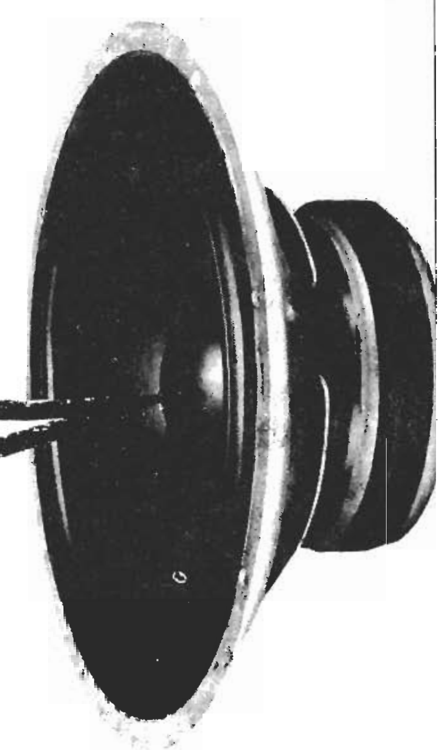
Designer's Notebook



Have you heard... we look at the unwanted sounds in the system and how to manage them.

By Kevin Crabshawe

NOISE, whether you like it or not, is always present in any electronic circuit. By definition, noise is any unwanted signal - so, although in everyday terms, noise is just unwanted sound (say, your next-door neighbour playing his 200-watt-per-channel quadraphonic music system at full steam), in electronics the term noise is used to describe those signals which prevent an electronic circuit or system from doing its required job, perfectly. Examples of noise in electronic circuits and systems are the crackling on a bad telephone line, the hiss from a replayed cassette recording, record surface noise, or 'snow' on a poor-quality television picture.

There are two main types of noise. One of the types, interference, may with safeguards and precautions be reduced to a level which is insignificant and has little or no effect on the circuit or system. We shall be looking at interference in great depth later; its effects, how it occurs, and how to prevent it. Interference is the type of noise which is generally created in an electronic circuit or system by the close proximity of another circuit or system. A good example of interference is the low frequency hum generated by a hifi amplifier. The hum, at a frequency of 60 Hz or 120 Hz, is generated initially within the amplifier because of the close proximity of the amplifier's power supply. The power supply is line-powered and so low-frequency noise at 60 Hz and/or 120Hz (if full-wave rectification takes place in the power supply) is picked up by the amplifier. It is the amplifier's job in life to amplify signals, and so the hum picked-up from the power supply is amplified along the required sound.

This is normally no problem when the sound you want is there, but when it isn't, say, between tracks or when your disk finishes, the hum may be quite noticeable. Some amplifiers use special techniques and methods to reduce the hum produced at the output, so much so that it may be inaudible, but it is always there to some greater or lesser extent.

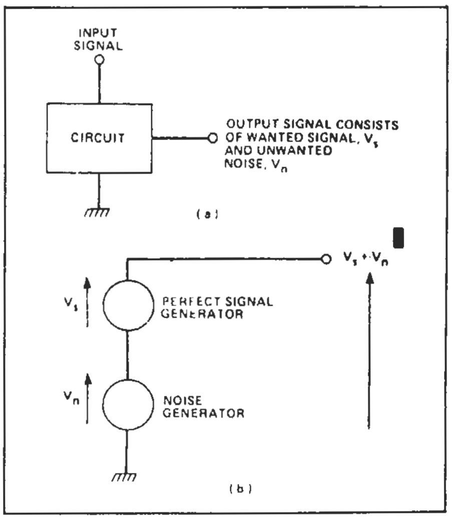


Figure 1a. Block diagram of a circuit generating unwanted noise; 1b shows the same circuit split into noiseless and noise producing sections.

Manmade Noise

Interference noise is, in fact, manmade noise, and because it is manmade it can usually be reduced, It generally has some pattern or form which makes it distinguishable from the other main type of noise - random noise. Random noise (sometimes called fundamental noise) is more difficult to reduce because it is caused by the basic physical properties of the components in the electronic circuit and system themselves, An example of random, fundamental noise is the background hiss which you can hear between pieces of music when listening to your radio. In this example the random noise is produced from two sources: the individual components within the set, and from the sky itself. We'll see how such noise is produced, shortly.

