The amplitude distribution of thermal noise is again Gaussian. Since both shot and thermal noise each have a flat frequency spectrum and a Gaussian amplitude distribution, they are indistinguishable once they are introduced into a circuit. The waveform of shot and thermal noise combined with a sinewave of equal power is shown in Fig. 11.21.

11.2.3 Flicker Noise[6,7,8] (1/*f* Noise)

This is a type of noise found in all active devices, as well as in some discrete passive elements such as carbon resistors. The origins of flicker noise are varied, but it is caused mainly by traps associated with contamination and crystal defects. These traps capture and release carriers in a random fashion and the time constants associated with the process give rise to a noise signal with energy concentrated at low frequencies.

Flicker noise, which is always associated with a flow of direct current, displays a spectral density of the form

$$\overline{i^2} = K_1 \frac{I^a}{f^b} \Delta f \tag{11.7}$$

where

Δf = small bandwidth at frequency f
I = direct current
K_1 = constant for a particular device
a = constant in the range 0.5 to 2
b = constant of about unity

If $b = 1$ in (11.7), the noise spectral density has a $1/f$ frequency dependence (hence the alternative name $1/f$ *noise*), as shown in Fig. 11.8. It is apparent that flicker noise is most significant at low frequencies, although in devices exhibiting high flicker noise levels, this noise source may dominate the device noise at frequencies well into the megahertz range.

It was noted above that flicker noise only exists in association with a direct current. Thus, in the case of carbon resistors, no flicker noise is present until a direct current is passed through the resistor (however, *thermal* noise *always* exists in the resistor and is *unaffected* by any direct current as long as the temperature remains constant). Consequently, carbon resistors can be used if required as external elements in low-noise, low-frequency integrated circuits as long as they carry no direct current. If the external resistors for such circuits must carry direct current, however, metal film resistors that have no flicker noise should be used.

In earlier sections of this chapter, we saw that shot and thermal noise signals have well-defined mean-square values that can be expressed in terms of current flow, resistance, and a

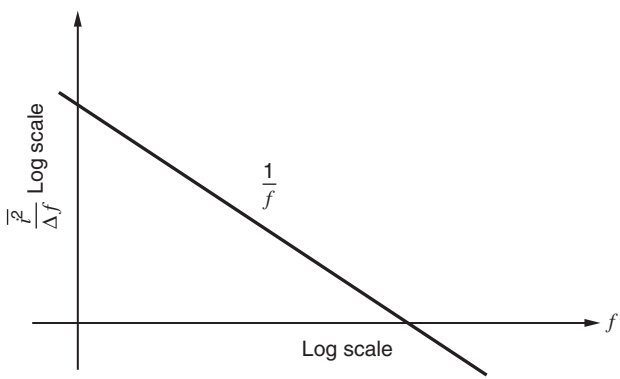

Figure 11.8 Flicker noise spectral density versus frequency.