Designing low-noise audio amplifiers

In any system, the front-end amplifier sets important limits to performance. This article examines the limitations of low-noise amplifers as defined by the laws of physics and the practicality of real-world components.

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Since the invention of electronic amplifiers, their dynamic range (the ratio between the smallest signal just above amplifier noise and the largest possible signal at a given level of distortion) has increased steadily. Despite this improvement, the dynamic range of a modern microphone amplifier is considerably less than the capability of the human ear or of a modern microphone (**Fig.1**). Therefore in the quest for fidelity it is desirable to improve the dynamic range of electronic amplifiers still further.

The main factors behind the expanded dynamic range of modern amplifiers have been an improved knowledge of distortion mechanisms and methods of combating distortion, together with a better understanding of noise sources in amplifiers and the way in which external noises are picked up.

Modern transducers general analogue signals at low level, mainly because of their poor efficiency in converting the input energy into electrical energy. Analogue signal amplification is therefore needed to match the transducer signal to the subsequent analogue or digital signal processing circuitry. The noise performance of this first amplification stage is of considerable importance, because signal information from the transducer which is lost through noise in the first stage cannot normally be recovered through signal processing later on.

One type of interference which influences the performance of the first amplification stage may arise from external sources such as radio frequency signals, in all frequency ranges. Such interference may vary statistically or may be of a repetitive nature. It may be coupled into the amplifier either inductively or capacitively.

Other forms of interference are generated within the amplifying circuitry itself. They are of a statistical nature and are also present at all frequencies. It is on this class of interference that this article will concentrate.

NOISE AND PHYSICS

In audio amplifier design, several varieties of internally generated noise must be considered.

Thermal noise. This occurs at all frequencies and is the dominant noise from around 100Hz right up into the multi-GHz range. The cause of thermal noise is thermal oscillation of electrons; for example, in the crystal lattice of a conductor. Thermal noise is frequently also called Johnson noise or (not quite correctly) white noise – there are other sources of white noise. The amplitude of thermal noise increases with temperature; it is proportional to the bandwidth and the resistance value. The so-called Nyquist equation gives the relationship

$$E_n = \sqrt{4 \times k \times T \times b \times R}$$

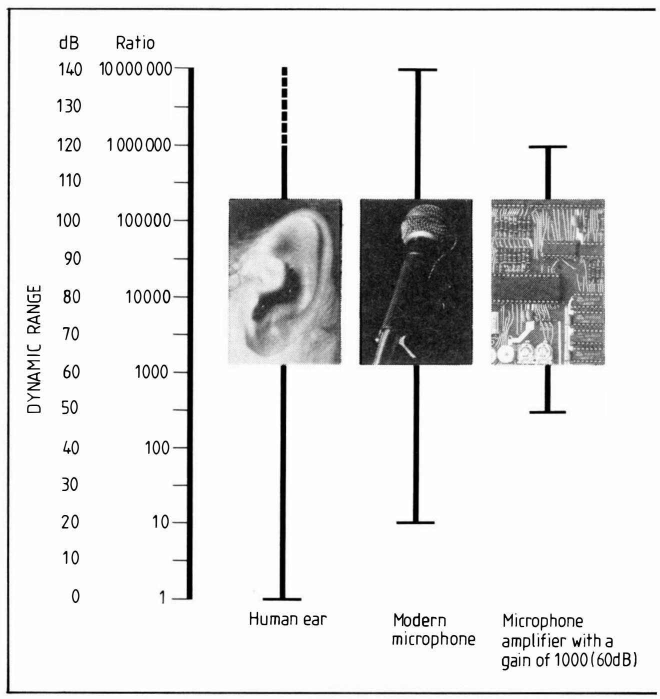


Fig.1. Comparison between the dynamic range of the human ear, a modern microphone and a microphone amplifier with a gain of 1000 (60dB).

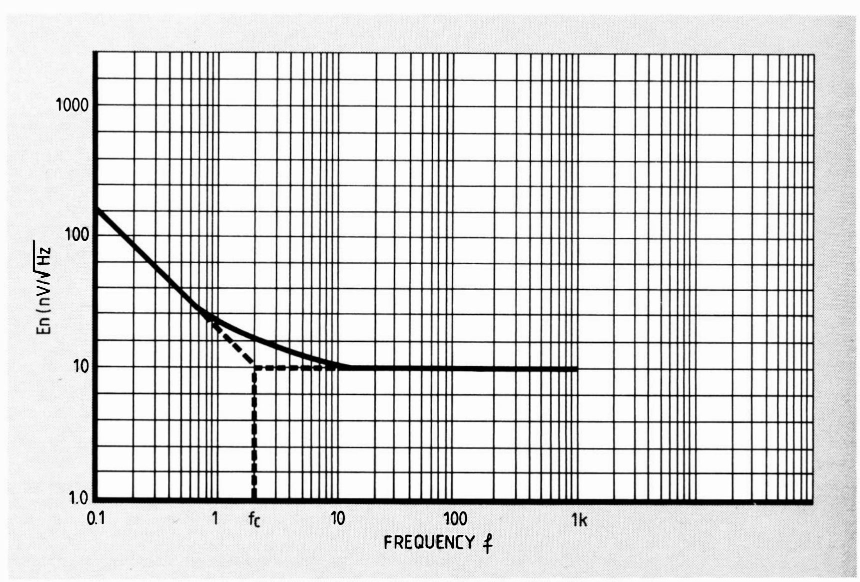


Fig.2. Noise spectral density plot showing white noise and flicker noise components of a bipolar op-amp for audio, and the definition of corner frequency f_c.

