Introduction to low-noise amplifier design

How to optimize collector current and calculate noise figure

by A. Foord

Many constructors still settle for more noise in their amplifiers than necessary because of the complexity of a full mathematical treatment and because manufacturers often fail to specify their transistor parameters in a convenient form. This article shows how to calculate the optimum collector current for a given source resistance and the minimum noise figure at that current, and gives practical circuits for instrumentation use and sound reproduction.

Once the basic design requirement of optimum collector current has been satisfied, the remaining amplifier parameters can be determined from the normal design relationships. For example, as the noise figure is independent of the transistor configuration and overall feedback, the usual feedback pair arrangements are practicable. Therefore the transistor and its operating point can be selected to meet the circuit noise requirements and the configuration or feedback can be determined to meet gain, bandwidth and impedance requirements. This approach allows the noise and other circuit constraints to be optimized independently.

The selection of a suitable input device depends mainly on the source resistance and bandwidth requirements. At the lowest values of source resistance it is necessary to use transformer coupling at the input to match the source resistance to the optimum for the amplifier, Fig. 1. Unfortunately transformers introduce extra losses and degrade the basic noise figure of the amplifier. For example, an amplifier designed for a 5kohm source might have a noise figure of less than 1dB. When matched with a transformer to a 30 ohms dynamic microphone this noise figure could be degraded to 2.7dB.

If integrated circuits are used their parameters are well specified by the manufacturer, but their noise levels are in general about two to five times that of a discrete transistor circuit. This makes them more suitable as second and succeeding stages. Fortunately bipolar transistors can be used for most audio front-end applications and this article is restricted to their use.

There is a slight difference between p-n-p and n-p-n transistors. A p-n-p transistor can have a lower base spreading resistance due to a higher carrier mobility in its base
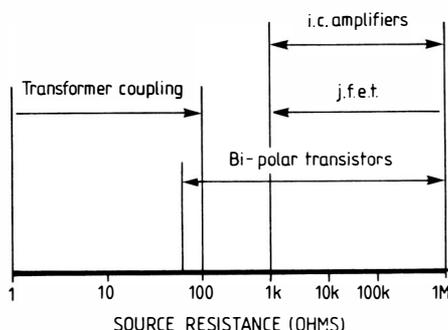

Fig. 1. Choice of input amplifying device depends on source resistance.

region, while an n-p-n transistor often has a slightly larger current gain and bandwidth. This makes the p-n-p type more useful with low source resistances, with the n-p-n transistor useful at the higher end of the resistance range. For this reason, and also for direct coupled circuits, it is desirable to have information on a range of p-n-p and n-p-n devices.

A table of suitable low-noise transistors and their parameters is shown in Table 1. These are measured values and may not agree with those obtained from the manufacturers' specification sheets. Details of

some low-noise i.cs are included for comparison.

Some noise mechanisms are process-dependent and result from faults such as surface defects, surface contamination, defective contacts, impurities, dislocations, and irregularities at the base-emitter junction. For this reason transistors with the same type number may vary from maker to maker. This is particularly true for low frequency noise below 1kHz where poor processing techniques become more apparent.

Any source unavoidably generates an amount of thermal noise power which depends on its temperature, Boltzmann's constant, and the system's noise bandwidth. Noise factor, as a ratio, is defined as

$$F = \frac{\text{total available output noise power}}{\text{portion of output power caused by source only}}$$

Noise figure is simply this noise factor expressed in decibels. **NF =**

$$10 \log \frac{\text{total available output noise power}}{\text{portion of output power caused by source only}}$$

or $NF = 10 \log F$. The noise figure is a measure of the signal-to-noise degradation attributed to the amplifier. For a perfect

Table 1. Measured values of low-noise device parameters may not agree with manufacturers data

		β at I_c of			$r_{bb'}$ (Ω)	Application
		1mA	100µA	10µA		
2N930	n-p-n	300	200	130	700	High source resistance
2N4124	n-p-n	300	200	110	100	Low source resistance
BC109	n-p-n	350	300	200	400	General purpose
2N3707	n-p-n	350	250	200	200	General purpose
2N4403	p-n-p	200	140	80	40	Low source resistance
2N4125	p-n-p	150	120	90	50	Low source resistance
2N3964	p-n-p	350	310	260	150	Low broadband noise
2N4250	p-n-p	350	310	260	150	Low broadband noise

