Chapter 15
Sine Wave Oscillators

Literature Number SLOA087

Excerpted from
Op Amps for Everyone

Literature Number: SLOD006A

TEXAS INSTRUMENTS

Sine Wave Oscillators

Ron Mancini and Richard Palmer

15.1 What is a Sine Wave Oscillator?

Op amp oscillators are circuits that are unstable — not the type that are sometimes unintentionally designed or created in the lab — but circuits intentionally designed to remain in an unstable state. Oscillators are useful for creating uniform signals that are used as a reference in applications such as audio, function generators, digital systems, and communication systems.

Two general classes of oscillators exist: sinusoidal and relaxation. Sinusoidal oscillators consist of amplifiers with RC or LC circuits that have adjustable oscillation frequencies, or crystals that have a fixed oscillation frequency. Relaxation oscillators generate triangular, sawtooth, square, pulse, or exponential waveforms, and they are not discussed here.

Op amp sine wave oscillators operate without an externally applied input signal. Some combination of positive and negative feedback is used to drive the op amp into an unstable state, causing the output to transition back and forth at a continuous rate. The amplitude and the oscillation frequency are set by the arrangement of passive and active components around a central op amp.

Op amp oscillators are restricted to the lower end of the frequency spectrum because op amps do not have the required bandwidth to achieve low phase shift at high frequencies. Voltage-feedback op amps are limited to a the low kHz range since their dominant, open loop pole may be as low as 10 Hz. The new current-feedback op amps have a much wider bandwidth, but they are very hard to use in oscillator circuits because they are sensitive to feedback capacitance and are beyond the scope of this chapter. Crystal oscillators are used in high frequency applications up to the hundreds of MHz range.

15.2 Requirements for Oscillation

The canonical, or simplest form, of a negative feedback system is used to demonstrate the requirements for oscillation to occur. The block diagram of this system is shown in Fig-

ure 15–1, and the corresponding classic expression for a feedback system is shown in Equation 15–1. The derivation and explanation of the block diagram and equation can be found in Chapter 5.
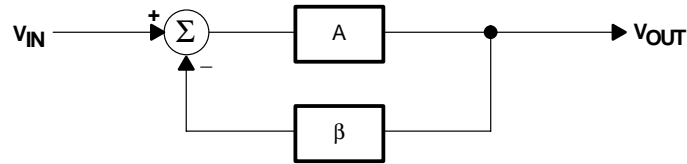

Figure 15–1. Canonical Form of a Feedback System with Positive or Negative Feedback

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \tag{15–1}$$

Oscillators do not require an externally applied input signal, but instead use some fraction of the output signal created by the feedback network as the input signal. It is the noise voltage that provides the inital boost signal to the circuit when positive feedback is employed. Over a period of time, the output builds up, oscillating at the frequency set by the circuit components[1].

Oscillation results when the feedback system is not able to find a stable state because its transfer function can not be satisfied. The system becomes unstable when the denominator in Equation 15–1 is 0. When $(1 + A\beta) = 0$, $A\beta = -1$. The key to designing an oscillator, then, is to ensure that $A\beta = -1$. This is called the Barkhausen criterion. This constraint requires the magnitude of the loop gain be 1 with a corresponding phase shift of 180° as indicated by the minus sign. An equivalent expression using complex math is $A\beta = 1\angle-180°$ for a negative feedback system. For a positive feedback system, the expression becomes $A\beta = 1\angle0°$ and the sign is negative in Equation 15–1.

Once the phase shift is 180° and $A\beta = |1|$, the output voltage of the unstable system heads for infinite voltage in an attempt to destroy the world, and is only prevented from succeeding by an energy-limited power supply. When the output voltage approaches either power rail, the active devices in the amplifiers change gain, causing the value of A to change so the value of $A\beta \neq 1$; thus the charge to infinite voltage slows down and eventually halts. At this point, one of three things can occur. First, nonlinearity in saturation or cutoff can cause the system to become stable and lock up at the power rail. Second, the initial charge can cause the system to saturate (or cutoff) and stay that way for a long time before it becomes linear and heads for the opposite power rail. Third, the system stays linear and reverses direction heading for the opposite power rail. Alternative two produces highly distorted oscillations (usually quasi square waves), and the resulting oscillators are called relaxation oscillators. Alternative three produces sine wave oscillators.