where E_n=noise voltage (RMS); k = Boltzmann's constant (1.38×10^{-23}VA s K^{-1}); T= absolute temperature in kelvins; b = bandwidth in Hz; and R = resistance in ohms. Using this equation it is possible to calculate the noise voltage of, for example, a 50Ω (=50VA) resistor at a temperature of 27°C (300K) and a bandwidth of 20 000Hz (=20 000s^{-1}),

$$E_n = \sqrt{\begin{matrix}4\times1.38\times10^{-23}\text{VA s K}^{-1}\times\\ 300\text{K}\times20\,000\text{s}^{-1}\times50\text{VA}^{-1}\end{matrix}}$$

Listed in the table are noise voltages for a number of useful resistances common in audio engineering.

R(Ω)	E_n(nV) b=20kHz	E_n(dBm) b=20kHz	E_n(nV/√Hz)
50	125	−136	0.91
75	153	−134	1.12
200	250	−130	1.82
600	433	−125	3.15
1k	559	−122	4.07

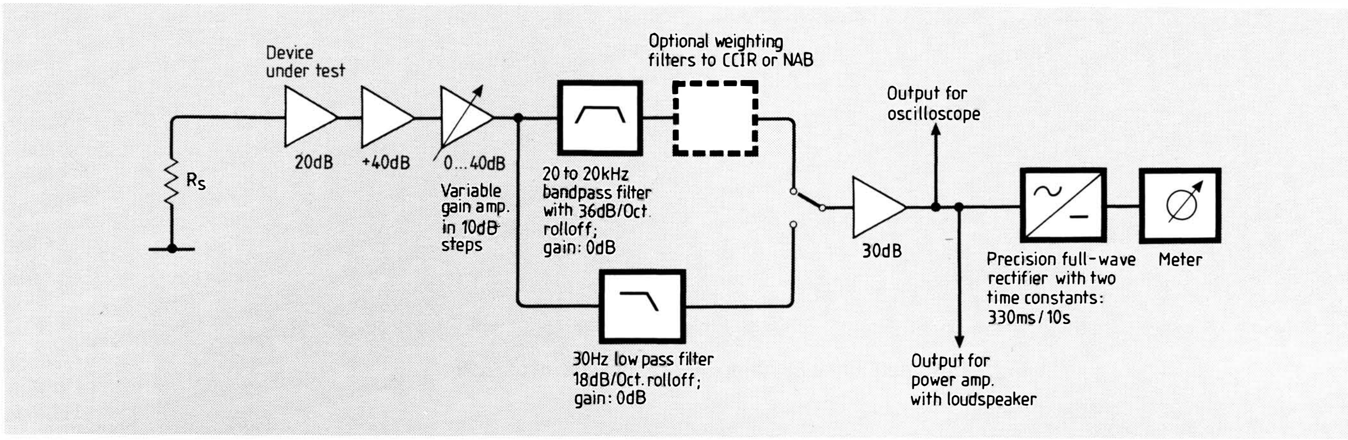
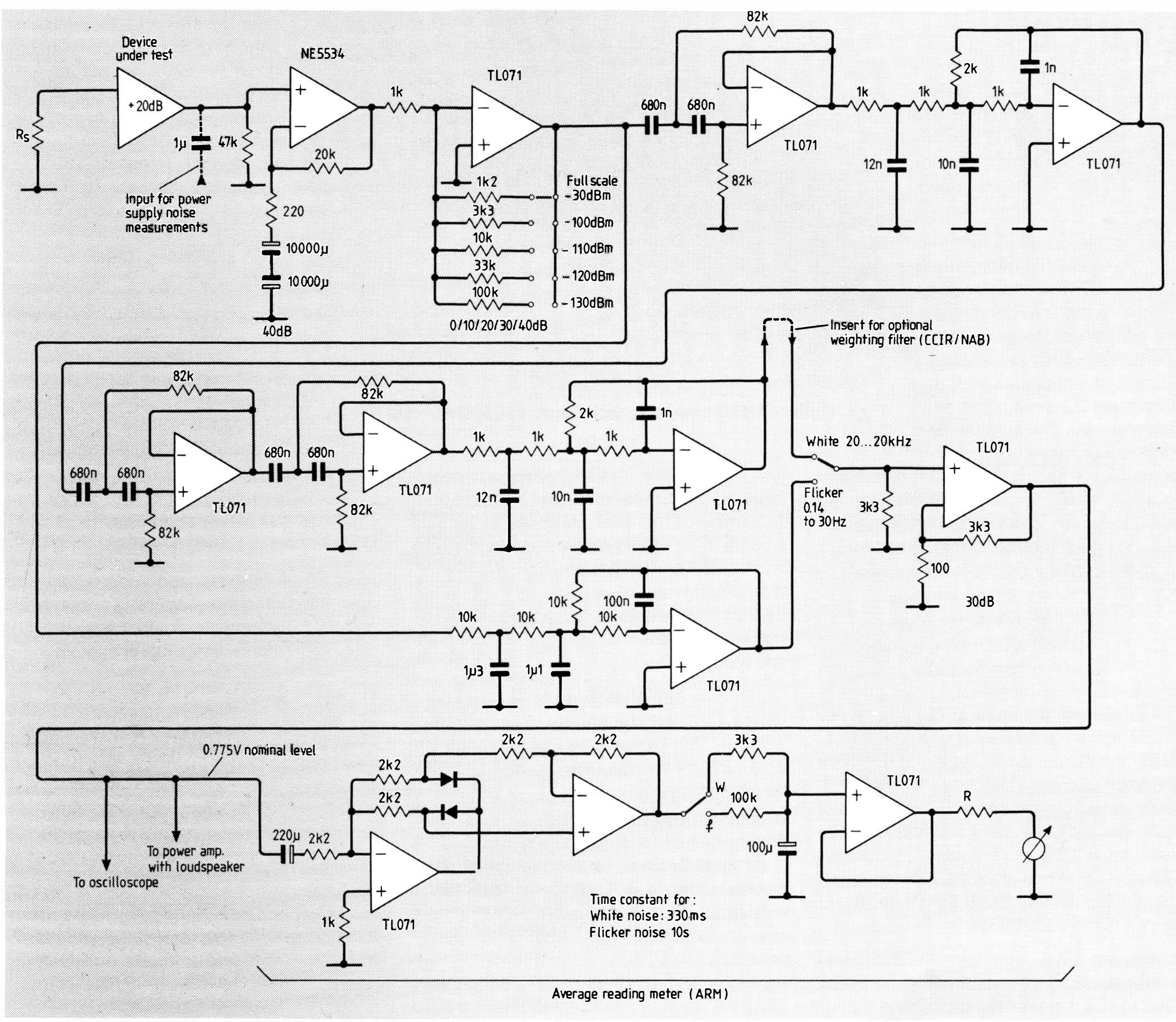
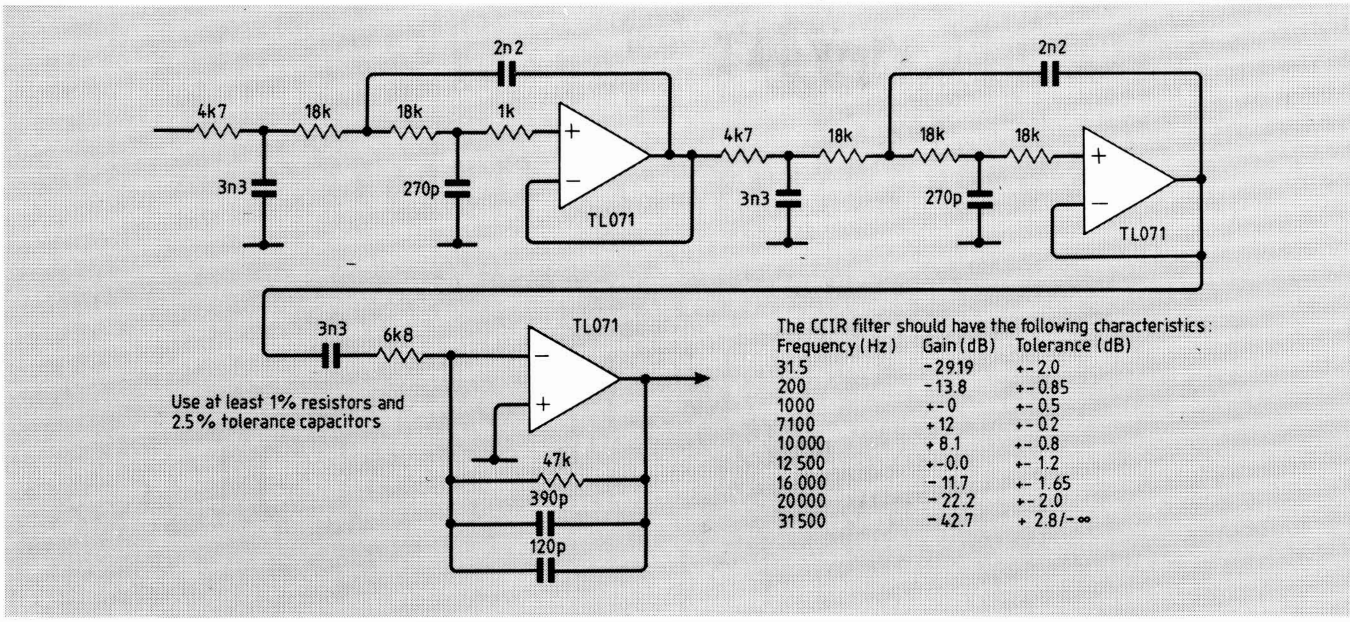


Fig.3. Block diagram of a noise measurement circuit for white noise and flicker noise.

Fig.4. Circuit for the measurement of white noise and flicker noise.





The CCIR filter should have the following characteristics:

Frequency (Hz)	Gain (dB)	Tolerance (dB)
31.5	-29.19	+-2.0
200	-13.8	+-0.85
1000	+-0	+-0.5
7100	+12	+-0.2
10 000	+8.1	+-0.8
12 500	+-0.0	+-1.2
16 000	-11.7	+-1.65
20000	-22.2	+-2.0
31 500	-42.7	+2.8/-∞

Fig.5. Optional CCIR weighting filter for the circuit of Fig.6.