When we discuss noise, it is convenient to consider it as a small, unwanted voltage which is superimposed upon the wanted signal voltage. If, for example, we have a circuit performing a particular task as in Figure 1a, the wanted signal voltage is Vs. This signal voltage may be the output of an audio amplifier used to drive a loudspeaker, or it may be the output voltage of an electron gun driving circuit of a television, or any number of wanted signals.

The unwanted noise voltage, superimposed upon this wanted signal is Vn. The total output of the circuit in Figure 1a is thus Vs plus Vn.

We may, in fact, consider the circuit of Figure 1a to be a noisy circuit or, as is more usual, think of it as being a prefect, noiseless circuit, with a separate noise generator. Figure 1b shows an equivalent circuit to that of Figure 1a, and we can see that a perfect noiseless voltage generator with a series noise voltage generator replaces the noisy circuit. The output of this equivalent circuit, Vs + Vn, is the same as before - only the internal concept differs.

Equivalent circuits are a common method in electronics of representing complex circuits and concepts, often having unknown quantities, by replacing them with known, simple circuits and components which follow the basic electronic laws such as Ohm's law. Although the example in Figure 1b is a simple one, the concept is true of all equivalent circuits, and we will see more complex equivalent circuits soon.

Signal to Noise Ratio

It is often convenient to think of the two voltages, Vs and Vn - the signal voltage and the noise voltage, as a ratio. But the ratio most commonly used, signal-to-noise ratio, is not just a simple ratio of the magnitudes of the voltages; it is a ratio of the powers associated with the voltages. So:

$$\text{signal-to-noise ratio} = \frac{\text{signal power}}{\text{noise power}}$$

The power associated with the two voltages is found by calculating the voltages' mean square value, i.e., the mean of the square value, and dividing this value by the circuit's output resistance such that

$$\text{signal power} = \frac{\overline{V_s^2}}{R}$$

and:

$$\text{noise power} = \frac{\overline{V_n^2}}{R}$$

Note that the line above the square voltages indicates the mean value. We can now define the signal-to-noise ratio as being:

$$\frac{S}{N} = \frac{\frac{\overline{V_s^2}}{R}}{\frac{\overline{V_n^2}}{R}} = \frac{\overline{V_s^2}}{\overline{V_n^2}}$$

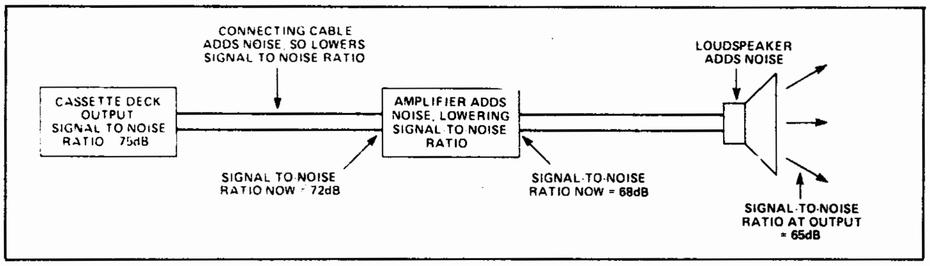


Figure 2. Block diagram of a hifi system, showing the sources of noise.

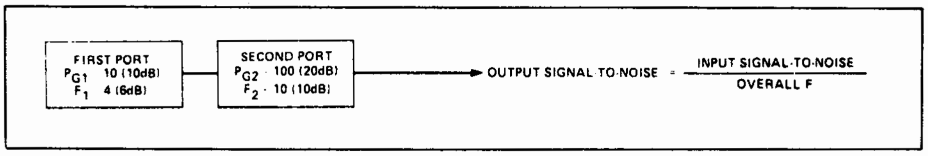


Figure 3. Calculating the noise generated by two sections of a system.