15.3 Phase Shift in the Oscillator

The 180° phase shift in the equation $A\beta = 1\angle{-180°}$ is introduced by active and passive components. Like any well-designed feedback circuit, oscillators are made dependent on passive component phase shift because it is accurate and almost drift-free. The phase shift contributed by active components is minimized because it varies with temperature, has a wide initial tolerance, and is device dependent. Amplifiers are selected such that they contribute little or no phase shift at the oscillation frequency. These constraints limit the op amp oscillator to relatively low frequencies.

A single pole RL or RC circuit contributes up to 90° phase shift per pole, and because 180° of phase shift is required for oscillation, at least two poles must be used in the oscillator design. An LC circuit has two poles, thus it contributes up to 180° phase shift per pole pair. But LC and LR oscillators are not considered here because low frequency inductors are expensive, heavy, bulky, and very nonideal. LC oscillators are designed in high frequency applications, beyond the frequency range of voltage feedback op amps, where the inductor size, weight, and cost are less significant. Multiple RC sections are used in low frequency oscillator design in lieu of inductors.

Phase shift determines the oscillation frequency because the circuit oscillates at the frequency that accumulates 180° phase shift. The rate of change of phase with frequency, $d\phi/d\omega$, determines frequency stability. When buffered RC sections (an op amp buffer provides high input and low output impedance) are cascaded, the phase shift multiplies by the number of sections, *n* (see Figure 15–2).
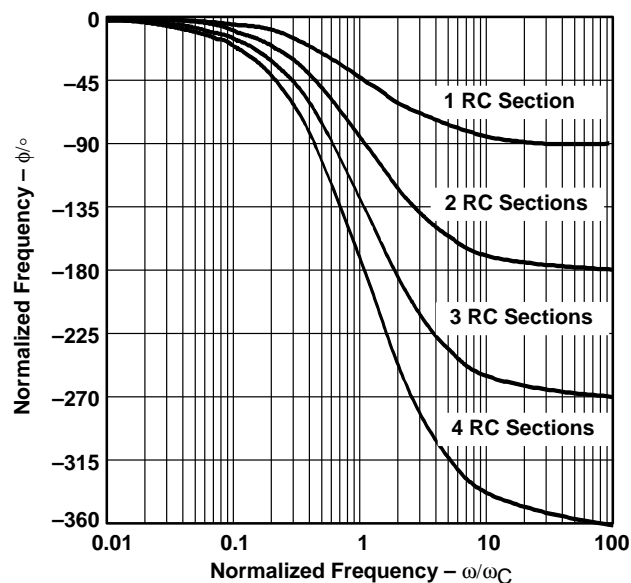

Figure 15–2. Phase Plot of RC Sections

The frequency of oscillation is very dependent upon the change in phase at the point where the phase shift is 180°. A tight frequency specification will require a large change in phase shift, dϕ, for a small change in frequency, dω, at 180°. Figure 15–2 demonstrates that, although two cascaded RC sections eventually provide 180° phase shift, dϕ/dω at the oscillator frequency is unacceptably low. Thus, oscillators made with two cascaded RC sections have poor frequency stability. Three equal cascaded RC filter sections have a much higher dϕ/dω (see Figure 15–2), and the resulting oscillator has improved frequency stability. Adding a fourth RC section produces an oscillator with an excellent dϕ/dω (see Figure 15–2); thus this is the most stable RC oscillator configuration. Four sections are the maximum number used because op amps come in quad packages, and the four-section oscillator section yields four sine waves 45° phase shifted relative to each other. This oscillator can be used to obtain sine/cosine or quadrature sine waves.

Crystal or ceramic resonators make the most stable oscillators because resonators have an extremely high dϕ/dω resulting from their nonlinear properties. Resonators are used for high frequency oscillators, but low frequency oscillators do not use resonators because of size, weight, and cost restrictions. Op amps are not generally used with crystal or ceramic resonator oscillators because op amps have low bandwidth. Experience shows that it is more cost effective to build a high frequency crystal oscillator, count the output down, and filter the output to obtain a low frequency than it is to use a low frequency resonator.

