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EEE3090F Electronic Devices and Circuits

Noise in Electronic Circuits: Intrinsic Noise

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Intrinsic noise is a random signal generated by the components of the circuit (mainly; resistors, diodes, transistors and amplifiers). The intrinsic noise is associated with the charge transportation and generation-recombination processes in semiconductors and conductors, which can not be eliminated, although its effect can be mitigated through proper circuit design. Therefore, intrinsic noise is associated with random, time dependent electrical variable, such as a voltage, current, and power.

Contents

- Thermal Noise
- Shot Noise
- Flicker Noise
- Signal-to-Noise Ratio (SNR)
- Noise Factor and Noise Figure

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In this lecture, the following are discussed:
-Thermal noise.
-Shot noise.
-Flicker noise.
-Signal-to-Noise Ratio (SNR).
-Noise Factor and Noise Figure.

Thermal Noise

Noise generated in a resistor.

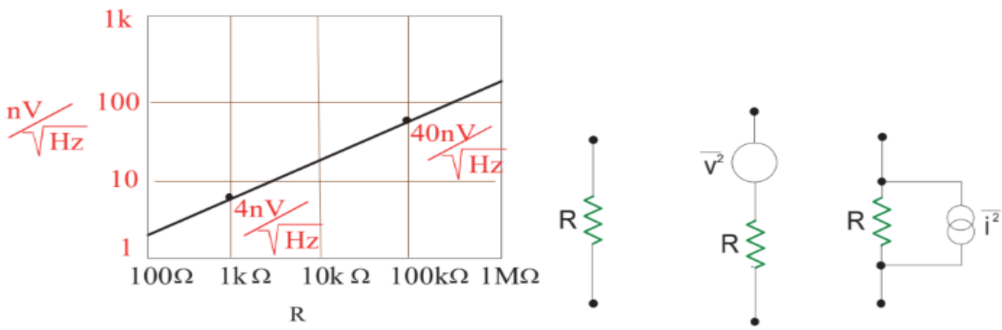

Figure 1: Thermal noise versus resistance value (on the left), thermal noise of a series and parallel resistance representation.

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The noise generated in a resistor is termed thermal or Johnson noise and is produced by the random motion of electrons due to thermal agitation. This random motion does not depend on the presence of a DC current, since the velocity of electrons in a conductor is much lower than the thermal velocity of electrons. Therefore, this phenomenon is very dependent on absolute temperature. Thermal noise is classified as white noise because its noise spectral density is independent of frequency.

Thermal Noise

Thermal noise is a function of temperature and has a mean-square value, open-circuit noise voltage$\left(V_{noise(rms)}\right)$ and thermal noise power (P_{noise}) given by the equation below;

$$V_{noise(rms)} = \sqrt{4kTR(f_2 - f_1)}$$

$$P_{noise} = kT(f_2 - f_1)$$

Where; $k = Boltzmann's\ constant\ (1.38 \times 10^{-23} W.s)$
$T = resistor\ temperature\ in\ degrees\ kelvin (K)$
$R = resistance\ in\ ohms (\Omega)$
$f_2 - f_1 = noise\ bandwidth\ in\ hertz\ (Hz)$

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In a resistor (R), the thermal noise can be modelled by a voltage generator $\left(\overline{V^2}\right)$ in series to its terminal or by a current generator $\left(\overline{I^2}\right)$ in parallel to the resistor as shown in Figure 1. Therefore, $\overline{V^2} = 4kTR(f_2 - f_1)$ as shown in the slide above; while $\overline{I^2} = \frac{4kT(f_2 - f_1)}{R}$.

Thermal Noise

There are three main methods to mitigate thermal noise in a circuit;

- Choice of the resistor
- Operating temperature
- Operating bandwidth

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The noise from a resistor is proportional to its resistance and temperature. It is important not to operate resistors at elevated temperatures in high gain input stages. Lowering resistance values also reduces thermal noise. Therefore, large resistors should not be used as the input resistor of an op amp gain circuit, their thermal noise is amplified by the gain in the circuit. Also, smaller bandwidths would also reduce thermal noise.