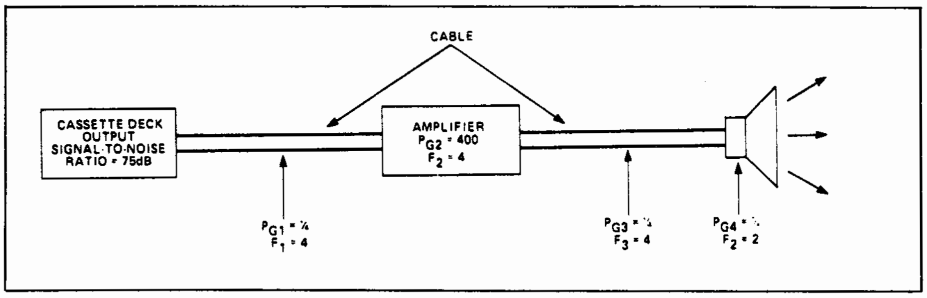


Figure 4. The power gain and noise factor of each of the sections shown in Figure 2.

Because the signal-to-noise ratio is a power ratio it is commonly expressed in decibels, where:

$$\text{signal-to-noise ratio (in dB)} = 10 \log_{10} \frac{S}{N} = 10 \log_{10} \frac{\overline{V_s^2}}{\overline{V_n^2}}$$

Comparing Systems

A signal-to-noise ratio expressed in decibels is very useful if we wish to compare two or more similar systems with regards to their background noise. Good quality sound reproduction, for example, must have a signal-to-noise ratio of around 70dB or so to avoid that irritating hiss between pieces of music. This is the reason why cassette recorders often require some form of noise reduction facility (eg Dolby, dbx), as their basic output signal-to-noise ratio is only around 55dB. Dolby B noise reduction adds approximately 10dB to this ratio, Dolby C a further 10dB, and dbx a still further 10dB.

In comparison a compact disk player has an output signal-to-noise ratio of around 90dB, which means that as far as a listener may detect, there is no noise at all. In reality, there is still noise present. It is simply so much weaker than the signal that it becomes undetectable to the ear.

Such a high output signal-to-noise ratio is not important in other systems: a 40dB ratio will allow a quite acceptable telephone conversation, and a 50dB television aerial signal will allow creation of an excellent picture on the television screen. Obviously, the required signal-to-noise ratio to give acceptable performance depends on the system itself, but the very fact that we know a system's output signal-to-noise ratio means we may compare it with similar systems.

Down the Line

When we combine two systems, or two subsystems, we have to remember that each system or subsystem has an effect on the output signal-to-noise ratio. The total signal-to-noise ratio must therefore be a combination of the individual effects. For example, let's look more closely at an audio system consisting of a cassette deck, amplifier, and loudspeaker, as shown in figure 2. The cassette deck is a good quality type, with Dolby C noise reduction facilities giving an overall signal-to-noise ratio of, say, 75dB. As we know, this is adequate for good quality sound reproduction.

Between the cassette deck and the amplifier is a length of connector, made of wire conductor. Now, you may think this connector cannot affect the overall system's signal-to-noise, but it does. Any length of wire has a definite resistance and so the input of the wire (consisting of a wanted signal and unwanted noise) will be attenuated. The wanted signal will be attenuated the same amount as the unwanted noise. However, the very resistance of the wire will add some extra noise, so the output signal-to-noise ratio of the wire will be lower than the input signal-to-noise ratio. The output signal-to-noise ratio, which forms the input signal-to-noise ratio of the amplifier, will now be say, 72dB.

The amplifier will amplify both wanted signal and unwanted noise by the same amount, depending on volume, tone and other controls. So, the output signal-to-noise ratio of a perfect noiseless amplifier would be the same as the input signal-to-noise ratio. However, as you've guessed, no amplifier is perfect and some extra noise will be added by the very components such as resistors, capacitors, transistors, ICs etc., which form the amplifier. The amplifier's output signal-to-noise ratio is thus lower than its input signal-to-noise ratio and will be, say, 68dB.

In the same way as this, both the connecting wire to the loudspeaker, and the loudspeaker itself, contribute extra noise to the system and the overall signal-to-noise ratio of the whole system may be, say, 65dB.

Of course, the system chosen in this example and the signal-to-noise ratios are all arbitrary. The signal-to-noise ratios in other systems will be very different, but nevertheless the example shows that every part of a system causes a reduction of the signal-to-noise ratios of the signals passing through the system.