15.4 Gain in the Oscillator

The oscillator gain must equal 1 (Aβ = 1$\angle$–180°) at the oscillation frequency. Under normal conditions, the circuit becomes stable when the gain exceeds 1 and oscillations cease. However, when the gain exceeds 1 with a phase shift of –180°, the active device nonlinearity reduces the gain to 1 and the circuit oscillates. The nonlinearity happens when the amplifier swings close to either power rail because cutoff or saturation reduces the active device (transistor) gain. The paradox is that worst case design practice requires nominal gains exceeding 1 for manufacturability, but excess gain causes more distortion of the output sine wave.

When the gain is too low, oscillations cease under worst case conditions, and when the gain is too high, the output wave form looks more like a square wave than a sine wave. Distortion is a direct result of excess gain overdriving the amplifier; thus gain must be carefully controlled in low-distortion oscillators. Phase shift oscillators have distortion, but they achieve low-distortion output voltages because cascaded RC sections act as distortion filters. Also, buffered phase shift oscillators have low distortion because the gain is controlled and distributed among the buffers.

Most circuit configurations require an auxiliary circuit for gain adjustment when low-distortion outputs are desired. Auxiliary circuits range from inserting a nonlinear component in

the feedback loop, to automatic gain control (AGC) loops, to limiting by external components such as resistors and diodes. Consideration must also be given to the change in gain due to temperature variations and component tolerances, and the level of circuit complexity will be determined based on the required stability of the gain. The more stable the gain, the better the purity of the sine wave output.

15.5 Active Element (Op Amp) Impact on the Oscillator

Up to now, it has been assumed that the op amp has an infinite bandwidth and the output is not frequency dependent. In reality, the op amp has many poles, but it has been compensated so that they are dominated by a single pole over the specified bandwidth. Thus $A\beta$, is now frequency dependant through the op amp gain term, A. Equation 15–2 shows this dependance, where a is the maximum open loop gain, ω_a is the dominant pole frequency, and ω is the frequency of the signal. Figure 15–3 graphically depicts the frequency dependence of the op amp gain and phase. The closed loop gain, $A_{CL} = 1/\beta$ does not contain any poles or zeros and its therefore constant over frequency to the point where it impacts the op amp open-loop gain at ω_{3dB}. Here, the signal amplitude is attenuated by 3 dB and the phase shift introduced by the op amp is 45°. The amplitude and phase really begin to change one decade below this point at 0.1 ω_{3dB}, and the phase will continue to shift until it has reached 90° at 10 ω_{3dB}, one decade beyond the 3–dB point. The gain continues to roll off at –20 dB/decade until other poles and zeros come into play. The higher the closed-loop gin, the earlier A_{CL} intercepts the op amp gain.

$$A_{CL} = \frac{A}{1 + A\beta} = \frac{\frac{1}{\beta}}{1 + \frac{1}{A\beta}} = \frac{A_{CLideal}}{1 + \frac{A_{CLideal}}{A_{OL}}} \qquad (15\text{–}2)$$

The phase shift contributed by the op amp will impact the performance of the oscillator circuit by lowering the oscillation frequency, and the reduction in A_{CL} can make $A\beta < 1$ and the oscillator will not oscillate.
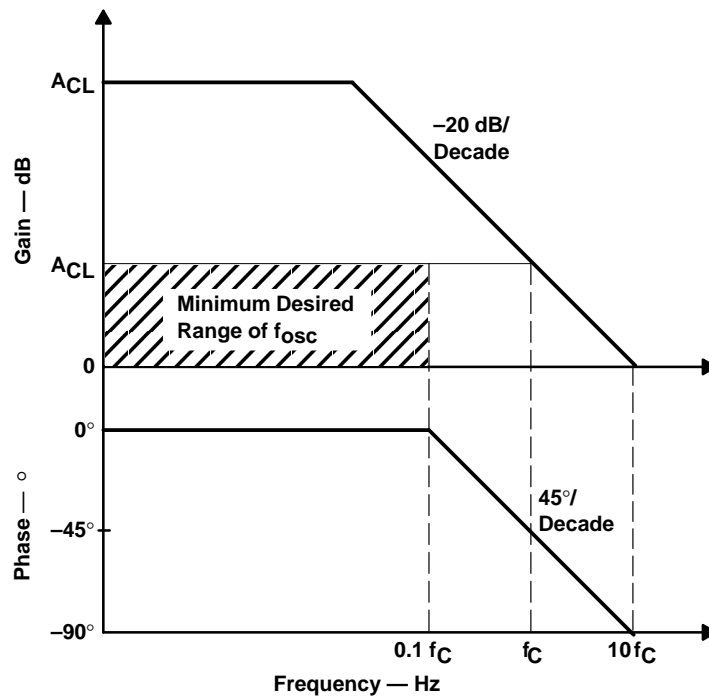
Figure 15–3. Op Amp Frequency Response

