainder of the text.

Output Resistance

Initially, to find the output resistance of the emitter-follower circuit shown in Figure 6.52, we will assume th the input signal source is ideal and that $R_S = 0$. The circuit shown in Figure 6.55 can be used to determi the output resistance looking back into the output terminals. The circuit is derived from the small-sig equivalent circuit shown in Figure 6.54 by setting the independent voltage source V_s equal to zero, wh means that V_s acts as a short circuit. A test voltage V_x is applied to the output terminal and the resulting current is I_x. The output resistance, R_o, is given by

$$R_o = \frac{V_x}{I_x} \quad (6$$

In this case, the control voltage V_π is not zero, but is a function of the applied test voltage. From F 6.55, we see that $V_\pi = -V_x$. Summing currents at the output node, we have

$$I_x + g_m V_\pi = \frac{V_x}{R_E} + \frac{V_x}{r_o} + \frac{V_x}{r_\pi}$$

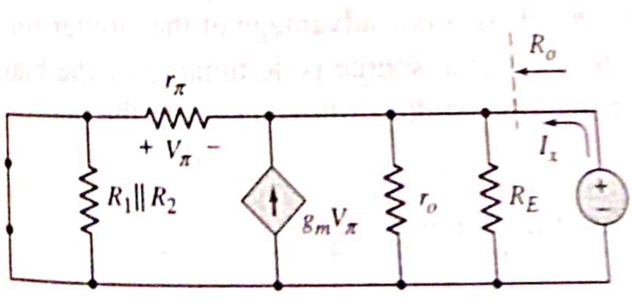


Figure 6.55 Small-signal equivalent circuit of the emitter-follower used to determine the output resistance. resistance R_S is assumed to be zero (an ideal signal source).

Since $V_\pi = -V_x$, Equation (6.70) can be written as

$$\frac{I_x}{V_x} = \frac{1}{R_o} = g_m + \frac{1}{R_E} + \frac{1}{r_o} + \frac{1}{r_\pi} \tag{6.71}$$

or the output resistance is given by

$$R_o = \frac{1}{g_m} \| R_E \| r_o \| r_\pi \tag{6.72}$$

The output resistance may also be written in a slightly different form. Equation (6.71) can be written in the form

$$\frac{1}{R_o} = \left(g_m + \frac{1}{r_\pi}\right) + \frac{1}{R_E} + \frac{1}{r_o} = \left(\frac{1+\beta}{r_\pi}\right) + \frac{1}{R_E} + \frac{1}{r_o} \tag{6.73}$$

or the output resistance can be written in the form

$$R_o = \frac{r_\pi}{1+\beta} \| R_E \| r_o \tag{6.74}$$

Equation (6.74) says that the output resistance looking back into the output terminals is the effective resistance in the emitter, $R_E \| r_o$, in parallel with the resistance looking back into the emitter. In turn, the resistance looking into the emitter is the total resistance in the base circuit divided by $(1 + \beta)$. This is an important result and is called the **inverse resistance reflection rule** and is the inverse of the reflection rule looking to the base.

EXAMPLE 6.14

Objective: Calculate the input and output resistance of the emitter-follower circuit shown in Figure 6.52. Assume $R_S = 0$.

The small-signal parameters, as determined in Example 6.13, are $r_\pi = 3.28\,\text{k}\Omega$, $\beta = 100$, and $r_o = 100\,\text{k}\Omega$.

Solution (Input Resistance): The input resistance looking into the base was determined in Example 6.13 as

$$R_{ib} = r_\pi + (1+\beta)(r_o \| R_E) = 3.28 + (101)(100\|2) = 201\ \text{k}\Omega$$

and the input resistance seen by the signal source R_i is

$$R_i = R_1 \| R_2 \| R_{ib} = 50\|50\|201 = 22.2\ \text{k}\Omega$$

Comment: The input resistance of the emitter-follower looking into the base is substantially larger than that of the simple common-emitter circuit because of the $(1 + \beta)$ factor. This is one advantage of the emitter-follower circuit. However, in this case, the input resistance seen by the signal source is dominated by the bias resistors R_1 and R_2. To take advantage of the large input resistance of the emitter-follower circuit, the bias resistors must be designed to be much larger.

Solution (Output Resistance): The output resistance is found from Equation (6.74) as

$$R_o = \left(\frac{r_\pi}{1+\beta}\right) \| R_E \| r_o = \left(\frac{3.28}{101}\right) \| 2 \| 100$$

$R_o = 0.0325 \| 2 \| 100 = 0.0320\ k\Omega \to 32.0\ \Omega$

The output resistance is dominated by the first term that has $(1+\beta)$ in the denominator.

Comment: The emitter-follower circuit is sometimes referred to as an **impedance transformer**, since the input impedance is large and the output impedance is small. The very low output resistance makes the emitter-follower act almost like an ideal voltage source, so the output is not loaded down when used to drive another load. Because of this, the emitter-follower is often used as the output stage of a multistage amplifier.