IC type	V_n (nV/Hz$^{1/2}$)	I_n (pA/Hz$^{1/2}$)	R_s (kΩ)	f (Hz)	NF at R_s (dB)
TDA1034N	9.0	3.0	3.00	10	6.41
	3.5	0.4	8.75	1k	0.70
RM4739	20.0	4.0	5.00	10	10.41
	10.0	0.5	20.00	1k	2.11
LM201A	22.0	0.74	29.73	10	4.82
	16.0	0.20	80.00	1k	1.46
OP10EY	10.3	0.32	32.19	10	1.50
	9.6	0.12	80.00	1k	0.58
AD517	35.0	0.05	700	10	0.86
	20.0	0.03	667	1k	0.31
ZN460	0.8	1.0	0.800	5k	0.41

amplifier, one which adds no extra noise to the thermal noise of the source, the noise factor is unity, and the noise figure zero. Usually there is not a great deal of value in reducing the noise figure much below 3dB. A noise figure of 3dB is equivalent to saying that the amplifier and source are contributing an equal amount of noise to the wanted signal. Even if the amplifier noise could be reduced to 0.1 of the source noise, the total system noise is now about 0.7 of the 3dB condition. However it must be remembered that an amplifier with a noise figure of 0.5dB at 1kHz with a source resistance of 5kΩ will have a higher figure at low frequencies and at source resistances away from the optimum.

The normal procedure is to design the amplifier for a minimum noise figure at the desired source resistance. The optimum collector current for the transistor depends on the driving source resistance R_s and the direct current gain β.

Optimum collector current

$$I_c = \frac{(\beta)^{1/2}}{40R_s}$$

For example, determine the optimum current for a 2N4403 transistor with a source resistance of 400 ohms. Initially β can be taken as 200.

$$I_c = \frac{(200)^{1/2}}{40 \times 400} = 0.88\text{mA}.$$

As shown in Table 1 a β of 200 at 0.88mA is possible. If the formula had given a much lower optimum collector current, say 50µA, then the β would have to be reduced to about 100 and the optimum collector current recalculated. This procedure is repeated if necessary until the β is believable for the calculated collector current.

The procedure is not too critical because of the wide variations in β between one transistor and the next and because the optimum collector current is proportional to the square root of β.

The minimum noise factor F at the optimum collector current can be calculated from the source resistance R_s, the current gain β, and the intrinsic base spreading resistance $r_{bb'}$

$$F = 1 + \frac{r_{bb'}}{R_s} + \left(\frac{1}{\beta}\right)^{1/2}$$

For the conditions previously discussed for the 2N4403 transistor

$$F = 1 + \frac{40}{400} + \left(\frac{1}{200}\right)^{1/2} = 1.17 \text{ times}$$

Then the minimum noise figure is

$NF = 10 \log F = 10 \log 1.17 = 0.68\text{dB}.$

Microphone preamplifier example

Many dynamic microphones have impedances of 200 or 600 ohms. The previous examples suggest that a 2N4403 transistor run at a collector current of about 1mA could be used for this application, and a suitable circuit is shown in Fig. 2.
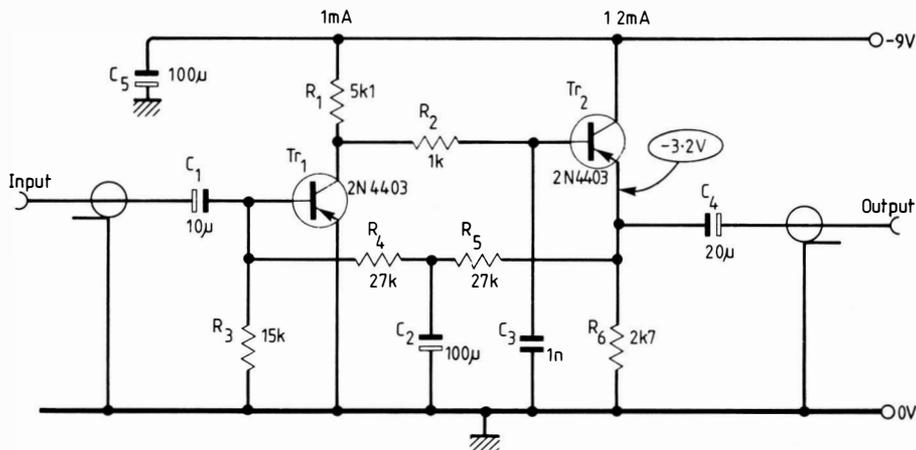