Most op amps are compensated and may have more than the $45°$ of phase shift at ω_{3dB}. The op amp should therefore be chosen with a gain bandwidth that is at least one decade above the oscillation frequency, as shown by the shaded area of Figure 15–3. The Wien bridge requires a gain bandwidth greater than $43\omega_{OSC}$ to maintain the gain and frequency within 10% of the ideal values [2]. Figure 15–4 compares the output distortion versus frequency of an LM328, a TLV247x, and a TLC071 op amp, which have bandwidths of 0.4 MHz and 2.8 MHz, and 10 MHz, respectively, in a Wien bridge oscillator with nonlinear feedback (see Section 15.7.1 for the circuit and transfer function) The oscillation frequency ranged from 16 Hz to 160 kHz. The graph illustrates the importance of choosing the correct op smp for the application. The LM328 achieved a maximum oscillation of 72 kHz and was attenuated more than 75%, while the TLV247x achieved 125 kHz with 18% attenuation. The wide bandwidth of the TLC071 provided a 138 kHz oscillation frequency with a mere 2% attenuation. The op amp must be chosen with the proper bandwidth or the output may oscillate at a frequency well below the design specification.
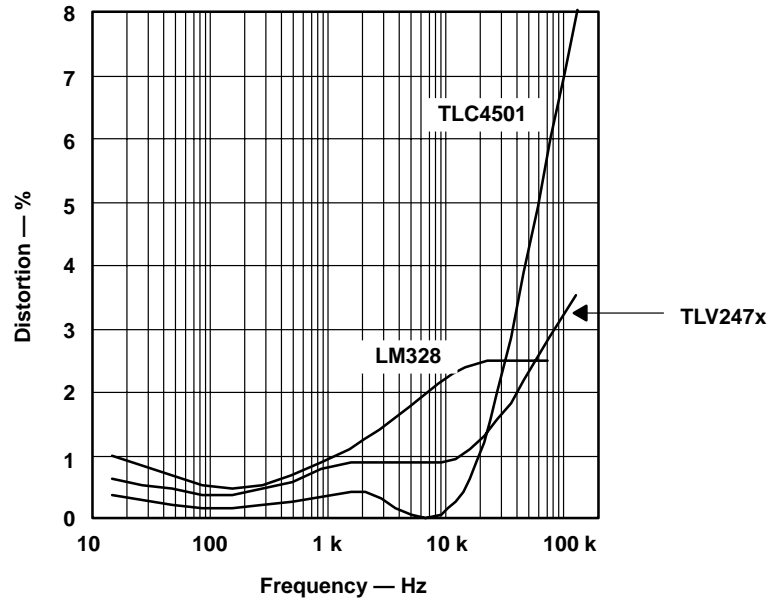
Figure 15–4. Op Amp Bandwidth and Oscillator Output

Care must be taken when using large feedback resistors since they interact with the input capacitance of the op amp to create poles with negative feedback, and both poles and zeros with positive feedback. Large resistor values can move these poles and zeros into the proximity of the oscillation frequency and impact the phase shift [3].

A final consideration is given to the slew-rate limitation of the op amp. The slew rate must be greater than $2\pi V_P f_0$, where V_P is the peak output voltage and f_0 is the oscillation frequency, or distortion of the output signal will result.