In the right-hand column, the table also gives the noise voltage in units of nV/√Hz, i.e. normalized to a bandwidth of 1Hz. This has the advantage that it is not necessary to state the bandwidth to which a particular noise voltage applies. In the case of white noise this is permissible since the noise spectral density is constant – the noise voltage is the same within any bandwidth interval, no matter where this interval is placed in the frequency spectrum.

Flicker noise. In taking a closer look at the low-frequency noise from an amplifier in the frequency range below 100Hz one discovers an additional noise component. Flicker noise is caused by material impurities and also depends on the production process employed. The amplitude of flicker noise increases at lower frequencies, where it very much dominates the white noise, especially in view of the small bandwidth under consideration. Since the flicker noise amplitude is proportional to the inverse frequency it is also called 1/f noise:

$$E_{nf}=K/f$$

where E_{nf} is the flicker noise voltage, K a constant of proportionality and f the frequency.

In expressing the amount of flicker noise present in an amplifer, the frequency at which the flicker noise region starts is of particular interest. This corner frequency, f_c is defined in the noise spectral density plot of **Fig.2**. For audio purposes a corner frequency well below 100Hz is desirable.

Besides these two principal types of noise, several others are significant in the design of low-noise audio amplifiers:

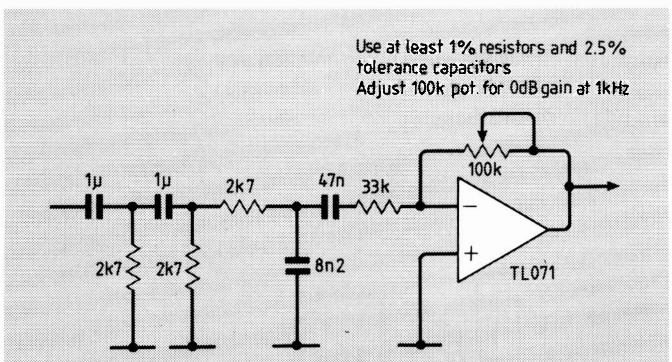
Shot noise. Noise from active components such as vacuum tubes and transistors contains, in the frequency range above 100Hz, one further white noise component superimposed on the ever-present thermal noise. The cause of this shot noise lies in the fact that the flow of an electric current depends on the motion of discrete particles – electrons. Shot noise occurs only in active devices. Its voltage is proportional to the current through the device, the bandwidth and resistance:

$$E_s=\sqrt{2q\times I_{dc}\times b\times R}$$

where q equals the charge of an electron, 1.6×10^{-9}As; I_{dc} is the current through the device; b is the bandwidth; and R is the resistance.

Recombination noise. A further noise component only to be found in semiconductors is the so-called recombination noise – noise which occurs when electrons recombine with holes. This type of noise occurs mainly at high frequencies. Its amplitude drops in proportion to $1/f^2$.

Popcorn noise. This noise component occurs at frequencies below 100Hz. It is of an impulsive nature, consisting of momentary changes of the output voltage due to fluctuations in the current through an active device. Contaminated semiconductor surfaces aggravate this type of noise. Other factors which may increase popcorn noise are low temperatures and high-value resistors. The "pops" occur quite randomly with the device, sometimes being absent for several minutes and then appearing several times per second[1]. The precise causes of popcorn noise, or burst noise as it is sometimes called, are not known.



The NAB filter should have the following characteristics:

Frequency (Hz)	Gain (dB)	Tolerance (dB)
31.5	-39.4	+-3.0
200	-10.9	+-1.0
1000	+-0	+-1.0
2500	+1.3	+-1.0
6300	-0.1	+1.5/-2.0
12 500	-4.3	+3.0/-6.0
16 000	-6.6	+3.0/-∞
20 000	-9.3	+3.0/-∞

Fig.6. Optional NAB weighting filter for the circuit of Fig.6.

Current flow through resistors. Besides thermal noise, resistors generate excess noise when a current flows through them or when a high voltage is applied. The reason for this excess noise is inhomogeneity in the resistor material. Metal film resistors produce less excess noise than carbon film types and small-sized resistors are noisier than large ones.

Mechanical contacts. Inhomogeneous and unstable contacts in connectors or potentiometers cause voltage fluctuations and are especially troublesome sources of noise.

Vibration. Noise can also be generated by mechanical vibration of components such as vacuum tubes and transistors. This causes a displacement current which makes itself felt as noise. It is especially noticeable in coaxial cables where vibrations cause a change in capacitance. Large components such as capacitors or printed circuit boards are also affected.

Leakage currents. Noise may arise from leakage currents due to contaminants such as finger prints and soldering residues on printed circuit boards or across components.

NOISE MEASUREMENT

To measure noise precisely demands a spectrum analyser, with which to measure the spectral noise density distribution. This instrument is not part of everybody's electronics tool kit because of its price; but simpler means, suitable for the purposes of comparison, may be used for measuring the two principal noise components.