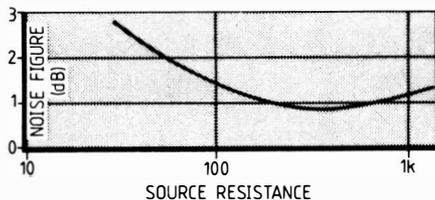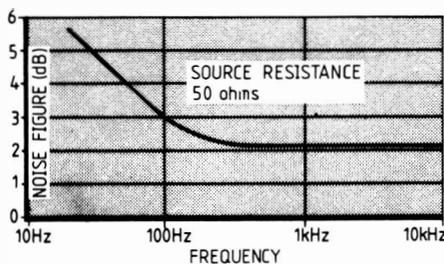Fig. 2. Instrumentation preamplifier is suitable for microphone use.

Fig. 3. Noise figure plotted against source resistance for the microphone preamplifier (top), and against frequency (bottom).

A common-emitter amplifier is followed by an emitter follower. The dc conditions are determined by the bias chain from Tr_2 emitter to Tr_1 base, but this does not provide negative feedback at signal frequencies because of C_2. The low frequency response is determined mainly by the input and output coupling capacitors at 10Hz, while the high frequency response is determined by C_3 at 26kHz. If C_3 is not included the high frequency response would extend to 1MHz, which is undesirable.

The first transistor is essentially an unloaded common-emitter stage, and its gain at room temperature is

$$\frac{V_o}{V_i} \approx 40R_1I_c = 204 \text{ times or 46dB.}$$

Measured results on two amplifiers gave gains within 1dB of the calculated value. The input resistance was 2.7k ohms. As

Tr_1 has a high gain the noise contribution by Tr_2 is negligible. Fig. 3 shows the noise figure plotted against the source resistance, while Fig. 4 shows the noise figure plotted against frequency for a fixed source resistance; in this case the non-optimum value of 50 ohms.

These results confirm the theory, and show that the 2N4403 transistor is particularly suitable for both low source resistances and low frequency applications where noise is important.

Measurements on several 2N4403 transistors suggested that about one quarter of them had excess noise at low frequencies, but mid-frequency results were consistently low. For critical applications the amplifier input should be terminated with a 390-ohm wirewound resistor and Tr_1 selected for a minimum amount of noise. This noise can be measured at the output of the amplifier chain with an oscilloscope or a.c. voltmeter. An oscilloscope is particularly valuable because any low frequency or burst noise can be observed. If the preamp does not dominate the noise generated from succeeding stages (with the gain control at a maximum) then these stages need to be examined!

The full design of a general-purpose audio preamplifier can be quite a problem, and a magnetic pickup may be the most difficult source to match. Its impedance rises with frequency, the amplifier has an equalization curve which gives 20dB boost below 50Hz and 20dB cut at 20kHz, and the basic amplifier noise may be increasing at low frequencies.

The theoretically correct approach is to allow for all these factors and design for the lowest total noise over the complete audio bandwidth. This really demands an exact model for the circuit and a good computer program. In practice a reasonable answer can be obtained by designing for a source impedance of about 6k ohm.

In Table 2 several transistors are compared for this source impedance. All of these transistors appear to be suitable,

Table 2. Comparison of several transistors for a 6kohm source.