15.6 Analysis of the Oscillator Operation (Circuit)

Oscillators are created using various combinations of positive and negative feedback. Figure 15–5 shows the basic negative feedback amplifier block diagram with a positive feedback loop added. When positive and negative feedback are used, the gain of the negative feedback path is combined into one gain term (representing the closed loop gain) and Figure 15–5 reduces to Figure 15–1. The positive feedback network is then represented by $\beta = \beta_2$ and subsequent analysis is simplified. When negative feedback is used, then the positive feedback loop can be ignored since β_2 is 0. The case of positive and negative feedback combined is covered here since the negative feedback case was reviewed in Chapters 5 and 6.
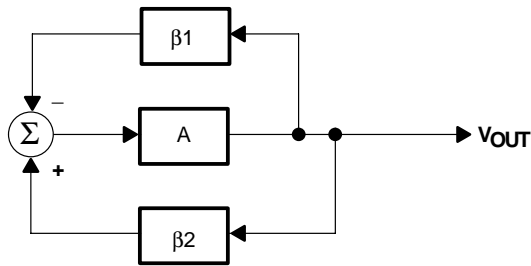
Figure 15–5. Block Diagram of an Oscillator: a) Positive and Negative Feedback Loops, and b) Simplified Diagram w

A general form of an op amp with positive and negative feedback is shown in Figure 15–6a. The first step is to break the loop at some point without altering the gain of the circuit. The positive feedback loop is broken at the point marked with an X. A test signal (V_{TEST}) is applied to the broken loop and the resulting output voltage (V_{OUT}) is measured with the equivalent circuit shown in Figure 15–6b.

(a) Original Circuit   **(b) Loop Gain Calculation Equivalent Circuit**
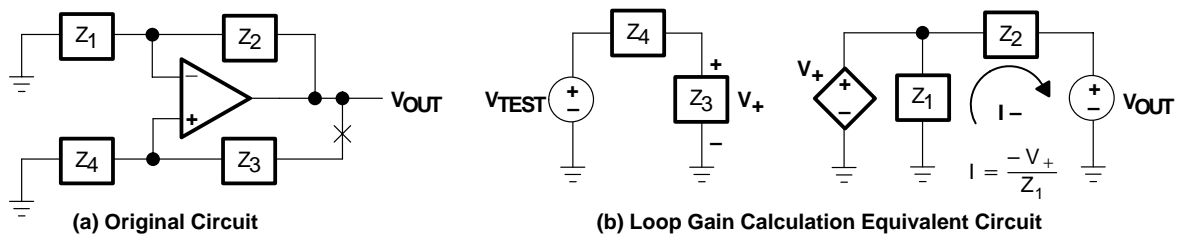
Figure 15–6. Amplifier with Positive and Negative Feedback

V_+ is calculated first in Equation 15–3, and then is treated as an input signal to a noninverting amplifier, resulting in Equation 15–4. Equation 15–3 is substituted for V_+ into Equation 15–4 to get the transfer function in Equation 15–5. The actual circuit elements are then substituted for each impedance and the equation is simplified. These equations are valid when the op amp open-loop gain is large and the oscillation frequency is $< 0.1\ \omega_{3dB}$.

$$V_+ = V_{TEST}\left(\frac{Z_4}{Z_3 + Z_4}\right) \tag{15–3}$$

$$V_{OUT} = V_+\left(\frac{Z_1 + Z_2}{Z_1}\right) \tag{15–4}$$

$$\frac{V_{OUT}}{V_{TEST}} = \left(\frac{Z_3}{Z_3 + Z_4}\right)\left(\frac{Z_1 + Z_2}{Z_1}\right) \tag{15–5}$$

Phase shift oscillators generally use negative feedback, so the positive feedback factor (β_2) becomes zero. Oscillator circuits such as the Wien bridge use both negative (β_1) and positive (β_2) feedback to achieve a constant state of oscillation. This circuit is analyzed in detain in Section 15.7.1 using Equation 15–5.

