Noise in Transistors

A short explanation of noise performance of bipolar and field effect transistors at frequencies of a few kHz to a few MHz

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At low frequencies, below a few kHz, the chief source of transistor noise is flicker, or $1/f$ noise, and no simple, generally valid, theory exists. Above a few hundred MHz the noise behaviour, like the signal behaviour, becomes quite complicated and cannot profitably be discussed in simple terms. In the intervening region, i.e. about 5 decades in frequency, noise in both bipolar and field effect transistors is remarkably simple.

In bipolar transistors the current injected into the base by the emitter consists of electrons which had enough thermal energy to surmount the potential barrier at the depletion layer. It is therefore completely random and displays full shot noise. In a bandwidth df the mean square fluctuations in the emitter current I_e are given by

$$di_e^2 = 2eI_e\,df \qquad (1)$$

where e is the electronic charge. In the base, some electrons recombine and constitute the base current, the remainder reach the collector. This random division, of a random current, leads to two uncorrelated sets of fluctuations in the base current I_b and the collector current I_c. Their magnitudes are

$$di_b^2 = 2eI_b\,df \qquad (2)$$

and

$$di_c^2 = 2eI_c\,df \qquad (3)$$

and, because they are uncorrelated, $d(i_b i_c) = 0$.

Because any equivalent circuit for a transistor must lead to the relation $i_e = i_b + i_c$, we do not need to consider i_e separately. Thus the noise properties are completely specified by i_b and i_c. A complete noise equivalent circuit for the transistor is shown in Fig. 1. www.keith-snook.info

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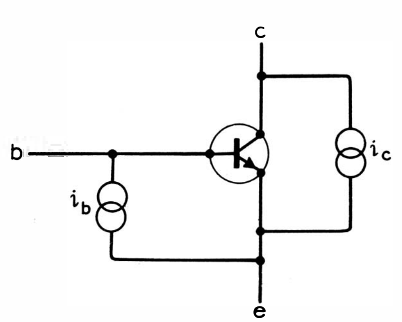

Fig. 1. Noise equivalent circuit for a bipolar transistor, valid up to 200 MHz.

The strengths of the two current generators are given by (2) and (3) and they are uncorrelated. This circuit is valid up to frequencies approaching $f_T/\beta^{\frac{1}{2}}$. If $f_T = 2$ GHz and $\beta = 100$ this can be as high as 200 MHz.

If the transistor is used in the common emitter connection it will have a mutual conductance

$$g_m = \frac{eI_c}{kT} \qquad (4)$$

and we can transfer the current generator i_c to the input as a voltage generator $v = i_c/g_m$. Its strength is therefore

$$dv^2 = \frac{2kT}{g_m}\,df \qquad (5)$$

In Fig. 2 is shown an equivalent circuit for a common-emitter stage connected to a signal source of internal impedance R_s. The

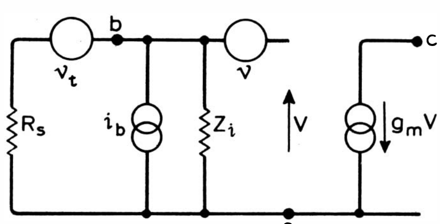

Fig. 2. An equivalent circuit for a common-emitter stage.

circuit includes the two noise generators i_b and v and the thermal noise generator v_t associated with the source at a temperature T_s

$$dv_t^2 = 4kT_sR_s\,df \qquad (6)$$

If we assume that the input impedance Z_i of the transistor is large compared with the source impedance R_s the total noise input is given by

$$dV^2 = 4kT_sR_s\,df + \frac{2kT\,df}{g_m} + 2eI_bR_s^2\,df \qquad (7)$$

The noise figure F is the ratio of this total noise to the noise due to the source alone (the first term in (7)), so that

$$F = 1 + \frac{T}{2T_s}\left(\frac{1}{g_mR_s} + \frac{eI_bR_s}{kT}\right)$$

We can also write this as

$$F = 1 + \frac{T}{2T_s}\left(\frac{1}{g_mR_s} + \frac{I_b}{I_c}g_mR_s\right) \qquad (8)$$

The optimum source resistance is

$$R_s = \frac{1}{g_m}\sqrt{\frac{I_c}{I_b}} = \sqrt{\frac{dv^2}{di_b^2}} \qquad (9)$$

Since the input impedance is approximately $1/g_m\, I_c/I_b$ we see that our initial assumption that $R_s \ll Z_i$ was justified. The optimum noise figure is now

$$F = 1 + \frac{T}{T_s}\sqrt{\frac{I_b}{I_c}} \qquad (10)$$

If for example $T = T_s$ and the d.c. current gain is 100 we have $F = 1{\cdot}1$ or about $\frac{1}{2}$ dB. If the collector current is 1 mA we have $1/g_m = 25\,\Omega$ and $R_s = 250\,\Omega$ compared with $Z_i = 2{,}500\,\Omega$.

Notice first of all that a good low-noise transistor must have a high d.c. current gain and secondly that R_s is quite low. Fortunately an error of a factor 2 in R_s only increases F to $1{\cdot}125$ so that there is no point in attempting to be too precise in designing input stages.