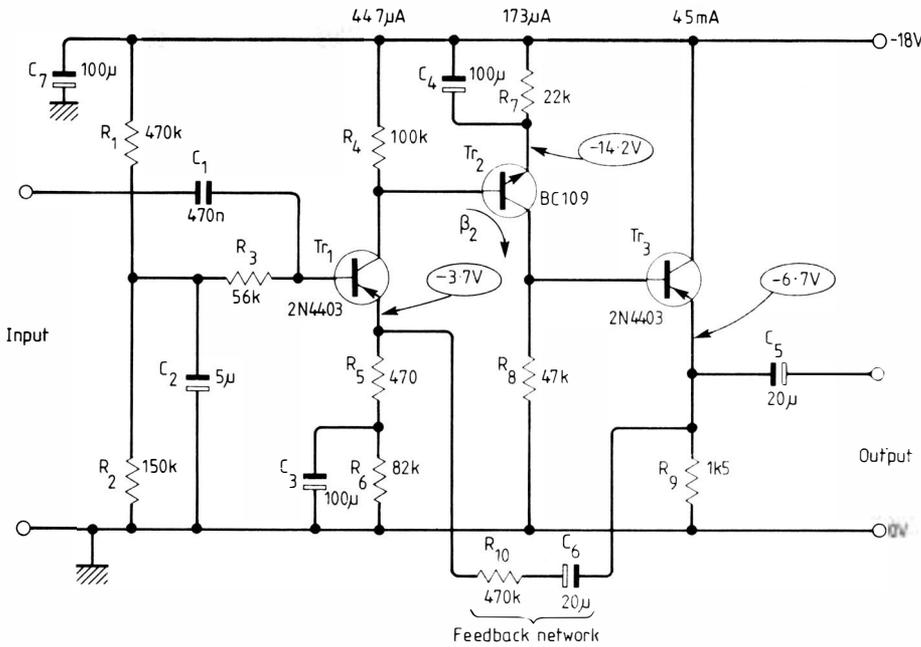|	β	I_c (µA)	$r_{bb'}$ (Ω)	F	NF
2N930	150	51	700	1.198	0.79
2N4124	150	51	100	1.098	0.41
BC109	250	65.9	400	1.130	0.53
2N3707	220	61.8	200	1.101	0.42
2N4403	100	41.7	40	1.107	0.44
2N4125	100	41.7	50	1.108	0.45
2N3964	280	69.7	150	1.085	0.35
2N4250	280	69.7	150	1.085	0.35

Fig. 4. Preamplifier as shown has flat frequency response; for use with magnetic pick-up replace feedback network with appropriate equalization network. Author recommends metal film or metal oxide resistors, as wirewound ones are bulky and expensive. Tantalum electrolytics are preferred over aluminium because of their lower leakage.

Fig. 5. Noise figure plotted against frequency for the general-purpose preamplifier of Fig. 4.

apart from the 2N930. The 2N4403 transistor has been chosen for the practical circuit, and the examples.

$$I_c=\frac{(\beta)^{\frac{1}{2}}}{40R_s}=\frac{(100)^{\frac{1}{2}}}{40\times6\times10^3}=41.7\mu A$$

$$F=1+\frac{40}{6000}+\left(\frac{1}{100}\right)^{\frac{1}{2}}=1.107$$

$$NF=10\log1.107=0.44dB$$

One practical circuit might be similar to that shown in Fig. 5, where two common-emitter stages are followed by a common collector stage to drive the feedback network and the next stage. When Tr_1 is biased from a potential divider as shown, the only bias component which contributes noise is R_3. The actual voltage drop across R_3 is small and therefore any excess noise generated by the resistor, due to the current flowing through it, is also small. The amount of thermal noise it generates is attenuated by the source. The value shown will provide the load resistance required for most magnetic cartridges, and can be shunted if necessary for other inputs.

The approximate open-loop gain for this type of circuit is

$$\frac{\beta_2R_8}{R_5+\frac{1}{40I_{c1}}}=\frac{320\times47\times10^3}{470+\frac{1}{40\times44.7\times10^{-6}}}$$

$$=14,600\text{ times}=83dB.$$

A practical measurement of this circuit gave an open-loop gain of 80dB, which is perhaps more realistic.

