are used in similar situations, but because of the greater delay between copies of the sound and corresponding perception of multiple instruments, chorus is somewhat less likely to be used on complex audio sources such an entire mix.

Chorus

In music, the chorus effect occurs when several individual sounds with similar pitch and timbre play in unison. This phenomenon occurs naturally with a group of singers or violinists, who will always exhibit slight variations in pitch and timing, even when playing in unison. These slight variations are crucial to producing the lush or shimmering sound we are accustomed to hearing from large choirs or string sections. The chorus audio effect simulates these timing and pitch variations, making a single instrument source sound as if there were several instruments playing together.

Theory

Basic Chorus

Figure 2.16 shows a block diagram of a basic chorus, in which a delayed copy of the input signal is mixed with the original. As with the flanger and vibrato effect, the delay length varies with time (modulated delay line). The input/output relationship can be written as

$$y[n] = x[n] + gx\big[n - M[n]\big] \tag{2.29}$$

Notice that this formula is identical to the basic flanger presented in the previous section. In general, the chorus effect is nearly identical to the flanger, using the same structure with different parameters. The main difference is the *delay length*, which in a chorus is usually between 20 and 30 ms, in

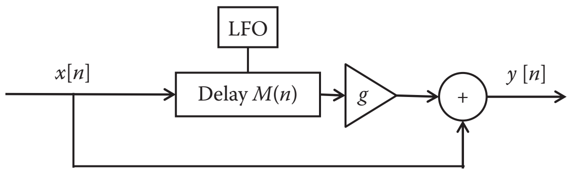

FIGURE 2.16
The flow diagram for the chorus effect including its LFO dependence. The delay changes with time.

contrast to delays between 1 and 10 ms in the flanger. We saw previously that the flanger produces patterns of *constructive* and *destructive interference*, resulting in a frequency response characterized by evenly spaced peaks and notches:

$$\left|H(e^{j\omega})\right| = \sqrt{1 + 2g\cos\left(\omega M[n]\right) + g^2} \tag{2.30}$$

with the peaks (points of maximum frequency response) located at

$$\omega_p = 2\pi p/M \quad \text{where} \quad p = 0, 1, 2, \ldots, M-1 \tag{2.31}$$

and the notches (minimum frequency response) at

$$\omega_n = (2n+1)\pi/M \quad \text{where} \quad n = 0, 1, 2, \ldots, M-1 \tag{2.32}$$

Thus, the *comb filtering* produced by the flanger also occurs in the chorus. However, the longer delay $M[n]$ substantially alters its perceived effect. At a sample rate of 48 kHz, a 30 ms delay corresponds to $M = 1440$ samples. There will therefore be 1440 peaks and 1440 notches in the frequency response, each located at intervals of f_s/M (recalling that $\omega = 2\pi$ corresponds to the sampling frequency f_s). Thus, a peak will occur every 33.3 Hz, with notches likewise spaced every 33.3 Hz. These are close enough together that the characteristic sweeping timbre of the flanger is no longer perceptible. In particular, any sense that the comb filter has a definite pitch (owing to its regularly spaced peaks) will be lost at such close spacing. Nonetheless, though the sound is different from the flanger, this comb filtering is an important part of the sonic signature of the chorus effect.

Considered a different way, a delay on the order of 20–30 ms begins to approach the threshold where two separate sonic events can be perceived, though a clear perception of an echo requires a longer delay still (100 ms or more). So the chorus can also be heard as two separate copies of the same sound, whose exact timing relationship changes over time as $M[n]$ changes. Both understandings are mathematically correct; the only difference lies in human audio perception.

Low-Frequency Oscillator

In the chorus, as in the flanger, the delay length $M[n]$ varies under the control of a low-frequency oscillator. Several waveforms can be used for the LFO, with sinusoids being the most common. In comparison to the flanger, slower LFO sweep rates (3 Hz or less) but higher LFO sweep widths (5 ms or more) are typically used. As with all modulated delay effects, interpolation is used to calculate the output of the delay line whenever $M[n]$ is not an integer.

Pitch-Shifting in the Chorus

The wider sweep width (delay variation) in the chorus has an important consequence on the pitch of the delayed sound. As was shown for the vibrato effect, changing the length of a delay line introduces a *pitch shift* into its output, where lengthening the delay scales all frequencies in a signal down, and reducing the delay scales them up. Recall the formula for pitch shift as a function of LFO frequency f, sweep width W, and sample rate f_s:

$$f_{ratio}[n] \approx 1 - 2\pi f W \cos\left(2\pi n f / f_s\right) \tag{2.33}$$

Given that the cosine function ranges from –1 to 1, we can find the maximum pitch shift for any given set of parameters as

$$f_{ratio,\max} = 1 + 2\pi f W \tag{2.34}$$

For $f = 1$ Hz and sweep width $W = 10$ ms, this results in a pitch ratio of 1.063 (6.3% variation), slightly more than a semitone (5.9%) in either direction. This is a noticeable amount of tuning variation between the original and delayed copies of the signal, which can simulate and even exaggerate the natural variation in pitch between musicians playing in unison. Note that in comparison to the vibrato effect, the chorus mixes the original and delayed copies, so a single pitch shift is not heard.