15.7 Sine Wave Oscillator Circuits

There are many types of sine wave oscillator circuits and variations of these circuits — the choice depends upon the frequency and the desired purity of the output waveform. The focus of this section is on the more prominent oscillator circuits: Wien bridge, phase shift, and quadrature. The transfer function is derived for each case using the techniques described in Section 15.6 of this chapter and in Chapters 3, 5, and 6.

15.7.1 Wien Bridge Oscillator

The Wien bridge is one of the simplest and best known oscillators and is used extensively in circuits for audio applications. Figure 15–7 shows the basic Wien bridge circuit configuration. This circuit has only a few components and good frequency stability. The major drawback of the circuit is that the output amplitude is at the rails, saturating the op amp output transistors and causing high output distortion. Taming this distortion is more of a challenge than getting the circuit to oscillate. There are a couple of ways to minimize this effect, which will be covered later. It is now time to analyze this circuit and come up with the transfer function.
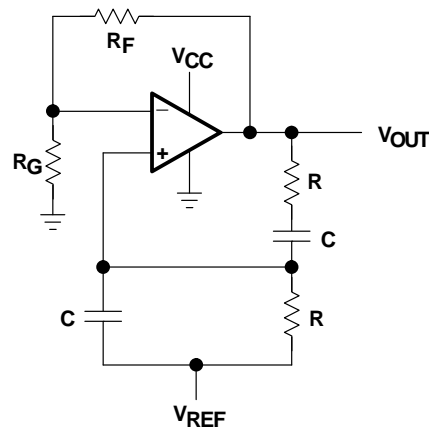

Figure 15–7. Wien Bridge Circuit Schematic

The Wien bridge circuit is of the form that is detailed in Section 15.6. The transfer function for the circuit is created using the technique described in that section. It is readily apparent that $Z_1 = R_G$, $Z_2 = R_F$, $Z_3 = (R_1 + 1/sC_1)$ and $Z_4 = (R_2 \| 1/sC_2)$. The loop is broken between

the output and Z_1, V_{TEST} is applied to Z_1, and V_{OUT} is calculated. The positive feedback voltage, V_+, is calculated first in Equations 15–6 through 15–8. Equation 15–6 shows the simple voltage divider at the noninverting input. Each term is then multiplied by (R_2C_2s + 1) and divided by R_2 to get Equation 15–7.

$$V_+ = V_{TEST}\left(\frac{Z_4}{Z_3 + Z_4}\right) = V_{TEST}\left[\frac{\left(\frac{R_2}{R_2C_2s+1}\right)}{\left(\frac{R_2}{R_2C_2s+1}\right) + \left(R_1 + \frac{1}{C_1s}\right)}\right] \qquad (15\text{–}6)$$

$$\frac{V_+}{V_{TEST}} = \frac{1}{1 + R_1C_2S + \frac{R_1}{R_2} + \frac{1}{R_2C_1s} + \frac{C_2}{C_1}} \qquad (15\text{–}7)$$

Substitute s = jω_0, where ω_0 is the oscillation frequency, ω_1 = 1/R_1C_2, and ω_2 = 1/R_2C_1 to get Equation 15–8.

$$\frac{V_+}{V_{TEST}} = \frac{1}{1 + \frac{R_1}{R_2} + \frac{C_2}{C_1} + j\left(\frac{\omega_0}{\omega_1} - \frac{\omega_2}{\omega_0}\right)} \qquad (15\text{–}8)$$

Some interesting relationships now become apparent. The capacitor in the zero, represented by ω_1, and the capacitor in the pole, represented by ω_2, must each contribute 90° of phase shift toward the 180° required for oscillation at ω_0. This requires that $C_1 = C_2$ and $R_1 = R_2$. Setting ω_1 and ω_2 equal to ω_0 cancels the frequency terms, ideally removing any change in amplitude with frequency since the pole and zero negate one another. An overall feedback factor of β = 1/3 is the result (Equation 15–9).

$$\frac{V_+}{V_{TEST}} = \frac{1}{1 + \frac{R}{R} + \frac{C}{C} + j\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)} = \frac{1}{3 + j\left(\frac{\omega_0}{\omega_0} - \frac{\omega_0}{\omega_0}\right)} = \frac{1}{3} \qquad (15\text{–}9)$$

