This article, the fourth in a series on phase-locked loops, is about a tone and frequency decoder monolithic integrated circuit. The tone decoder IC contains a stable phase-locked loop and a transistor switch that produces a grounded squarewave when a selected tone is introduced at its input. Tone decoders can decode tones at various frequencies. For example, it can detect telephone Touch Tones. The tone-decoder ICs are also found in communications pagers, frequency monitors and controllers, precision oscillators, and telemetry decoders.

The last three articles in this series explained the basic operating principles of the phase-locked loop and then went on to examine popular PLL ICs. Those included the Harris CD4046B PLL IC, the Philips (formerly Signetics) NE565 PLL IC, and the NE566 function generator IC.

This article is based on the Philips NE567 tone decoder/phase-locked loop. The device is a low-cost commercial version of the 567 packaged in an eight-pin plastic DIP. Figure 1 shows the pin configuration of that package, and Fig. 2 shows the internal block diagram of the device. It can be seen that its principal blocks are the phase-locked loop, a quadrature phase detector, an amplifier, and an output transistor. The phase-locked loop block contains a current-controlled oscillator (CCO), a phase detector and a feedback filter.

The Philips NE567 has an operating temperature range of 0 to +70°F. Its electrical characteristics are nearly identical to those of the Philips SE567, which has an operating temperature range of −55 to +125°F. However, the 567 has been accepted as an industry standard tone decoder, and it is alternate-
sourced by many other multinational semiconductor integrated circuit manufacturers.

For example, Analog Devices offers three versions of its AD567; Exar offers five versions of its XR567, and National Semiconductor offers three versions of its LM567. All of the different brands and models of this device will work in the circuits described in this article. Because of the similarities between these devices, they will be referred to collectively as the “567” for the remainder of this tone decoder article.

The 567 basics

The 567 is primarily used as a low-voltage power switch that turns on whenever it receives a sustained input tone within a narrow range of selected frequency values. Stated in another way, the 567 can function as a precision tone-operated switch.

The versatile 567 can also function as either a variable waveform generator or as a conventional PLL circuit. When it is organized as a tone-operated switch, its detection center frequency can be set at any value from 0.1 to 500 kHz, and its detection bandwidth can be set at any value up to a maximum of 14% of its center frequency. Also, its output switching delay can be varied over a wide time range by the selection of external resistors and capacitors.

The current-controlled oscillator of the 567 can be varied over a wide frequency range with external resistor R1 and capacitor C1, but the oscillator can be controlled only over a very narrow range (a maximum of about 14% of the free-running value) by signals at pin 2. As a result, the PLL circuit can “lock” only to a very narrow range of preset input frequency values.

The 567’s quadrature phase detector compares the relative frequencies and phases of the input signal and the oscillator output. It produces a valid output waveforms at pins 5 and 6.
TABLE 1—ELECTRICAL CHARACTERISTICS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>CONDITIONS</th>
<th>NE567</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CENTER OF FREQUENCY</strong></td>
<td><strong>NE567</strong></td>
<td><strong>UNIT</strong></td>
</tr>
<tr>
<td>Highest center frequency ($f_o$)</td>
<td>-55 to +125°C</td>
<td>Min</td>
</tr>
<tr>
<td>Center frequency stability</td>
<td>0 to +70°C</td>
<td>Typ</td>
</tr>
<tr>
<td>Center frequency distribution</td>
<td>-10</td>
<td>Max</td>
</tr>
<tr>
<td>Center frequency shift with supply voltage</td>
<td>0.1</td>
<td>%/V</td>
</tr>
</tbody>
</table>

| **DETECTION BANDWIDTH**   | **NE567**  | **UNIT**|
| Largest detection bandwidth | 10 | % of $f_o$ |
| Largest detection bandwidth skew | 3 | % of $f_o$ |
| Largest detection bandwidth—variation with temperature | ±0.1 | %/°C |
| Largest detection bandwidth—variation with temperature | Vt = 300mVrms | ±2 | %/°C |

| **INPUT**                  | **NE567**  | **UNIT**|
| Input resistance | 15 | 20 | 25 kΩ |
| Smallest detectable input voltage | $I_L = 100$mA | 20 | 25 mVrms |
| Largest no-output input voltage | $I_L = 100$mA | 10 | 15 mVrms |
| Greatest simultaneous output signal to inband signal ratio | 2 | dB |
| Minimum input signal to wideband noise ratio | $B_n = 140$kHz | -6 | dB |

| **OUTPUT**                 | **NE567**  | **UNIT**|
| Fastest on-off cycling rate | $f_o/20$ | |
| "1" output leakage current | $V_o = 15$V | 25 | 0.01 μA |
| "0" output voltage | $I_L = 30$mA | 0.2 | 0.4 V |
| Output fall time | $R_L = 50$Ω | 30 | ns |
| Output rise time | $R_L = 50$Ω | 150 | ns |

| **GENERAL**                | **NE567**  |
| Operating voltage range | 4.75 | 9.0 V |
| Supply current quiescent | 7 | 10 mA |
| Supply current—activated | $R_L = 20$Ω | 12 | 15 mA |
| Quiescent power dissipation | 35 | mW |

The input-drive signal (which turns transistor Q1 on) only when these two signals coincide (i.e., when the PLL is locked). The center frequency of the 567 tone switch is equal to its free-running oscillator frequency, and its bandwidth is equal to the lock range of the PLL.