EXERCISE PROBLEM

Ex 6.14: Consider the circuit and transistor parameters described in Exercise Ex6.13 for the circuit shown in Figure 6.52. For the case of $R_S = 0$, determine the output resistance looking into the output terminals. (Ans. 11.1 Ω)

We can determine the output resistance of the emitter-follower circuit taking into account a nonzero source resistance. The circuit in Figure 6.56 is derived from the small-signal equivalent circuit shown in Figure 6.54 and can be used to find R_o. The independent source V_s is set equal to zero and a test voltage V_x is applied to the output terminals. Again, the control voltage V_π is not zero, but is a function of the test voltage. Summing currents at the output node, we have

$$I_x + g_m V_\pi = \frac{V_x}{R_E} + \frac{V_x}{r_o} + \frac{V_x}{r_\pi + R_1 \| R_2 \| R_S} \tag{6.75}$$

The control voltage can be written in terms of the test voltage by a voltage divider equation as

$$V_\pi = -\left(\frac{r_\pi}{r_\pi + R_1 \| R_2 \| R_S}\right) \cdot V_x \tag{6.76}$$

Equation (6.75) can then be written as

$$I_x = \left(\frac{g_m r_\pi}{r_\pi + R_1 \| R_2 \| R_S}\right) \cdot V_x + \frac{V_x}{R_E} + \frac{V_x}{r_o} + \frac{V_x}{r_\pi + R_1 \| R_2 \| R_S} \tag{6.77}$$

Noting that $g_m r_\pi = \beta$, we find

$$\frac{I_x}{V_x} = \frac{1}{R_o} = \frac{1+\beta}{r_\pi + R_1 \| R_2 \| R_S} + \frac{1}{R_E} + \frac{1}{r_o} \tag{6.78}$$

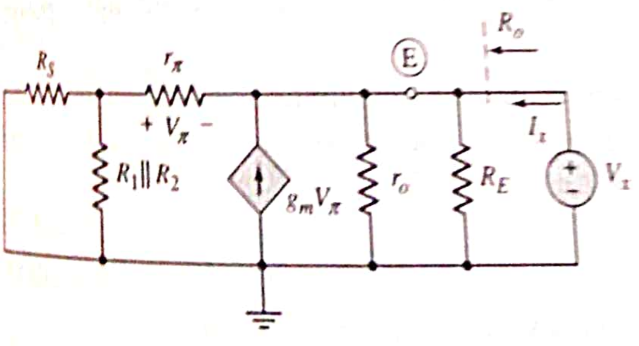


Figure 6.56 Small-signal equivalent circuit of the emitter-follower used to determine the output resistance including the effect of the source resistance R_S

or

$$R_o = \left(\frac{r_\pi + R_1 \| R_2 \| R_S}{1+\beta}\right) \| R_E \| r_o \tag{6.79}$$

In this case, the source resistance and bias resistances contribute to the output resistance.

6.6.3 Small-Signal Current Gain

We can determine the small-signal current gain of an emitter-follower by using the input resistance and the concept of current dividers. For the small-signal emitter-follower equivalent circuit shown in Figure 6.54, the small signal current gain is defined as

$$A_i = \frac{I_e}{I_i} \tag{6.80}$$

where I_e and I_i are the output and input current phasors.

Using a current divider equation, we can write the base current in terms of the input current, as follows:

$$I_b = \left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{ib}}\right) I_i \tag{6.81}$$

Since $g_m V_\pi = \beta I_b$, then,

$$I_o = (1+\beta) I_b = (1+\beta)\left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{ib}}\right) I_i \tag{6.82}$$

Writing the load current in terms of I_o produces

$$I_e = \left(\frac{r_o}{r_o + R_E}\right) I_o \tag{6.83}$$

Combining Equations (6.82) and (6.83), we obtain the small-signal current gain, as follows:

$$A_i = \frac{I_e}{I_i} = (1+\beta)\left(\frac{R_1 \| R_2}{R_1 \| R_2 + R_{ib}}\right)\left(\frac{r_o}{r_o + R_E}\right) \tag{6.84}$$

If we assume that $R_1 \| R_2 \gg R_{ib}$ and $r_o \gg R_E$, then

$$A_i \cong (1+\beta) \tag{6.85}$$

which is the current gain of the transistor.

Although the small-signal voltage gain of the emitter follower is slightly less than 1, the small-signal current gain is normally greater than 1. Therefore, the emitter- follower circuit produces a small-signal power gain.

Although we did not explicitly calculate a current gain in the common-emitter circuit previously, the analysis is the same as that for the emitter-follower and in general the current gain is also greater than unity.

DESIGN EXAMPLE 6.15

Objective: To design an emitter-follower amplifier to meet an output resistance specification.