4. BIPOLAR JUNCTION TRANSISTOR (BJT) NOISE MEASUREMENTS

4.1 Object

The objective of this experiment is to measure the mean-square equivalent input noise, $\overline{v_{ni}^2}$, and base spreading resistance, r_x, of some NPN Bipolar Junction Transistors (BJTs).

4.2 Theory

4.2.1 Equivalent Input Noise

It can be shown that v_{ni}^2, the mean-square equivalent input noise measured over a narrow frequency band Δf centered at frequency f, of a resistively loaded BJT amplifier with zero small-signal impedance from both base to ground and emitter to ground is given by

$$v_{ni}^2 = 4kTr_x\Delta f + \left(2q\frac{I_C}{\beta}\Delta f + \frac{K_f I_C \Delta f}{\beta f}\right) r_x^2 + 2qI_C\Delta f \left(\frac{r_x}{\beta} + \frac{V_T}{I_C}\right)^2 \tag{4.1}$$

where, r_x is the base spreading resistance (ohms), $\beta = \Delta I_C/\Delta I_B$ is the small-signal current gain (dimensionless), I_C is the dc collector current (amps), I_B is the dc base current (amps), $k = 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ is Boltzmann's constant, T is the Kelvin temperature, $q = 1.60 \times 10^{-19}\,\mathrm{C}$ is the electronic charge, $V_T = kT/q$ is the thermal voltage (volts), K_f is the flicker noise-coefficient, and f is the frequency at which the mean-square noise voltage v_{ni}^2 is measured. If the noise measurement is made at frequencies where the flicker noise may be ignored, the expression for the mean-square equivalent input noise simplifies to

$$v_{ni}^2 = 4kTr_x\Delta f + 2q\frac{I_C}{\beta}\Delta f r_x^2 + 2qI_C\Delta f \left(\frac{r_x}{\beta} + \frac{V_T}{I_C}\right)^2 \tag{4.2}$$

If β is sufficiently large, this can be approximated by

$$v_{ni}^2 = 4kTr_x\Delta f + 2qI_C\Delta f \left(\frac{V_T}{I_C}\right)^2 \tag{4.3}$$

This equation can be solved for r_x to obtain

$$r_x = \frac{v_{ni}^2}{4kT\Delta f} - \frac{2qI_C}{4kT}\left(\frac{V_T}{I_C}\right)^2$$

$$= \frac{v_{ni}^2}{4kT\Delta f} - \frac{V_T}{2I_C}$$

$$= \frac{v_{ni}^2}{4kT\Delta f} - \frac{1}{2g_m} \quad (4.4)$$

4.2.2 Base Spreading Resistance

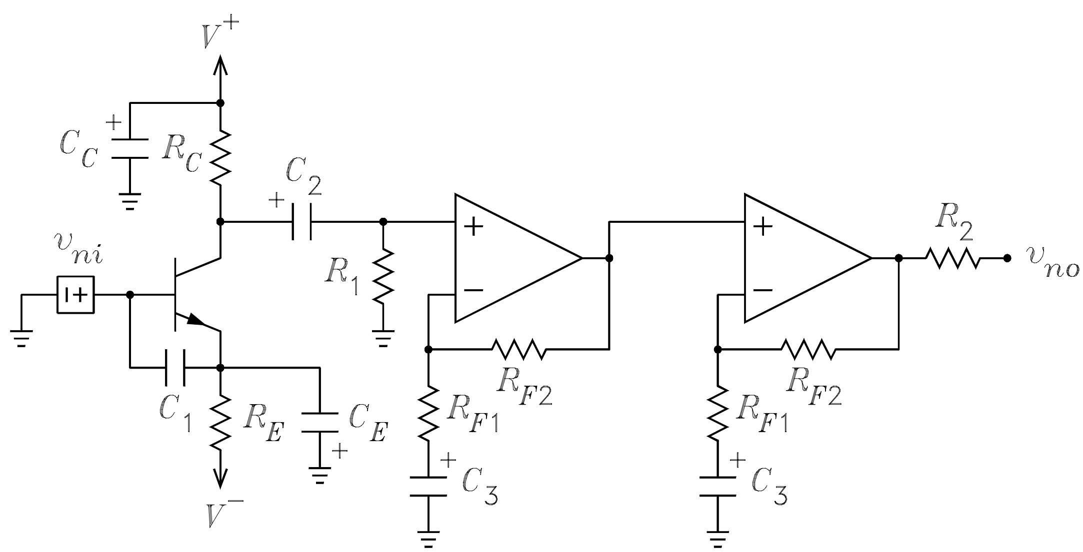

Figure 4-1 Circuit for measuring v_{no}.