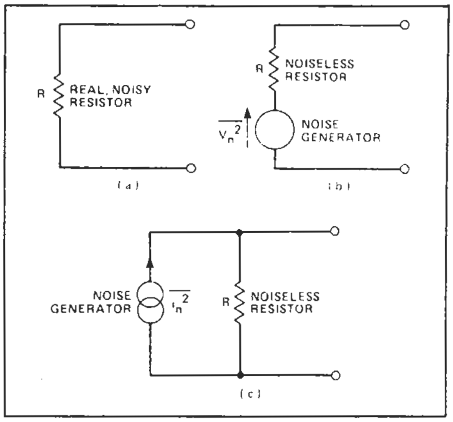


Figure 5. A single resistor, (a) broken down into 'noiseless' and 'noisy' sections (b) and further as a 'noiseless' resistor and a noise current generator.

Calculating S/N

In the previous example the overall signal-to-noise ratio was derived simply by starting with the signal-to-noise ratio of the first subsystem (i.e., the cassette deck) and merely subtracting an arbitrary amount from this quantity for every other subsystem in the system. However, in real life things are not quite that simple, and a few general rules and formulae are required.

First of all, we need to know how much each part of a system reduces the signal-to-noise ratio. This is defined by what is known as the noise factor (and also known as the noise figure). The noise factor is given the symbol F and may be calculated from:

$$F = \frac{\text{input S/N ratio}}{\text{output S/N ratio}}$$

Because the noise factor, like signal-to-noise ratio, is a power ratio, it is commonly given in decibels where:

$$F(\text{dB}) = 10 \log_{10} \frac{\text{input S/N ratio}}{\text{output S/N ratio}}$$

However, as input and output signal-to-noise ratios are almost always given in decibels anyway, the noise factor

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(in decibels) is calculated as F(dB) = input signal-to-noise ratio (dB) minus output signal-to-noise ratio (dB), because division of two numbers is effected by subtracting the logarithms of those two numbers. So, for example, an amplifier with an input signal-to-noise ratio of 70dB and an output signal-to-noise ratio of 65dB has a noise factor of 5dB.

The ideal noise factor of a system or subsystem will occur when the input and output signal-to-noise ratios are equal, and so F = OdB. This ideal noise factor is impossible of course, but noise factors of around 2dB to 10dB are common. The important point is that the lower the noise factor, the better the noise performance of the subsystem.

One final point before we move on to use noise factors in overall system signal-to-noise calculations, is that this idea of noise factor is rather simplified. The actual value of the noise factor depends to an extent on a number of other things, such as temperature, frequency range, and the previous stage's output resistance. However, for our purposes here, and in fact a great many practical purposes, the definition of noise factor given is adequate.

Overall Noise

Once we know each subsystem's noise factor we can begin to calculate the overall signal-to-noise ratio of the system. We do this by first calculating the overall noise factor.

Let's take the example shown in Figure 3 first, which shows two parts of a system connected directly with a small length of wire. The wire has negligible effect on the overall system. The first part of the system has a power gain of 10 (10dB) and a noise factor of 4 (6db). The second part of the system has a power gain of 100 (20dB) and a noise factor of 10 (10dB). Overall noise factor for the system is given by the formula:

$$F = F_1 + \frac{F_2 - 1}{P_{G1}}$$

where: F is the overall noise factor, F1 is the first part's noise factor, F2 is the second part's noise factor, Pg1 is the power gain of the first part. This gives us:

$$F = 4 + \frac{10 - 1}{10}$$

$$= 4.9 \text{ (about 7dB)}$$

We may now calculate the output signal-to-noise ratio if we know the input signal-to-noise ratio, from the formula:

$$F = \frac{\text{input S/N ratio}}{\text{output S/N ratio}}$$

because output S/N ratio = input S/N ratio over F. This procedure may be extended to allow us to calculate the output signal-to-noise ratio of a system with any number of parts, given the power gain and noise factor of each part. The previous example of cassette deck, amplifier and loudspeaker is redrawn in Figure 4, showing each part's power gain and noise factor. Note that the power gain of each connecting cable (and the loudspeaker) is shown as a fraction, because each is, in fact, a loss. They are passive parts which can provide no amplification - only attenuation.