A circuit suitable for evaluating white noise and flicker noise in audio amplifiers is shown in **Fig.3** and **Fig.4.** Its frequency range is 20Hz to 20kHz for white noise and 0.1Hz to 30Hz for flicker noise. Full scale deflection of the meter can be set in the range between −130dBm and −90dBm, so that the lowest noise voltage which can be indicated is in the region of −140dBm (75.5nV). In making measurements it is important to set the gain of the amplifier under test to 20dB, because otherwise the calibration of the range switch does not hold good. The device under test should be well screened from external interference such as mains hum, preferably by a metal box.

Optional weighting filters can be added as given in **Fig.5** and **Fig.6**. Note that the CCIR standard requires peak rectification and the NAB standard true-RMS rectification[2], whereas this circuit provides only full-wave averaging. If gain of the CCIR filter is set to 0dB at 2kHz this will correspond to the CCIR-ARM standard[3].

When switching to the measurement of flicker noise, wait for at least 10 seconds for the meter to stabilize. Usually it will be better to evaluate the amount of flicker noise on a DC-coupled oscilloscope. It is also a good idea to connect a power amplifier with an old loudspeaker to the output, so that one can listen to the noise as long as the loudspeaker can stand it. This helps to identify rapidly any noisy components and amplifiers, or any externally-injected mains hum and radio interference.

Input-referred noise. Results obtained from the instrument are the noise voltages at the input of the device under test; the 20dB gain of the device under test has already been subtracted. The value of input-referred noise is useful because it allows a quick calculation of the noise voltage at the output of the device for any gain setting. For example, the input-referred noise of an amplifier is −122dBm. At a gain of +20dB the output noise level will be −122+20=−102dBm and for a gain of +32dBm the output noise will be −90dBm and so on.

Optimum source resistance. By taking a series of measurements with different resistance values, preferably using fixed-value metal film resistors, connected to the input of the device under test, it is possible to determine the optimum source resistance of the amplifier under test. This is the source resistance at which the difference between the noise generated by the amplifier and the noise of the source resistance is at a minimum. **Figure 7** shows an example for the popular low-noise op-amp NE5534. From this diagram it can be seen that the optimum source resistance is approximately 5kΩ.

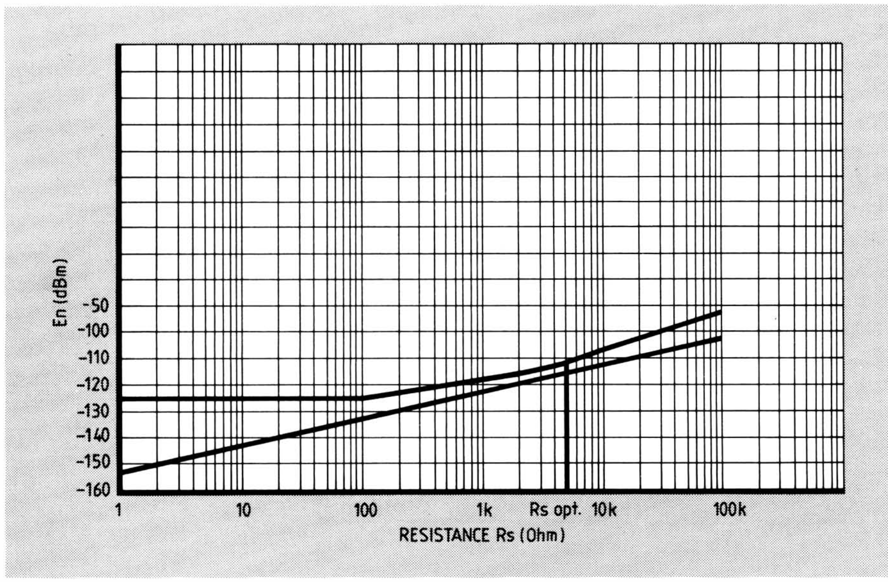


Fig.7. Optimum source resistance of an NE5534 op-amp (typical example without flicker noise in the audio band).

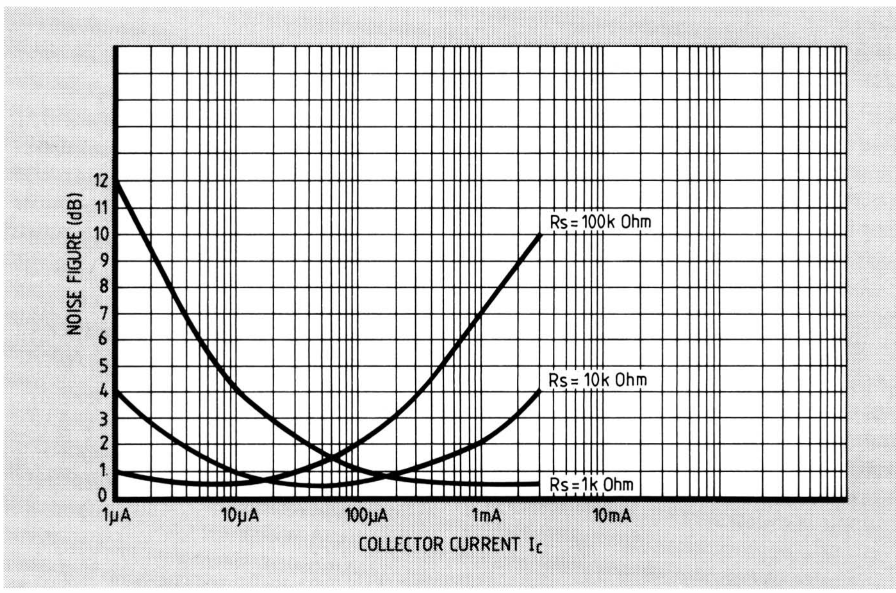


Fig.8. Noise figure and optimum source resistance R_s as a function of collector current I_c for an LM394 transistor.