If R_s is fixed then I_c (and thus g_m) should be adjusted to satisfy (9). If R_s is high e.g. 50 kΩ and the d.c. current gain is 400 it is easy to see that the optimum I_c is 10 μA. For this reason low-noise transistors should also have high current gain at low currents. This is not usually compatible with good r.f. response. Provided that the input capacitance of the transistor is tuned out, the formula for the optimum value of R_s is valid up to about $\frac{1}{3}f_T$ but the noise figure begins to deteriorate appreciably at about $f_T/\beta^{\frac{1}{2}}$. At very high frequencies, the effect of base series resistance becomes appreciable and, in any case, F exceeds $1 + f/f_T + (f/f_T)^2$.

In f.e.ts noise arises from thermal noise in the channel. When allowance has been made for the distributed nature of the noise source, the effect is equivalent to a current generator whose strength is

$$di_d^2 = \frac{2}{3}.\,4kTg_m\,df$$

connected between drain and source. This is equivalent to a voltage generator of strength

$$dv^2 = \frac{2}{3}\frac{4kT}{g_m}\,df \qquad (11)$$

in the gate lead.

At low frequencies there is also current noise in the gate lead due to leakage I_g

$$di_g^2 = 2eI_g\,df \qquad (12)$$

but at high frequencies this is swamped by induced current noise, produced by fluctuations in the channel under the gate. This noise is to all intents uncorrelated with the drain noise and is of magnitude

$$di^2 = \frac{1}{4}\frac{\omega^2 C^2}{g_m} 4kT\,df \qquad (13)$$

where C is the input capacitance. The complete equivalent circuit is shown in Fig. 3.

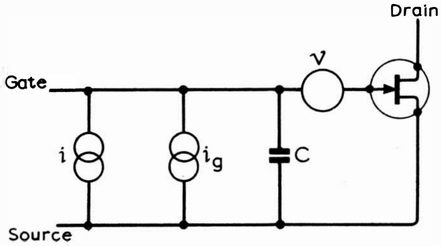

Fig. 3. An equivalent circuit for a field effect transistor.

The optimum source resistance and noise figure at low frequencies are

$$R_s = \left(\frac{dv^2}{di_g^2}\right)^{\frac{1}{2}} = \left(\frac{4kT}{3eI_g g_m}\right)^{\frac{1}{2}} \qquad (14)$$

and

$$F = 1 + \left(\frac{8eI_g}{3kTg_m}\right)^{\frac{1}{2}} \qquad (15)$$

If $I_g = 10^{-9}\,A$ and $g_m = 5$ millimho, we have $R_s \approx 100\,k\Omega$ and $F \approx 1{\cdot}005$.

At high frequencies the optimum values are

$$R_s = \frac{1}{\omega C}\sqrt{\frac{8}{3}} \qquad (16)$$

and

$$F_o = 1 + \frac{\omega C}{g_m}\sqrt{\frac{2}{3}} \approx 1 + \frac{f}{f_T} \qquad (17)$$

where $f_T = g_m/2\pi C$ is the gain bandwidth product. Obviously good low-noise r.f. amplifiers require f.e.ts with a high gain bandwidth product.

Insulated gate f.e.ts tend to have high flicker noise and these results are only valid above about 1 MHz., but, for junction f.e.ts, they are often valid down to low audio frequencies.

Perhaps the most important part to bear in mind is that there *is* an optimum source impedance, and that for bipolar transistors this is much less than the input impedance. If the source impedance is high, an f.e.t. will usually be the most suitable input stage. Conversely for low source impedances it will be a bipolar transistor. Finally it should be noted that the use of negative feedback, or other connections (e.g. common base) alters neither the optimum source impedance nor the optimum noise figure.

REFERENCE

1. "Equivalent Circuit for Noise in Bipolar Transistors", by H. Sutcliffe, *International Journal of Electrical Engineering Education*, vol. 6, number 3, October 1968.

Domestic video records

Machines for playing recorded vision programmes into domestic television sets are arriving from all directions. Some are players only, for reproducing programme material on records supplied by outside organizations. Others will, in addition, record and reproduce television programmes (broadcast or closed-circuit) selected by the user. The two latest are the Video Cassette Recorder, from Philips (Holland), shown below, and the Cartrivision system, from Avco (U.S.A.).

The Philips machine (called VCR, perhaps for its convenient euphonic relationship with EVR) was demonstrated in the U.K. at a convention of the Film Industry Organization at Brighton. As the name indicates the machine uses cassettes to hold the recording medium, which is ½-inch magnetic tape. The recorded material, colour or monochrome, is reproduced on a domestic television receiver, and connection to the set is made via the aerial socket.

Two versions of the machine have been produced. The first is a player only, intended for reproducing programme material supplied in cassettes by outside organizations—hence the interest of the film industry. This is expected to cost about £120 for a monochrome machine and about £140 for a colour machine. The second version, justifying the name, will record as well as reproduce, and for recording broadcast television programmes it obtains the video signal by means of a built-in tuner which receives its r.f. signal from the aerial connection on the home television set. This machine will cost about £230.

Each cassette contains enough tape for an hour's running. It can be put into or taken out of the machine very easily and at any required moment, regardless of the position of the tape. Programme material may be erased and fresh material recorded in its place, as with a sound tape recorder. No rewinding is required.

The cassettes are interchangeable in the sense that, provided they are of the right type to fit the VCR, they can come from any source. Also, colour and monochrome cassettes are compatible, in that either type can be played on monochrome machines and colour machines. On the ½-inch tape two sound record tracks are available, and these can be used, say, for stereophonic sound or for spoken commentaries in two languages.

Other domestic video reproducing systems already launched or announced have the trade names: EVR (Electronic Video Recording), Vidicord, Selectavision and Sony. Domestic v.t.r. machines are already on the market.