Figure 3 shows the basic connections for a 567 organized as a tone switch. The input tone signal is AC coupled through capacitor C4 to pin 3, which has an input impedance of about 20 kilohms. An external output load resistor ($R_o$) is inserted between pin 8 and a positive supply voltage whose maximum value is 15 volts.

Pin 8 is capable of sinking up to 100-milliampere load currents. Pin 7 is normally grounded, and pin 4 is connected to a positive supply with a minimum value of 4.75 volts and a maximum value of 9 volts. Pin 8 can also be connected to the same power source if that restriction is observed.

The center frequency ($f_o$) of the oscillator can be determined by the formula:

$$f_o = \frac{1.1}{R1 \times C1}$$

Where resistance is in kilohms and capacitance is in units of microfarads.

From this equation the value of capacitor $C1$ can be determined by transposing terms:

$$C1 = \frac{1.1}{f_o \times R1}$$

With these formulas, values for resistance and capacitance can be determined. The value of resistor $R1$, which should be in the range of 2 to 20 kilohms, and $C1$ can be determined from formula 2.

The oscillator generates an exponential sawtooth waveform that is available at pin 6 and a square waveform that is available at pin 5. The bandwidth of the tone switch (and thus the lock range of the PLL) is determined by $C2$ and a 3.9 kilohm resistor within the IC. The output switching delay of the circuit is determined by the value of $C3$ and a resistor within the IC. Table 1 lists the electrical characteristics of the Philips NE567 which has nearly identical characteristics to all other brands of the 567.
to-peak amplitude equal to the supply voltage value minus 1.4 volts. It can be externally loaded by any resistance value greater that 1 kilohm without adversely affecting the circuit's function. Alternatively, the squarewave output can be applied (in slightly degraded form) to a low impedance load (at peak currents up to 100 milliamperes at pin 8 output terminal, as shown in Fig. 5).

By applying formulas 1 and 2 for oscillator frequency and capacitance, respectively, as presented earlier, various values can be determined. Again, R1 must be restricted to the 2 to 20 kilohm range. To save time in making this determination, component values as they relate to oscillator frequency can be read directly from the nomograph, Fig. 6.

For example, if you want the decoder's oscillator to operate a 10 kHz, the values for C1 and R1 could be either 0.055 microfarads and 2 kilohms or 0.0055 microfarads and 20 kilohms, respectively.

Oscillator design

Figures 4 and 5 illustrate how to obtain various precision squarewave outputs from the 567. The nonlinear ramp waveform available at pin 6 has only limited usefulness, but the squarewave available at pin 5 has excellent characteristics. As shown in Fig. 4, that output can have both 20-nanosecond rise and fall times.

This squarewave has a peak-to-peak amplitude equal to the supply voltage value minus 1.4 volts. It can be externally loaded by any resistance value greater that 1 kilohm without adversely affecting the circuit's function. Alternatively, the squarewave output can be applied (in slightly degraded form) to a low impedance load (at peak currents up to 100 milliamperes at pin 8 output terminal, as shown in Fig. 5).

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The oscillator's frequency can be shifted over a narrow range of a few percent with a control voltage applied to pin 2 of the 567. If this voltage is applied, pin 2 should be decoupled by
dress DIP switches open, address zero with all eight switches closed, or anything in between. Regardless of the address you select, be sure to set the same address on the receiver/decoder board.

Apply power to the receiver and connect a 9-volt battery to the transmitter. Test the training transmitter and receiver by aiming the transmitter at the receiver and pressing the transmit switch. If the circuit is working correctly, the valid transmission LED on the receiver will light up as long as you hold down the transmit switch. The vt LED should light regardless of the settings of the DATA DIP switches (S2 a–d). If the LED does not light, find and repair the mistake.

Follow the manufacturer's instructions for programming the learning remote. Operate the training transmitter as you would any other remote control. As discussed earlier, the power-on command is decoded by the receiver as decimal 15. But, because the training transmitter understands only BCD, set all four data DIP switches at logic high (1111).

Now activate the learning remote's learning mode, press the on button, and press the transmit button on the training transmitter until the learning remote indicates that it has received the command. Next set the mute function as decimal 14 (1110), volume-up as decimal 13 (1101), and volume-down as 12 (1100).

How you program the remaining 12 receiver command codes is your choice. You might want to map 0 through 9 to buttons 0 through 9 on the remote. That still allows for two additional commands. Don’t forget to program all your other remote controls into the learning remote too.

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C2, whose value should be approximately double that of C1.

The circuits in Figs. 4 and 5 can be modified in several different ways, as shown in Figs. 7 to 10. In Fig. 7, the duty cycle or mark/space ratio of the generated waveform is fully variable over the range of 27:1 to 1:27 with trimmer potentiometer R2. Capacitor C1 alternately charges through resistor R1, diode D1, and the left side of R2, and it discharges through resistor R1, diode D2, and the right side of R2 in each operating cycle. The operating frequency varies only slightly as the mark/space ratio is varied.