Noise factors of such passive parts are related to the loss in that F = 1/power gain, so that the noise factor of the first connecting cable (ie, between cassette deck and amplifier) is:

$$F_1 = \frac{1}{1/4} = 4$$

Overall noise factor of the system is now calculated by an extended formula:

$$F = F_1 + \frac{F_2 - 1}{P_{G1}} + \frac{F_3 - 1}{P_{G1}\,P_{G2}} + \frac{F_4 - 1}{P_{G1}\,P_{G2}\,P_{G3}}$$

The formula may, in fact, be extended to cover any system of any number of cascaded elements.

Using this formula to calculate noise figure:

$$F = 4 + \frac{4 - 1}{\frac{1}{4}} + \frac{4 - 1}{100} + \frac{2 - 1}{25}$$

$$= 4 + 12 + 0.03 + 0.04$$

$$= 16.07 \ (\approx 12 \text{ dB})$$

Cause of Noise

We have now looked quite closely at how we can calculate noise performance of a system provided we know the noise performance of each part. But, we still don't know what causes the noise in the first place, or where it comes from.

There are three main types of electronic random noise: thermal noise, shot noise, and flicker noise. Others exist but are of only small significance and will not be discussed here. Two of these three types of noise are known as white noise, because the noise occurs evenly at all frequencies. This is, of course, analogous to white light.

Thermal Noise

Thermal noise is often called Johnson noise. It occurs in any component which has resistance - so all components, even capacitors and inductors, produce thermal noise to some extent.

The noise power, Pn, generated by any resistor may be calculated from: Pn = K T B, where K is Boltzmann's constant (1.38 x 10 to the -23 J K to the -1), T is the absolute temperature and B the bandwidth of the system. As the noise is, however, random, we must define this as the average noise power.

We can now find the random noise voltage produced by a particular value of resistor if we remember that P = V2/R. This means that the square of the voltage to be:

$$V^2 = k\,R\,T\,B$$

But, in our earlier calculations of signal-to-noise ratios we used the mean square voltage, Vn2. For our purposes, we may consider the mean square noise voltage to be:

$$\overline{V_n^2} = 4V^2$$

so that:

$$\overline{V_n^2} = 4\,k\,R\,T\,B$$

A real resistor, shown in Figure 5a can thus be represented by an equivalent circuit consisting of a noiseless resistor, and a noise generator producing a mean square noise voltage (Figure 5b).

We could (but won't) go through a similar procedure to define a mean square current of value:

$$\overline{I_n^2} = \frac{4\,k\,T\,B}{R}$$

and represent the real resistor of Figure 5 by an equivalent circuit of an ideal, noiseless resistor with a noise current generator, as shown in Figure 5c.

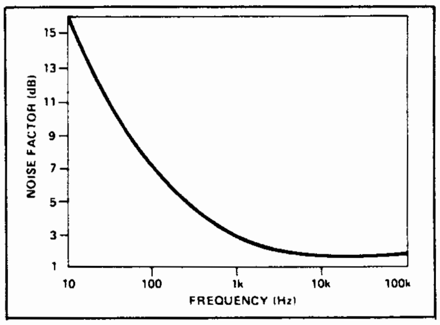

Figure 6. A graph of noise factor against frequency for a typical transistor.

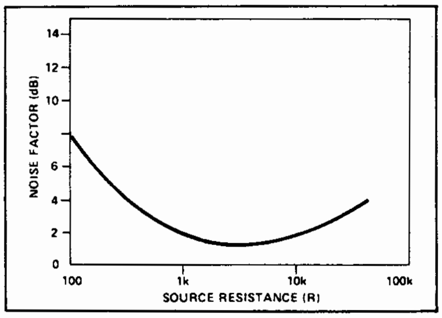

Figure 7. A graph of noise factor against source resistance: the noise can be minimised by the appropriate choice of source resistance values.