The gain of the negative feedback portion, A, of the circuit must then be set such that $|A\beta|$ = 1, requiring A = 3. R_F must be set to twice the value of R_G to satisfy the condition. The op amp in Figure 15–7 is single supply, so a dc reference voltage, V_{REF}, must be applied to bias the output for full-scale swing and minimal distortion. Applying V_{REF} to the positive input through R_2 restricts dc current flow to the negative feedback leg of the circuit. V_{REF} was set at 0.833V to bias the output at the midrail of the single supply, rail-to-rail input and output amplifier, or 2.5 V. See Cahpter 4 for details on dc biasing single-supply op amps. V_{REF} is shorted to ground for split supply applications.

The final circuit is shown in Figure 15–8, with component values selected to provide an oscillation frequency of ω_0 = 2πf_0, where f_0 = 1/(2πRC) = 15.9 kHz. The circuit oscillated at 1.57 kHz due to slightly varying component values with 2% distortion. This high value is due to the extensive clipping of the output signal at both supply rails, producing several

large odd and even harmonics. The feedback resistor was then adjusted ±1%. Figure 15–9 shows the output voltage waveforms. The distortion grew as the saturation increased with increasing R_F, and oscillations ceased when R_F was decreased by more than 0.8%.
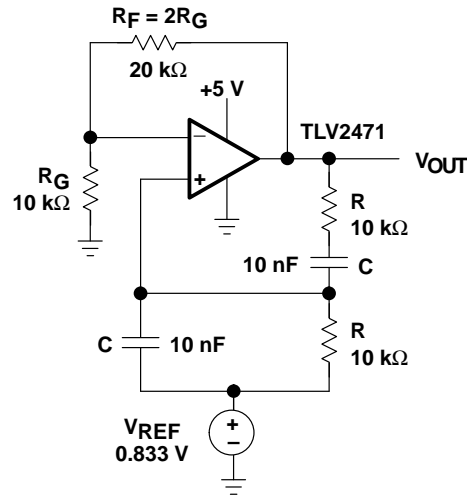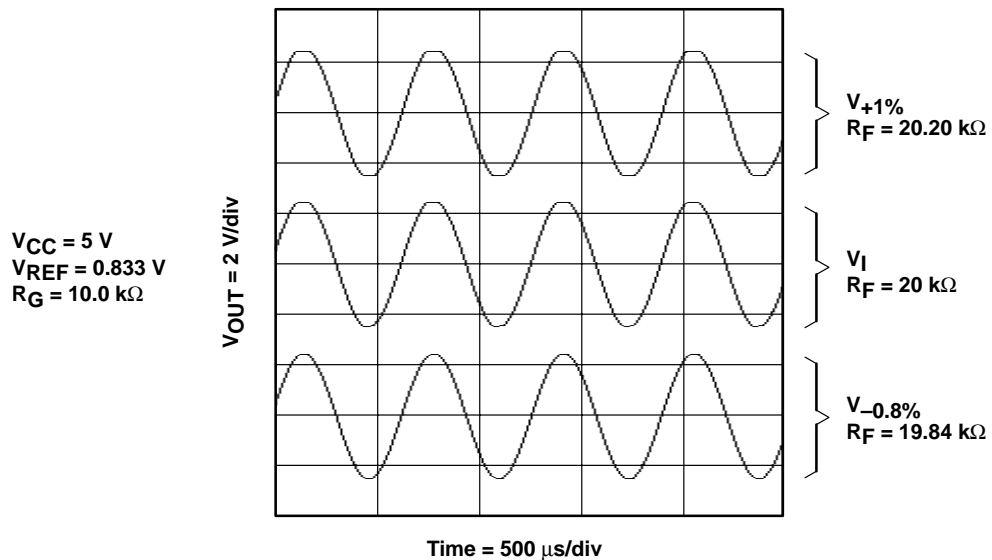