Thermal Noise

The noise in a 100 $k\Omega$ input resistor at 25°C (298 K) over the audio frequency range of 20 Hz to 20 kHz is;

$$V_{noise(rms)} = \sqrt{4kTR(f_2 - f_1)} = \sqrt{4 \times (1.38 \times 10^{-23}) \times 298 \times 100k\Omega \times (20{,}000 - 20)}$$

$$V_{noise(rms)} = 5.73\ \mu V$$

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From the worked example above, a reduced resistor value to 1 kΩ (a factor of 100) would reduce the thermal noise significantly. On the other hand, increasing the resistor to 10 MΩ would increase the thermal noise greatly.

Shot Noise

Shot noise is a type of white noise, mainly present in diodes and BJT.

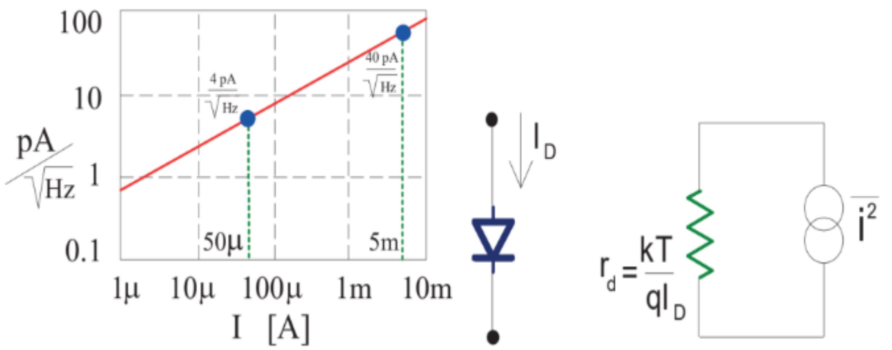

Figure 2: Shot noise versus current value (on the left), with small signal equivalent circuit of a diode, Including the shot noise.

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Shot noise is the result of random current fluctuations in the number of charge carriers when diffused across a semiconductor junction. Therefore, a DC current flowing in a P-N junction have an associated noise with amplitude proportional to the square root of the current itself. However, shot noise is absent in a resistor because the ubiquitous inelastic electron-phonon scattering mitigates current fluctuations that result from the discreteness of the electrons, leaving only thermal noise.

Shot Noise

The rms value of the shot noise current is given by the following equation:

$$I_{noise(rms)} = \sqrt{2qI_d(f_2 - f_1)}$$

Where; $\mathrm{q} = magnitude\ of\ the\ electron\ charge\ (1.6 \times 10^{-19} C)$
$I_d = average\ junction\ current (A)$
$f_2 - f_1 = noise\ bandwidth\ in\ hertz\ (Hz)$

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Flicker Noise

This is present in all active components and some passive devices and its associated with DC current flow.

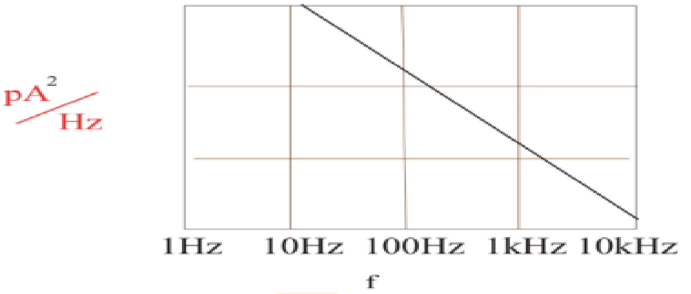

Figure 3:Flicker noise spectral density versus frequency

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Flicker noise is generated due to surface imperfections resulting from the fabrication process. The flicker noise have a power spectrum that decreases with increasing frequency and it is most important at low frequencies (from 0Hz to 100Hz). The drift of transistor amplifiers is as a result of flicker noise. The source of flicker noise varies from one device to another. It is often dependent on the variations of properties with time in devices which are not in thermal equilibrium but are subject to an external disturbance such as signal voltage. For example, a carbon resistor consists of many small granules with contact resistance between them. When a current passes, small random motions of the granules produce changes in the overall resistance, and the voltage across the resistor fluctuates with time.

Flicker Noise

Flicker noise can be expressed by the equation:

$$I_f^2 = kI_d \frac{f_2 - f_1}{f}$$

Where; $k = a\ constant\ of\ the\ semiconductor\ device$
$I_d = average\ junction\ current (A)$
$f_2 - f_1 = noise\ bandwidth\ in\ hertz\ (Hz)$
$f = frequency\ in\ hertz\ (Hz)$

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The spectral distribution is substantially inversely proportional to the frequency as shown in the equation above. Therefore, flicker noise is also called "1/f noise or pink noise", and its contribution is significant at low frequency. Therefore, the main characteristics of flicker noise are; (1) it increases as the frequency decreases, and (2) it is associated with a DC current in electronic devices, as represented in the equation above. Flicker noise is more prominent in FETs, and bulky resistors.