LOW-NOISE DEVICES

Bipolar transistors. P-n-p transistors are preferred in low-noise transistor circuits because of their marginally better noise characteristics at low source resistances, compared to equivalent n-p-n devices under the same conditions. The magnitude of the collector current influences the value of the base spreading resistance R_{bb} and thus the achievable optimum source resistance of a particular circuit. This is demonstrated in **Fig.8** for the LM394 transistor.

The base spreading resistance is effectively in series between the input terminal and the base of the transistor and generates most of the noise within the transistor. Unfortunately the value of base spreading resistance is not normally stated in manufacturers' data sheets and it cannot be measured easily.

This leaves the designer with three options when selecting a transistor for low-noise circuits:

1. Use special transistors designed for low-

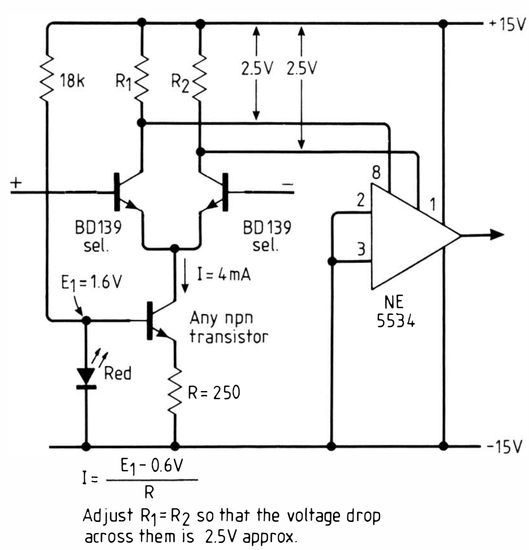


Fig.9. NE5534 op-amp with substituted differential transistor pair for optimum source resistance matching.

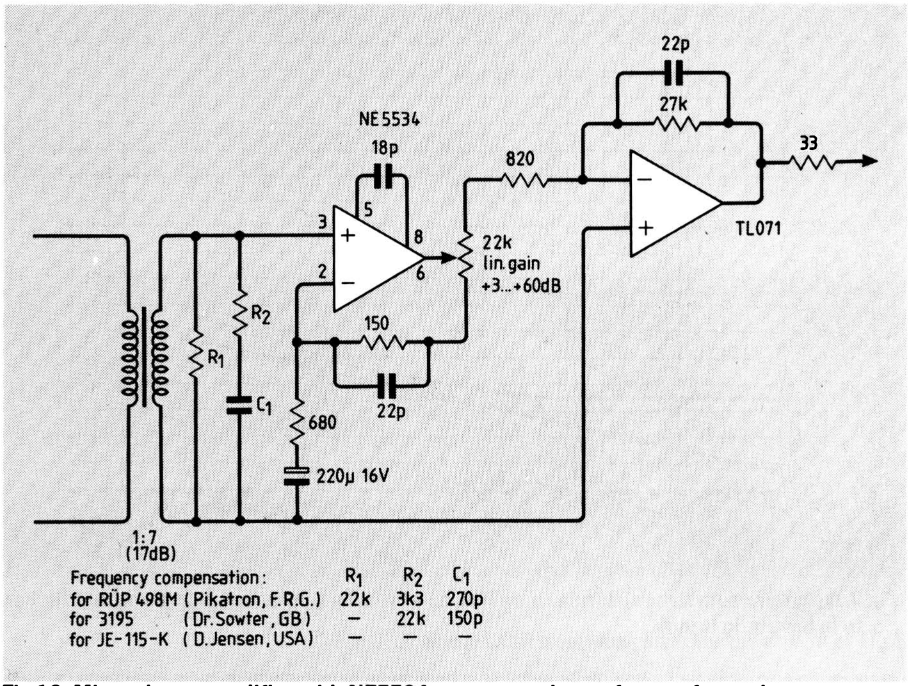


Fig.10. Microphone amplifier with NE5534 op-amp and transformer for optimum source resistance matching.

noise purposes such as the MAT01 (dual)[4], MAT03 (dual)[4], MAT04 (quad)[4], LM394 (dual)[5]. This may be expensive or the devices may be hard to obtain, but the advantage is that one can be sure that these devices are matched and will be essentially free of flicker or popcorn noise, because they have been screened by the manufacturer.

2. Use medium-power RF transistors. By design these transistors exhibit a low value of base spreading resistance, 4-30Ω being common, and they are usually free of flicker and popcorn noise, although it can be worthwhile to check this using the noise measurement circuit outlined above. A good example is the BFW16A with its R_{bb}' of less than 5Ω[6].

3. Use medium-power AF transistors. The familiar BD140 or medium current switching transistors such as the 2N4403[7] will work well because the chip is fairly large, as they are designed to handle currents of around 1A. They therefore exhibit a correspondingly low value of base spreading resistance. They are easily available, but before being used in a low-noise amplifier should be screened individually for low flicker and popcorn noise with the noise measurement circuit.