Multivoice Chorus

The basic chorus can be considered a *single-voice chorus* in that it adds a single delayed copy to the original signal. A *multivoice chorus*, by contrast, involves several delayed copies of the input signal mixed together, with each delayed copy moving independently. Figure 2.17 shows a diagram for an arrangement with two delayed copies (*dual voice*). Each individual voice can be analyzed identically to the basic chorus described in the preceding sections, but the sum total of all voices will produce a more complex, richer tone suggest-

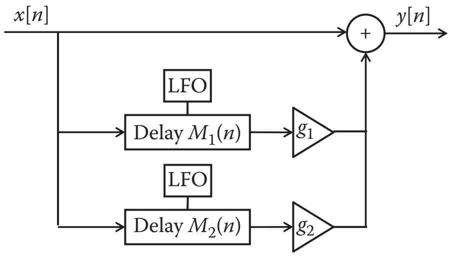

FIGURE 2.17
A multivoice chorus diagram.

ing multiple instruments played in unison. The "Implementation" section below discusses control strategies for the voices in a multivoice chorus.

Stereo Chorus

Stereo chorus is a variation on multivoice chorus, where each delayed copy of the signal is panned to a different location in the stereo field. When two voices are used, the delayed signals are typically panned completely to the left and right, with the original signal in the center. In this case, the two voices are usually run in quadrature phase: each LFO has the same sweep rate and same sweep width, but they differ in phase by 90°. When more than two voices are used, they may be spread evenly across the stereo field or split into two groups, with one group panned hard left and the other group panned hard right.

Properties

The chorus is implemented identically to a flanger without feedback, so it shares the same properties. Notably, since delay and mixing are linear operations, the chorus is a linear effect (for any number of voices). The delay $M[n]$ changes over time under the control of the LFO, so the chorus is a time-variant effect: an input signal applied at one time may produce a different result than the same signal applied at a different time if the LFO phase differs. Since the chorus never involves feedback, it is always stable, with a bounded input producing a bounded output.

Common Parameters

Chorus effects have several user-adjustable controls.

Depth (or Mix)

As with the flanger, the depth controls affect the amount of delayed signal(s) that are mixed in with the original. $g = 0$ produces no effect, whereas $g = 1$ produces the most pronounced chorus effect. Higher depth settings ($g > 1$) make the delayed copies louder than the original, a setting rarely found in practice as it produces a weaker chorus effect than $g = 1$. Some simple chorus effects may not have this control (always setting g to 1). Confusingly, the term *depth* is also sometimes used to refer to sweep width, or the amount of variation in the delay. When examining an existing chorus effect, it is thus important to find out what the depth control means.

Delay and Sweep Width

The *delay* parameter on the chorus controls the minimum amount of delay $M[n]$. Typical values are on the order of 20 to 30 ms, and this setting represents one of the primary differences between flanger and chorus. The *sweep width* (which is sometimes called *sweep depth*, but should not be confused with *depth/mix*) controls the amount of additional delay added by the LFO. In other words, sweep width controls the amplitude of the LFO, and the maximum delay is given by the sum of delay and sweep width. The relationship between the delay and sweep width parameters is depicted in Figure 2.15. Typical values for sweep width range from 1–2 to 10 ms or more. A larger sweep width will result in more pitch, creating a warbling effect, whereas changing the delay parameter will not affect the pitch modulation.

Speed and Waveform

As in the flanger, the *speed* (or *sweep rate*) sets the number of cycles per second of the LFO controlling the delay time. In addition to producing a more quickly oscillating chorus effect, higher speed will produce more pronounced pitch modulation for the same sweep width, since the delay line length will be changing more quickly over time. Typical values in the chorus are slower than in the flanger, ranging from roughly 0.1 to 3 Hz.

The *waveform* control selects one of several predefined LFO waveforms, including sine, triangle, sawtooth, or exponential (triangular in log frequency). In addition to controlling how the voices move in time, each waveform will affect the type of pitch modulation. For example, the derivative of a sine wave is a cosine, which is always changing, so the pitch is always changing as well. A triangular waveform, though, has only two discrete slopes, so the pitch will jump back and forth between two fixed values. Many chorus effects do not offer a waveform parameter and always use a sine LFO. As with the flanger, this results in a total delay $M[n]$ given by

$$M[n] = M_0 + \frac{M_W}{2}\left(1 + \sin\left(2\pi f_{LFO} n / f_s\right)\right) \tag{2.35}$$

where M_0 (in samples) is given by the *delay* control, M_W (in samples) is given by the *sweep width* control, f_{LFO} (in Hertz) is given by the speed control, and f_s (in Hertz) is the sampling frequency. $M[n]$ thus varies from M_0 to $M_0 + M_W$.

Number of Voices

As discussed in the previous section, a multivoice chorus uses more than one delayed copy of the input sound, simulating the effect of more than two instruments being played in unison. Many chorus units give the option of choosing the number of voices. In a simple implementation, each voice could be controlled by the same LFO, but with a different phase. The delay time will be different for each voice since they are at different points in the waveform, but they will remain synchronized to one another over time. More complex implementations can use different LFO waveforms and speeds for each voice.