Unlike the first circuit, where the gain was well defined by the collector current, the gain of this circuit depends on the β of the second transistor. Overall negative feedback is therefore essential to accurately define the closed-loop gain. In Fig. 5 the closed-loop gain is 60dB and the frequency response is 3dB down at 8Hz and 45kHz.
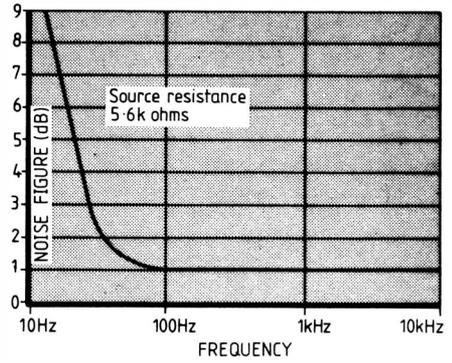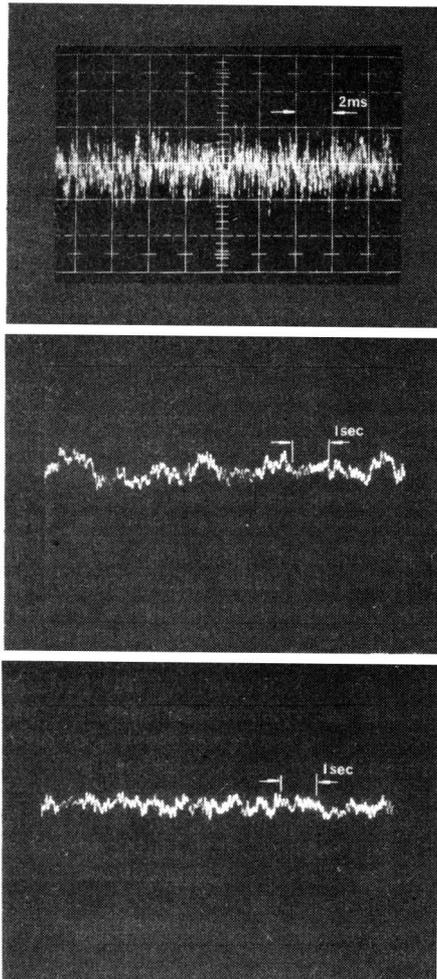

Fig. 6. Broadband noise from a 2N4403 transistor (top), low frequency noise from a poor 2N4403 transistor over 5 to 36Hz (middle), and low frequency noise from a typical 2N4403 transistor over 5 to 36Hz (bottom).

The closed-loop gain is defined at

$$G=1+\frac{R_{10}}{R_5}\text{times.}$$

Resistor 5 is required so that the closed-loop gain can be defined by overall negative feedback. It also provides series local feedback for Tr_1 and reduces the open-loop gain by about 7dB. However the open-loop gain of 80dB which was measured is adequate to provide a reasonable amount of feedback at low frequencies even though the equalization curve demands a 20dB gain boost (below 50Hz) above the mid-band gain. The value of R_5 cannot be made too low as this will force a reduction in the feedback impedance, reducing the available output voltage swing at high frequencies where the equalization curve falls at 6dB per octave.

Although negative feedback does not alter the amplifier's noise figure, R_5 is effectively in series with the source and can contribute an amount of thermal noise, the effect of which depends on the source resistance. It should be made much smaller than the source resistance. Noise factor with R_5 is

$$F_r=F+\frac{R_5}{R_s}.$$

In the example

$$F_r=1.107+\frac{470}{6000}=1.185\text{ times}$$

thus $NF_r=10\log1.185=0.74dB$.

Although this appears to be a significant degradation the resultant noise figure is still less than the 3dB level considered to be a reasonable value. It does indicate why an approach like Fig. 2 is valuable for critical applications, because the gain can be closely determined by the circuit parameters without using emitter degradation.

Further reading

Low-noise Electronic Design, by C. D. Motchenbacher and F. C. Fitchen (Wiley, 1973) gives many practical examples which are fully specified in terms of gain, bandwidth, and noise for up to four different values of passive components.