Signal-to-Noise Ratio (SNR)

The SNR is the ratio of the useful signal power to the noise power:

$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{\frac{V_s^2}{R}}{\frac{V_n^2}{R}} = \frac{V_s^2}{V_n^2}$$

Where; $P_{signal} = signal\ power$
$P_{noise} = noise\ power$
$V_S = rms\ signal\ voltage$
$V_n = rms\ noise\ voltage$

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The ratio of the information signal present in the received signal to the noise present is called as **Signal to Noise ratio**. This ratio must be higher for a system so that it produces pure information signal unaffected by the unwanted noise. Therefore, the higher the value of SNR, the greater will be the quality of the received output. SNR is often expressed in decibels (dB) as stated; $SNR_{dB} = 10\log_{10}\left(\frac{P_s}{P_n}\right)$. Some reasonable numbers of SNR (in dB) for circuits are; (1) 10 dB minimum for a good AM radio, (2) 12 dB minimum for a good FM radio, (3) 40 dB minimum for good television and (4) 80 to 100 dB for a good stereo receiver. SNR allows us to represent the quality of a system. For example, a SNR of 0 dB means that the amplitude of the signal and the noise fluctuations are similar; 60 dB means that the rms amplitude of the signal is 1000 times that of the noise.

Signal-to-Noise Ratio (SNR)

What is the SNR of the rms signal voltage of $120mV$ and rms noise voltage is $2.7\mu V$?

$$SNR = \frac{V_s^2}{V_n^2} = \frac{(120 \times 10^{-3})^2}{(2.7 \times 10^{-6})^2} = 1.97 \times 10^9$$

$$SNR_{dB} = 10\log_{10}(1.97 \times 10^9) = 92.9dB$$

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If the rms signal voltage was reduced by half, the SNR in decibels will be reduced to 6 decibels (dB).

Noise Factor

The noise factor of an electronic circuit is defined as the ratio of the signal to noise ratio at the input to the signal to noise ratio at the output of the circuit, as expressed:

$$Noise\ Factor = \frac{SNR_i}{SNR_o} = \frac{\frac{P_{si}}{P_{ni}}}{\frac{P_{so}}{P_{no}}} = \frac{P_{si}}{P_{ni}} \times \frac{P_{no}}{P_{so}}$$

Where; $P_{si} = signal\ input\ power$
$P_{ni} = noise\ input\ power$
$P_{so} = signal\ output\ power$
$P_{no} = noise\ output\ power$
$SNR_i = signal\ to\ noise\ ratio\ at\ the\ input$
$SNR_o = signal\ to\ noise\ ratio\ at\ the\ output$

Since the electronic circuit components such as amplifiers, will add noise, the signal to noise ratio at the output will always be less than that at the input. Therefore, the noise factor will always be greater than unity. The noise factor gives an indication of noise added by the circuit for which the noise factor is calculated. The noise factor is dependent on frequency and it is calculated at one single frequency where it is known as spot noise factor.

Noise Factor

The power gain (P_G) of the circuit is expressed below:

$$P_G = \frac{Signal\ power\ at\ output}{Signal\ power\ at\ input} = \frac{P_{so}}{P_{ni}}$$

$$Noise\ Factor = \frac{P_{si}}{P_{ni}} \times \frac{P_{no}}{P_{so}} = \frac{P_{no}}{P_{ni}} \times \frac{1}{P_G}$$

$$P_{no} = P_{ni} \times Noise\ Factor \times P_G$$

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An average value of the noise factor is calculated over a given frequency range. In this slide, we will present spot noise factor, assuming the frequency is known. The noise power at the input is given as; $P_{ni} = kTB$. Hence, noise power at output is given as; $P_{no} = Noise\ Factor \times P_G \times k \times T \times B$.

Noise Figure

If the noise factor is expressed in decibel (dB), it is known as noise figure of the circuit

$$Noise\ Figure = 10\log(Noise\ Factor)$$

Noise figure is the ratio of signal to noise power at the input to signal to noise power to output in decibel (dB). The amplifier or electronic circuit always add noise. Therefore, the signal to noise ratio at output is always less than that at input. Hence noise figure is always greater than unity.