11.5.2 Perception of Phase and Time Differences

The Fourier analysis in Equation (3.17a) produces a complex spectrum, which can be presented in polar coordinates using the magnitude and phase

$$\mathcal{F}\{x(t)\} = \mathrm{Re}\,\{X(\omega)\} + \mathrm{j}\,\mathrm{Im}\,\{X(\omega)\} = |X(\omega)|e^{\mathrm{j}\varphi(\omega)}. \tag{11.7}$$

The phase $\varphi(\omega)$ is mathematically problematic, since if it is computed from

$$\varphi(\omega) = \arctan[\mathrm{Im}\,\{X(\omega)\}\,/\,\mathrm{Re}\,\{X(\omega)\}] \tag{11.8}$$

the result is wrapped discontinuously between 0 and 2π. To obtain a continuous function of phase, it has to be *unwrapped*, which is numerically a critical operation and can lead to errors with a magnitude of 2π or its multiples.

The capability of the phase spectrum of sound to transmit information between humans in typical acoustic conditions is now discussed. As an example, the signals in Figure 11.9 have equal magnitude spectra but different phase spectra. In principle, such a prominent change in the temporal structure of the signal could be used to encode some meaning into communicated sounds, such as speech sounds. However, real listening conditions with a relatively distant source contain at least some reflections from nearby surfaces and potentially some reverberation. The impulse response of such a space corresponds to a very complex transfer function,

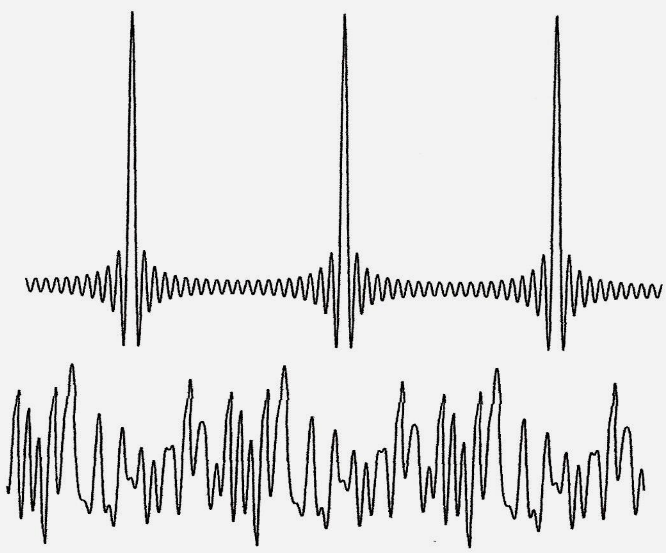

Figure 11.9 Two signals with 40 harmonic partials with identical magnitude spectra. In the upper signal, the phases of the harmonics are synchronized so that the partials have their maxima at the same temporal position. Correspondingly, the phases of the partials are randomly set in the lower signal.

which skews the phase spectrum to almost a random form. Thus, in practice, if the source emitted a signal such as in the upper panel of Figure 11.9, the signal reaching the receiver in a room outside the reverberation radius of the source would look something like the signal in the lower panel. It is thus natural that hearing has developed to be almost immune to phase, although some sensitivity to it exists. In 1843, Georg Ohm proposed that hearing measures the characteristics of a sound as the strengths of its partials and disregards the phase relations between them, which is known as Ohm's acoustic law. This is not completely true, as will be discussed below.

Such insensitivity to phase can often be assumed, although it has been shown that in some cases the phase and a modification of the phase have a prominent effect on perception. In fact, if the signals in Figure 11.9 are listened to with headphones or with loudspeakers closeby (without the effect of the room), a clear difference is perceived. In the upper panel, all partials of the harmonic complex have their maxima aligned at some temporal position, resulting in a prominent, repetitive peak at corresponding positions. In the lower panel, the phase relationships of the harmonics are random, and no such 'peakiness' is seen. The first signal is sharper; that is, it is perceived to have more energy at high frequencies. In addition, the tonal character of such sound has been called 'buzzy' (Moore, 2002), or as having high 'buzzyness' (Laitinen *et al.*, 2013), referring to a low vibrating sound like that of a bee.