Figure 8 shows how the oscillator generates quadrature outputs. The squarewave outputs of pins 5 and 8 are out of phase by 90°. In this circuit, input pin 3 is normally grounded. If it is biased above 2.8 volts, the square waveform at pin 8 shifts by 180°.

Figures 9 and 10 show how the oscillator circuit can be modified to allow timing resistor values to be increased to a maximum of about 500 kohms. This permits the value of timing capacitor C1 to be pro- (Continued on page 85)
In Fig. 9 this buffer is an emitter-follower transistor stage. Unfortunately, this stage causes a slight loss of waveform symmetry. By contrast, the circuit in Fig. 10 includes an operational amplifier follower as the buffer. It, however, causes no waveform symmetry loss.

FIG. 14—DUAL-TONE DECODER with a single output.

FIG. 15—DUAL-TONE SWITCH with 24% bandwidth.

Five 567 outputs.
The 567 has five output terminals. Two of these (pins 5 and 6) give access to the oscillator output waveforms. A third (pin 8) functions as the IC's main output terminal, as previously stated. The remaining two outputs are available on pins 1 and 2 of the decoder.

Pin 2 gives access to the phase detector output terminal of the PLL, and it is internally biased at a quiescent value of 3.8 volts. When the 567 receives in-band input signals, this voltage varies as a linear function of frequency over the typical range of 0.95 to 1.05 times the oscillator's free-running frequency. It has a slope of about 20 millivolts per percent of frequency deviation.

Figure 11 illustrates the time relationship between the outputs of pin 2 and pin 8 when the 567 is organized as a tone switch. The relationships are shown at two bandwidths: 14% and 7%.

Pin 1 gives access to the output of the 567's quadrature phase detector. During tone lock, the average voltage at pin 1 is a function of the circuit's in-band input signal amplitude, as shown in transfer graph Fig. 12. Pin 8 at the collector of the output transistor turns on when the average voltage at pin 1 is pulled below its 3.8-volt threshold value.

Detection bandwidth
When the 567 is configured as a tone switch, its bandwidth (as a percentage of center frequency) has a maximum value of about 14%. That value is proportional to the value of in-band signal voltage in the 25 to 200 millivolt RMS range. However, it is independent of values in the 800 to 300 millivolt range, and is inversely proportional to the product of center frequency and capacitor C2. The actual bandwidth (BW) is:

$$\text{BW} = 1070 \sqrt{\frac{V_i}{(f_c \times C2)}}$$

in % of $f_c$ and $V_i \leq 200$ millivolts RMS
Where $V_i$ is in volts RMS and C2 is in microfarads

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To select a C2 value by an educated trial and error process, start by selecting a value that is twice that of C1. Then either increase its value to reduce bandwidth, or reduce its value to increase bandwidth.

Detection band skew
Detection band skew is a measure of how well the band is centered about the center frequency. Skew is defined as:

$$f_{\text{max}} + f_{\text{min}} - 2f_0/2f$$

Where $f_{\text{max}}$ and $f_{\text{min}}$ are the frequencies corresponding to the edges of the detection band.

If a tone switch has a center frequency of 100 kHz and a bandwidth of 10 kHz, and its edge of band frequencies are symmetrically placed at 95 kHz and 105 kHz, its skew value is zero %. However, if its range of band values is highly nonsymmetrical at 100 kHz and 110 kHz, its skew value increases to 5 %.

The skew value can be reduced to zero, if necessary, by introducing an external bias trim voltage at pin 2 of the IC with a trimmer potentiometer R2 and 47 kilohm resistor R4. However, if its range of band values is highly nonsymmetrical at 100 kHz and 110 kHz, its skew value increases to 5 %.

Tone-switch design
Practical tone-switch circuits based on the typical connection diagram Fig. 3 are easy to design. Select the resistor R1 and capacitor C1 frequency control component values by referring to the nomograph, Fig. 6. Select the value of C2 on an empirical basis as described earlier. Start by making it twice the value of C1 and then adjusting its value (if necessary) to give the desired signal bandwidth. If band symmetry is critical in your application, add a skew adjustment stage, as shown in Fig. 13.

Finally, to complete the circuit design, give C3 a value double that of C2, and check the circuit response. If C3 is too small, the output at pin 8 might pulsate during switching because of transients.

Multiple switching
Any desired number of 567 tone switches can be fed from a common input signal to make a multitone switching network of any desired size. Figures 14 and 15 are two practical two-stage switching networks.

The circuit in Fig. 14 functions as a dual-tone decoder. It has a single output that is activated in the presence of either of two input tones. Here, the two tone switches are fed from the same signal source, and their outputs are noted by a CD4001B CMOS gate IC.

Figure 15 shows two 567 tone switches connected in parallel so that they act like a single tone switch with a bandwidth of 24 %. In this circuit, the operating frequency of the IC2 tone switch is made 1.12 times lower than that of the IC1 tone switch. As a result, their switching bandwidths overlap.