If the optimum source resistance obtained with one transistor is not low enough, several may be connected in parallel. This method suffers from diminishing returns, because the noise-free gain increases by the factor n, where n is the number of devices in parallel. For example, 50 transistors are paralleled within the LM394. Moreover each transistor may have to be screened for low flicker and popcorn noise. This can become quite unpractical when using a large number of devices per amplifier. Emitter resistors are necessary because transistors exhibit wide tolerances, but this increases noise because any emitter resistors are effectively in series with the input.

Bipolar transistors may be used with optimum source resistances between 3Ω and approximately 10kΩ. If the source resistance is higher it worth considering field-effect transistors. However, bipolar transistors might be preferable even for source resistances where field effect transistors might be used, because bipolar devices have a much lower flicker noise corner frequency of 1Hz to 100Hz; fets exhibit corner frequencies between 100Hz and 1kHz.

Field-effect transistors. If the source resistance is higher than approximately 10kΩ, n-channel field-effect transistors should be used on account of their lower current noise at high input resistances[8]. P-channel fets are noisier than n-channel ones. Here again, special low-noise devices such as J202[9], J203[9], NF5101[10], 2N4867A[10], 2N6483 (dual)[11] may be used although the good old dirty 2N3819 or BF264A will still do the trick, if measured for noise. Modern low-noise fets can be made to work at optimum source impedances as low as 500Ω if you dare (noise corner up to 1kHz).

Mosfets have no place in the front-end of low-noise amplifiers because their optimum source resistance is well above 100MΩ or so[12].

Bipolar, fet and c-mos op-amps. Bipolar op-amps can be selected by the noise voltage quoted in the data sheet and the curve giving the optimum source resistance. The flicker noise corner frequency of bipolar op-amps ranges between 1Hz and 100Hz compared to 100 to 1kHz for fet op-amps. C-mos op-amps also have corner frequencies in the region of 1kHz. With cheaper types of bipolar beware of flicker and popcorn noise. Frequently op-amps are stated to have low noise; this may have been so at the time they were first marketed, or they may be the lowest-noise devices of a quite noisy family.

Low-noise op-amps by today's standards are the LT1028[13], LT1037[14], OP4,[4], OP37[4], ZN459[15], ZN460[15], SSM2016[16] and SSM2134[16]. The NE5534 or the improved LM833 are standard devices for use in many low-noise circuits, although they have to be monitored for noise performance.

Op-amps may be paralleled by summing their outputs, to reduce the value of the optimum source resistance. But this technique suffers from the limitations described above for the paralleling of transistors.

Hybrid devices. There are some very good hybrid or discrete op-amps, such as the Transamp LZ[17], the Matchamp XTX129[18] or the Jensen JE990. The latter is notable for excellent op-amp design[19]. Besides being very low-noise devices with optimum source resistances in the region 200-500Ω, these components have the additional advantage of extended ±24V supply rails, thus increasing dynamic range by a further 6dB or so.

LOW-NOISE CIRCUITS

In designing a low-noise amplifier, the foremost task is to adapt the optimum source resistance of the amplifier (that source resistance at which the amplifier is quietest) to the value of the AC source resistance provided by the transducer. It is usually a good idea to measure the resistance of the source, as manufacturers' data usually states only the DC resistance, which in our case does not help, or some sort of nominal value. Source resistance is best measured by connecting a resistor across the source terminals and determining the resistance value at which the output drops by half. This is preferably done at several frequencies – say 100Hz, 1kHz and 10kHz – within the audio band. The average of these values is taken as the source resistance to which the optimum source resistance of the amplifier is to be matched. The maximum value of the three should be multiplied by 10, giving the input resistance value for which the amplifier has to be designed.

There are three different ways to lower the optimum source resistance of a given amplifier.

• Collector current through the transistor. Let us consider a common dynamic microphone having an average source resistance of 100Ω and a common low noise op-amp with an optimum source resistance of 5kΩ **(Fig.7)**. As **Fig.8** shows, the collector current determines the optimum source resistance of a transistor stage. For the given source resistance the corresponding collector current is around 2mA per transistor. If such a diagram is not at hand, for example when using medium-power transistors whose noise performance is not specified by the manufacturer, the following rule[20] may be applied:

$$I_c = \frac{\sqrt{\beta}}{40 \times R_s}$$

where I_c is the collector current, β is the current gain of the transistor and R_s is the source resistance. The collector current must be within the limits given in the data sheet of the transistor.

One can, of course, place a differential stage running at 2mA per transistor in front of the NE5534, but this creates stability problems. These can be avoided nicely by substituting the input differential pair of the NE5534. This is done by taking the normally used inverting and non-inverting inputs to −15V and feeding the signal from the difference amplifier running at 2mA per transistor into the offset adjustment pins 1 and 8. These are internally connected to the collectors of the now disabled internal differential pair (**Fig.9**). It is also necessary to parallel the internal collector resistors with external resistors so that the collector is maintained at 2.5V.

Resistance values around the op-amp should be made as low as possible to prevent the introduction of additional thermal noise from the feedback resistors. The NE5344 supports this, being capable of driving a 600Ω load without reduced output voltage.