The base spreading resistance r_x is one of the more prickly parameters to determine. To calculate it from Eq. (4.4), $\overline{v_{ni}^2}$ must be measured. This is the mean-square noise voltage in series with the base of the BJT. A possible circuit for measuring it is shown in Fig. 4-1. If it is assumed that the op amps are ideal and the thermal noise in the feedback resistors can be ignored, the mean-square noise output voltage of the op amp can be written

$$v_{no}^2 = A_v^2 \left(g_m R_L\right)^2 v_{ni}^2 \quad (4.5)$$

$g_m R_L$ is the voltage gain from base to collector of the BJT, $R_L = r_0 \| R_C \| R_1$ is the resistance seen looking out of the BJT collector, r_0 is the BJT collector-emitter resistance, and A_v is the gain of the two-stage op-amp amplifier given by

$$A_v = \left(1 + \frac{R_{F2}}{R_{F1}}\right)^2 \quad (4.6)$$

If v_{no} is measured, Eq. (4.5) can be solved for v_{ni}^2 with

$$v_{ni}^2 = \frac{v_{no}^2}{A_v^2 \left(g_m R_L\right)^2} \quad (4.7)$$

4.3 Laboratory Procedure

4.3.1 Base Spreading Resistance

Assemble the circuit shown in Fig. 4-1 on a solderless breadboard using a 2N4401 NPN BJT. Use a TL071 as the op amp. Use $V^+ = +15\ V$ and $V^- = -15\ V$ (these may be reduced to 9 V if the experimenters choose to assemble the circuits in the shielded boxes). Use $C_1 = 100\,\text{pF}$, $C_2 = 10\,\mu\text{F}$, $C_3 = 330\,\mu\text{F}$, $C_C = C_E = 330\,\mu\text{F}$, $R_{F1} = 3\,\text{k}\Omega$, and $R_2 = 100\,\Omega$. Calculate the value of R_{F1} which would give $A_v = 100$. In the circuit, use the next smaller 1% value for R_{F2}. Power supply decoupling networks on the supply rails consisting of $100\,\Omega$ resistors and $100\,\mu\text{F}$ capacitors should be used. The object of C_1 is to suppress undesired rf pickup. It is small enough to be considered an open circuit at the measurement frequencies. The purpose of R_2 is to suppress oscillations in the op amps. After the circuit is assembled, the gain and bandwidth of the op-amp stages should be measured.

Bias the circuit so that the collector current is $I_C = 0.1\,\text{mA}$. The collector current is given by

$$I_C = \frac{-V^- - V_{BE}}{R_E} \tag{4.8}$$

where V_{BE} may be assumed to be 0.65 V. Eq. (4.8) may be used to calculate R_E. (It should be borne in mind that V^- is a negative voltage so $-V^-$ is a positive voltage.)

Select $R_C = R_E/2$. This places the collector to emitter bias voltage at approximately one-half the positive power supply voltage. The choice of this bias is somewhat arbitrary.

Place the BJT in the circuit and connect R_C as shown in the circuit diagram. Measure the dc collector current by using the DMM (Digital Multimeter) to measure the dc voltage across R_C and then use Ohm's law to determine the current. Measure the dc voltage at each terminal of the transistor.

Use the Dynamic Signal Analyzer to measure the rms noise output noise voltage v_{no} at a frequency that is high enough so that flicker noise may be neglected and at a low enough frequency so that the frequency response of the op amp and transistor in combination has not begun rolling. That is, make the measurement at a frequency where the noise output voltage is white (or flat) as a function of frequency. Call this value v_{no1}.

With the BJT not in the circuit, connect R_C from the left terminal to C_2 to ground. Measure the rms noise output voltage v_{no}. Call this v_{no2}.

Repeat the measurement for bias currents of $I_C = 30\,\mu\text{A}$ and $I_C = 50\,\mu\text{A}$ for the 2N4401 NPN BJT.

Repeat the measurement for the 2N3904 NPN BJT.

4.3.2 Transistor Parameters

Use a transistor curve tracer to measure the small-signal current gain β and the collector-emitter resistance r_0 of the 2N4401 and 2N3904 BJTs for collector currents of $I_C = 0.1\,\text{mA}$, $I_C = 30\,\mu\text{A}$, and $I_C = 50\,\mu\text{A}$ that were used above. In the small-signal model, r_0 is given by

$$r_0 = \frac{V_A + V_{CE}}{I_C}$$

where V_A is the Early voltage, V_{CE} is the collector-emitter bias voltage, and I_C is the collector bias current.

4.3.3 Resistance Measurement

Use the DMM (Digital Multimeter) or the LCR meter to measure the value of each resistor that was used.

4.3.4 Measurement Bandwidth

Record the measurement bandwidth that was used by the Dynamic Signal Analyzer. Press Disp Format and then Measurement State.

4.4 Laboratory Report

4.4.1 Bias

Tabulate the quiescent bias voltages and currents for each transistor for each of the three values of collector current for which data was taken.

4.4.2 Base Spreading Resistance

From the data obtained, use Eqs. (4.4) and (4.7) to calculate r_x for each transistor at the three collector bias currents that were used. For v_{no}^2 in Eq. (4.7), use

$$v_{no}^2 = v_{no1}^2 - v_{no2}^2$$

Calculate the average value of r_x for each transistor type at the three collector bias currents. Also tabulate the values of r_x for each of the transistors.

4.4.3 Equivalent Input Noise

Use the values of that r_x were obtained to calculate v_{ni}^2 using Eq. 4.2. Compare these results to those obtained from Eq. 4.7 and the measured values of v_{no}^2. Explain any significant differences between these results.