7.10 Origins and kinds of noise

Since the term *noise* can be applied to anything that obscures a desired signal, noise can itself be another signal ("interference"); most often, however, we use the term to describe "random" noise of a physical (often thermal) origin. Noise can be characterized by its frequency spectrum, its amplitude distribution, and the physical mechanism responsible for its generation. Let's next look at the chief offenders.

Johnson noise

Any old resistor just sitting on the table generates a noise voltage across its terminals known as Johnson noise. It has a flat frequency spectrum, meaning that there is the same noise power in each hertz of frequency (up to some limit, of course). Noise with a flat spectrum is also called "white noise." The actual open-circuit noise voltage generated by a resistance R at temperature T is given by

$$V_{\text{noise}}\,(\text{rms}) = V_{nR} = (4kTRB)^{1/2}$$

where k is Boltzmann's constant, T is the absolute temperature in degrees Kelvin (°K = °C + 273.16), and B is the bandwidth in hertz. Thus V_{noise} (rms) is what you would measure at the output if you drove a perfect noiseless bandpass filter (of bandwidth B) with the voltage generated by a resistor at temperature T. At room temperature (68°F = 20°C = 293°K),

$$4kT = 1.62 \times 10^{-20}\ \text{V}^2/\text{Hz-}\Omega$$
$$(4kTR)^{1/2} = 1.27 \times 10^{-10}\ \text{R}^{1/2}\ \text{V/Hz}^{1/2}$$
$$= 1.27 \times 10^{-4}\ R^{1/2}\ \mu\text{V/Hz}^{1/2}$$

For example, a 10k resistor at room temperature has on open-circuit rms voltage of 1.3μV, measured with a bandwidth of 10kHz (e.g., by placing it across the input of a high-fidelity amplifier and measuring the output with a voltmeter). The source resistance of this noise voltage is just R. Figure 7.26 plots the simple relationship between Johnson noise voltage density (rms voltage per square root bandwidth) and source resistance.

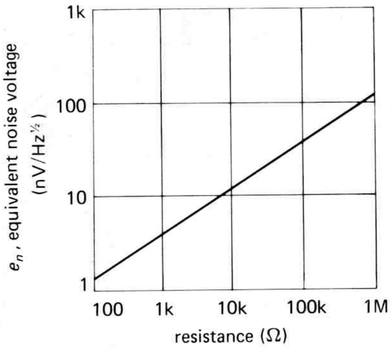

Figure 7.26
Thermal noise voltage versus resistance. (National Semiconductor Corp.)

The amplitude of the Johnson noise voltage at any instant is, in general, unpredictable, but it obeys a Gaussian amplitude distribution (Fig. 7.27), where $p(V)\,dV$ is the probability that the instantaneous voltage lies between V and $V + dV$, and v_n is the rms noise voltage, given earlier.

The significance of Johnson noise is that it sets a lower limit on the noise voltage in any detector, signal source, or amplifier having resistance. The resistive part of a source impedance generates Johnson noise, as do the bias and load resistors of an amplifier. You will see how it all works out shortly.

$$p(V, V+dV) = \frac{1}{V_n\sqrt{2\pi}}\, e^{-\left(\frac{V^2}{2V_n^2}\right)}\, dV \quad \text{where } V_n \text{ is rms noise}$$

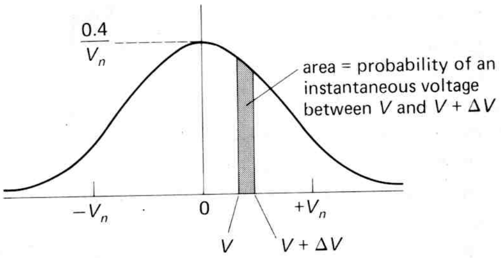

Figure 7.27

It is interesting to note that the physical analog of resistance (any mechanism of energy loss in a physical system, e.g., viscous friction acting on small particles in a liquid) has associated with it fluctuations in the associated physical quantity (in this case, the particles' velocity, manifest as the chaotic Brownian motion). Johnson noise is just a special case of this fluctuation-dissipation phenomenon.

Johnson noise should not be confused with the additional noise voltage created by the effect of resistance fluctuations when an externally applied current flows through a resistor. This "excess noise" has a $1/f$ spectrum (approximately) and is heavily dependent on the actual construction of the resistor. We will talk about it later.

Shot noise

An electric current is the flow of discrete electric charges, not a smooth fluidlike flow. The finiteness of the charge quantum results in statistical fluctuations of the current, given by

$$I_{\text{noise}}\,(\text{rms}) = I_{nR} = (2qI_{dc}B)^{1/2}$$

where q is the electron charge (1.60×10^{-19} coulomb) and B is the measurement bandwidth. For example, a "steady" current of 1 amp actually has an rms fluctuation of 57nA, measured in a 10kHz bandwidth; i.e., it fluctuates by about 0.000006%. The relative fluctuations are larger for smaller currents: A "steady" current of 1μA actually has an rms current noise fluctuation, measured over a 10kHz bandwidth, of 0.006%, i.e., −85dB. At 1pA dc, the rms current fluctuation (same bandwidth) is 56fA, i.e. a 5.6% variation! Shot noise is "rain on a tin roof." This noise, like resistor Johnson noise, is Gaussian and white.

1/f Noise (flicker noise)

Shot noise and Johnson noise are irreducible forms of noise generated according to physical principles. The most expensive and most carefully made resistor has exactly the same Johnson noise as the cheapest carbon resistor (of the same resistance). Real devices have, in addition, various sources of "excess noise." Real resistors suffer from fluctuations in resistance, generating an additional noise voltage (which adds to the ever-present Johnson noise) proportional to the dc current flowing through them. This noise depends on many factors having to do with the construction of the particular resistor, including the resistive material and especially the end-cap connections. Here is a listing of typical excess noise for various resistor types, given as rms microvolts per volt applied across the resistor, measured over one decade of frequency:

Carbon-composition	0.10μV to 3.0μV
Carbon-film	0.05μV to 0.3μV
Metal-film	0.02μV to 0.2μV
Wire-wound	0.01μV to 0.2μV

This noise has approximately a $1/f$ spectrum (equal power per decade of frequency) and is sometimes called "pink noise." Other noise-generating mechanisms often produce $1/f$ noise, examples being base current noise in transistors and cathode current noise in vacuum tubes. Curiously enough, $1/f$ noise is present in nature in unexpected places, e.g., the speed of ocean currents, the flow of sand in an hourglass, the flow of traffic on Japanese expressways, and the yearly flow of the Nile measured over the last 2000 years. If you plot the loudness of a piece of classical music versus time, you get a $1/f$ spectrum! No unifying principle has been found for all the $1/f$ noise that seems to be swirling around us, although particular sources can often be identified in each instance.

Interference

As we mentioned earlier, an interfering signal or stray pickup constitutes a form of noise. Here the spectrum and amplitude characteristics depend on the interfering signal. For example, 60Hz pickup has a sharp spectrum and relatively constant amplitude, whereas car ignition noise, lightning, and other impulsive interferences are broad in spectrum and spiky in amplitude. Other sources of interference are radio and television stations (a particularly serious problem near large cities), nearby electrical equipment, motors and elevators, subways, switching regulators, and television sets. In a slightly different guise you have the same sort of problem generated by anything that puts a signal into the parameter you are measuring. For example, an optical interferometer is susceptible to vibration, and a sensitive radiofrequency measurement (e.g., NMR) can be affected by ambient radiofrequency signals. Many circuits, as well as detectors and even cables, are sensitive to