- Paralleling. When going for even lower source resistances, several transistors can be directly paralleled as outlined above. However, to avoid excessive offsets at the output, the transistors should be selected so that each one carries the same current.
- Resistance transformation through a transformer. A transformer converts a low impedance into a high impedance and vice versa. If a low signal source resistance is to be matched to the higher optimum source resistance of an amplifier the required transformer turns ratio is given by

$$n=\sqrt{\frac{R_{opt}}{R_s}}$$

where n is the turns ratio of the transformer, R_s the source resistance and R_{opt} the optimum source resistance of the amplifier. With R_s at 100Ω and R_{opt} at 5kΩ, n=7.

Fig.10 shows the use of a 1:7 step-up transformer with a rather clever circuit[21,22] which allows the gain to be varied over a very wide range of 60dB by a single linear potentiometer, whilst maintaining optimum noise conditions (i.e. first-stage gain is always higher than the gain of the second stage).

Don't be put off by rumours that transformers have a bad reputation. In the days of valves with their high optimum source resistances (30kΩ or more), there was no other way than to use step up transformers with ratios up to 1:20 with consequently nasty frequency response and distortion characteristics, and with less-than-perfect production techniques and materials. However, modern audio transformers are produced using much improved materials and techniques, and excessive step-up ratios are no longer necessary, thanks to the lower optimum source resistance of modern transistors and op-amps.

Inverting summing amplifiers have their particular noise problems, which are due firstly to the unavoidable series input resistor and secondly to the amount of noise gain as defined in **Fig.11**, which shows the circuit of a typical summing amplifier with five inputs. As far as each input is concerned, the gain of this stage is 0dB. But as far as noise gain is concerned there is 14dB of noise gain (2.2kΩ divided by the 440Ω of the five parallel input resistors). This consequently increases the noise level of, say, −110dB to −96dB. So, surprisingly, this stage must be designed for low noise by using, for example, the circuit of Fig.9 as the operational amplifier. What is even worse, the more inputs, the noiser the summing amplifier will be.

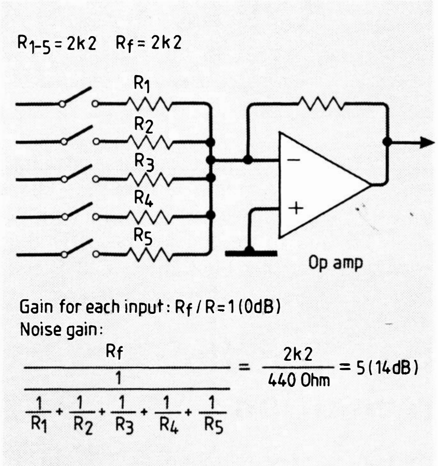


Fig.11. Noise performance of the inverting summing amplifier with five inputs.

TRAPS AND PITFALLS

Besides taking into account the design rules outlined above, you should note some pitfalls to avoid.

Reverse biasing of transistors. During tests with an ohmmeter or while the circuit is being switched off, the transistors may become reverse biased, leading to an increase in flicker and popcorn noise. If, for example, a circuit measures well the first time after it has been switched on and develops noise the next time it is used, it is very likely that the transistors are briefly reverse-biased during switch-off. This fault can be cured only by changing the discharging time constant in question and replacing the front-end transistor.

Power supply noise. Noise can be injected into an otherwise low-noise power amplifier via the power supply. Circuits usually exhibit good power supply noise rejection ratios of typically 120dB at 50 or 100Hz, but values decrease significantly to 20–40dB in the range between 1 and 20kHz. This means, for example, if there is a noise level of −60dBm on the power supply voltages (a value typical for most fixed-value voltage regulators), a noise voltage of −100dBm will appear at the output of the low-noise amplifier, if its power supply rejection ratio is 40dB. So some care must also put into the design of low-noise power supplies. Consequently all types of switching power supply should be avoided in such applications because they cannot be made to run sufficiently quiet. Zener diodes also produce significant amounts of white noise if not properly bypassed with low series-resistance capacitors.

Noise levels of power supply voltages can be measured by connecting the supply voltage via a capacitor to the input of the NE5534 amplifier (Fig.4). Note that in this case 20dB must be subtracted from the calibration values of the stepped gain switch.

Capacitive reactance. When using the input capacitor and input resistor time constant to cut off low-frequency signal components, low-frequency noise is introduced. For example, with a 1μF capacitor and a 10kΩ resistor giving a cut-off frequency of 16Hz, a horribly high series resistance X_r of 8kΩ at 20Hz and still 160Ω at 1kHz is placed in series with the input. This produces considerable amounts of noise. Since the capacitive resistance increases at lower frequencies irrespective of whether you are using foil capacitors or electrolytics, the noise spectrum due to the capacitive reactance is similar to that of flicker noise. Designers have spent many hours, happy and otherwise, finding this one. The only thing to do is to use very large and therefore electrolytic capacitors so as to achieve a cut-off frequency of well below 0.01Hz. Bypass the electrolytics with ceramic capacitors, if you must. Remove any low-frequency signal components after the low-noise amplifier stage.

Spurious oscillations. Be warned that intermodulation products of RF oscillations produced by an unstable amplifier will cause unexpected noise. ■

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