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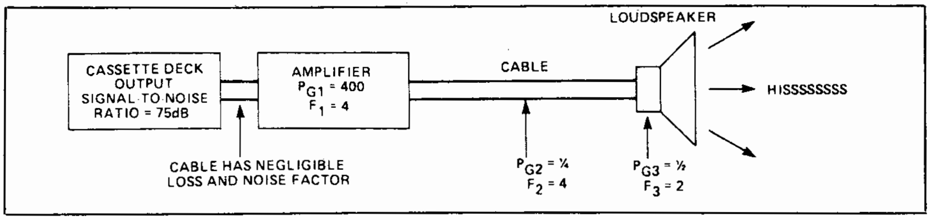

Figure 8. The example of Figure 3, here shown with short, low loss, low noise connections.

Shot Noise

Like thermal noise, shot noise is also a white noise, and so any calculation of it must also be dependent on bandwidth. Unlike thermal noise, however, shot noise occurs only in active devices such as semiconductors. It occurs due to the random nature of the flow of electrons through the semiconductor material.

Generally, shot noise is calculated as a mean square current.

$$\overline{i_n^2} = 2\,e\,I\,B$$

where e is the electron charge 1.6019 x 10–19C, 1 is the DC current flowing and B is the bandwidth.

Flicker Noise

Of relatively minor importance, compared with thermal and shot noise, is flicker noise, which is sometimes called excess noise or 1/f noise. Unlike both thermal and shot noise, flicker noise is not a white noise and, in fact, as one of its names suggests, decreases with increasing frequency.

It is produced in semiconductors and resistors with an applied voltage, but is fortunately not significant in most components above about 1kHz.

In a very approximate way, the mean square noise current of flicker noise may be calculated from:

$$\overline{i_n^2} = \frac{B}{f}$$

where: f is the frequency at which the measurement is taken.

Transistors

We can illustrate the effects of noise in components by looking at a graph of noise factor against frequency for one particular component, for example a transistor. Figure 6 shows such a graph for a typical transistor, which is seen to be level over the range of approximately 1kHz and upwards. Below this, however, the noise factor rises rapidly due to the increased flicker noise.

Figure 7 shows a graph of noise factor against source resistance (ie output resistance of the preceding stage). We can see that noise factor is dependent to a large extent on source resistance, and so, by carefully choosing the resistance value, the noise factor may be optimised to a minimum level.

Getting the Best

With all of these types of noise, and their potential sources (every resistor, capacitor, inductor, transistor, diode in a circuit), it makes you wonder how it is that any circuit can ever work with an acceptable noise performance. After all, most circuits consist of a number of components and if each one has a noise factor of, say, only a few dB, surely the overall noise factor is going to be extremely high. This will mean that no matter how high the input signal–to–noise ratio is, the output signal–to–noise ratio is must be low.

Fortunately, as we shall now see, with careful design this need not be so. Let's take, for an example the system we have already seen, of a cassette deck, amplifier and speaker with lossy connecting leads. We previously calculated that the noise factor is 12dB for the amplifier, speaker and leads. So, if the cassette deck gave an output signal–to–noise ratio, of, say, 75dB (it has Dolby C noise reduction), the output signal–to–noise ratio of the whole system is:

$$75 - 12 = 63\text{dB}$$

which is not high enough for good quality audio reproduction.

However, Figure 8 shows the same system but with the amplifier positioned very close to the cassette deck (in terms of connection length) with a connection of negligible loss and noise factor. We can now recalculate the system noise factor as:

$$F = F_1 + \frac{F_2 - 1}{P_{G1}} + \frac{F_3 - 1}{P_{G1}\,P_{G2}}$$

$$= 4 + \frac{3}{400} + \frac{1}{100}$$

$$= 4.1 \text{ (about 6dB)}$$

which will provide an output signal–to–noise ratio of:

$$75 - 6 = 69\text{dB}$$

just about acceptable for good quality audio reproduction.

This result illustrates that to keep a system's noise factor as low as possible it is vitally important to make sure that the first stage in the system has a high gain. In this way the noise factor formula becomes almost totally dependent on the first term in the formula – the first stage noise factor.

This is one of the reasons why all practical amplifiers have a high-gain, low noise pre-amplifiers as their input stage. ■