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 5kΩ microphone might have a noise figure of less than 1 dB.

When matched with a transformer to a 30 ohms dynamic microphone this noise figure could be degraded to 2.7 dB.

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 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, and transformer coupling, 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 ICs are included for comparison.

Noise figure is simply this noise factor expressed in decibels. $NF = 10 \log_{10} \left( \frac{F \times 10^{NF}}{RF} \right)$

<table>
<thead>
<tr>
<th>IC type</th>
<th>$V_c$ (nV/Hz^{1/2})</th>
<th>$I_b$ (pA/Hz^{1/2})</th>
<th>$R_e$ (kΩ)</th>
<th>$f$ (Hz)</th>
<th>NF at $R_e$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDA1034N</td>
<td>9.0</td>
<td>3.0</td>
<td>3.00</td>
<td>10</td>
<td>6.41</td>
</tr>
<tr>
<td>RM4739</td>
<td>3.5</td>
<td>0.4</td>
<td>8.75</td>
<td>1k</td>
<td>0.70</td>
</tr>
<tr>
<td>LM201A</td>
<td>20.0</td>
<td>4.0</td>
<td>1.00</td>
<td>1k</td>
<td>2.11</td>
</tr>
<tr>
<td>OP10EY</td>
<td>16.0</td>
<td>0.20</td>
<td>80.00</td>
<td>1k</td>
<td>1.46</td>
</tr>
<tr>
<td>AD517</td>
<td>9.6</td>
<td>0.12</td>
<td>80.00</td>
<td>1k</td>
<td>0.58</td>
</tr>
<tr>
<td>ZN460</td>
<td>8.0</td>
<td>0.05</td>
<td>70.00</td>
<td>1k</td>
<td>0.86</td>
</tr>
</tbody>
</table>

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 1 kHz 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 $F = \frac{100}{10 \log_{10} \left( \frac{F \times 10^{NF}}{RF} \right)}$

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

Optimum collector current

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

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

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

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

$$F = 1 + \frac{40}{R_s} + \frac{1}{\beta^{1/2}}.$$  

For the conditions previously discussed for the 2N4403 transistor

$$F = 1 + \frac{40}{200} + \frac{1}{200}^{1/2} = 1.17 \text{ times}.$$  

Then the minimum noise figure is

$$NF = 10 \log F = 10 \log 1.17 = 0.68dB.$$  

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.](image)

![Fig. 3. Noise figure plotted against source resistance for the microphone preamplifier (top), and against frequency (bottom).](image)
apart from the 2N930. The 2N4403 transistor has been chosen for the practical circuit, and the examples.

\[ I_c = \frac{(b)^3}{40R_s} = \frac{(100)^3}{40 \times 6 \times 10^3} = 41.7 \mu A \]

\[ F = 1 + \frac{40}{6000} \left( \frac{1}{100} \right) = 1.107 \]

\[ NF = 10 \log 1.107 = 0.44 dB \]

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 Tr1 is biased from a potential divider as shown, the only bias component which contributes noise is \( R_5 \). The actual voltage drop across \( R_5 \) 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

\[ NF = 10 \log 10 \log (1 + \frac{470}{6000}) = 0.44 dB \]

\[ NF = 10 \log 1.107 = 0.44 dB \]

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 \( b \) 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. 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.

The closed-loop gain is defined at

\[ G = 1 + \frac{R_{10}}{R_5} \]

Resistor 5 is required so that the closed-loop gain can be defined by overall negative feedback. It also provides series local feedback for Tr1 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

\[ NF = 10 \log \left( 1 + \frac{R_5}{R_s} \right) \]

In the example

\[ NF = 1.107 + \frac{470}{6000} = 1.185 \text{ times} \]

\[ thus \ NF = 10 \log 1.185 = 0.74 dB \]

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. Finch (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.