Figure 15–8. Final Wien Bridge Oscillator Circuit

Time = 500 μs/div

Figure 15–9. Wien Bridge Output Waveforms

Applying nonlinear feedback can minimize the distortion inherent in the basic Wien bridge circuit. A nonlinear component such as an incandescent lamp can be substituted into

the circuit for R_G as shown in Figure 15–10. The lamp resistance, R_{LAMP}, is nominally selected as half the feedback resistance, R_F, at the lamp current established by R_F and R_{LAMP}. When the power is first applied the lamp is cool and its resistance is small, so the gain is large (> 3). The current heats up the filament and the resistance increases, lowering the gain. The nonlinear relationship between the lamp current and resistance keeps output voltage changes small. Figure 15–11 shows the output of this amplifier with a distortion of 1% for f_{OSC} = 1.57 kHz. The distortion for this variation is reduced over the basic circuit by avoiding hard saturation of the op amp transistors.
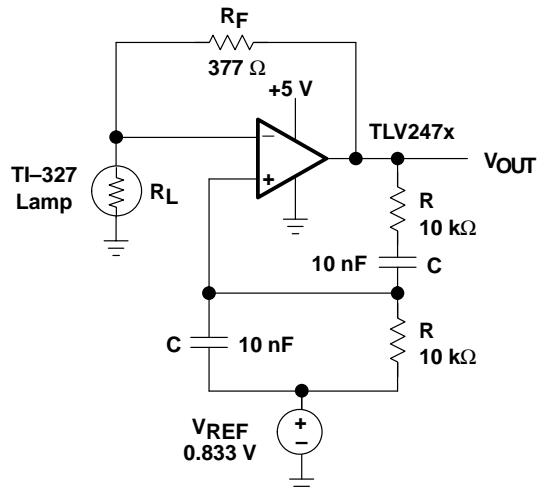

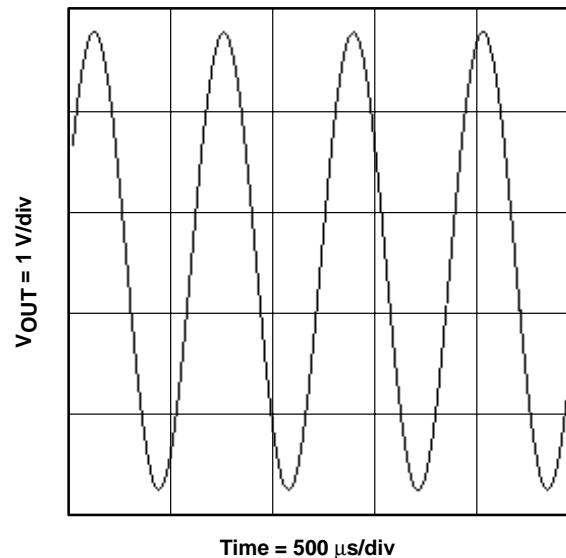Figure 15–10. *Wien Bridge Oscillator with Nonlinear Feedback*

Figure 15–11. *Output of the Circuit in Figure 15–10*

The impedance of the lamp is mostly due to thermal effects. The output amplitude is then very temperature sensitive and will tend to drift. The gain must be set higher than 3 to compensate for any temperature variations, which increases the distortion in the circuit [4]. This type of circuit is useful when the temperature does not fluctuate over a wide range or when used in conjunction with an amplitude limiting circuit.

The lamp has an effective low frequency thermal time constant, $t_{thermal}$ (4). As f_{OSC} approaches $t_{thermal}$, distortion is greatly increased. Several lamps can be placed in series to increase $t_{thermal}$ and reduce distortion. The drawbacks are that the time required for oscillations to stabilize is increased and the output amplitude is reduced.

An automatic gain control (AGC) circuit must be used when neither of the two previous circuits yield low distortion. A typical Wien bridge oscillator with an AGC circuit is shown in Figure 15–12, with the output waveform of the circuit shown in Figure 15–13. The AGC is used to stabilize the magnitude of the sinusoidal output to an optimum gain level. The JFET serves as the AGC element, providing excellent control because of the wide range of the drain to source resistance (R_{DS}), which is controlled by the gate voltage. The JFET gate voltage is 0 V when the power is applied, and the JFET turns on with low R_{DS}. This places $R_{G2}+R_S+R_{DS}$ in parallel with R_{G1}, raising the gain to 3.05, and oscillations begin and gradually build up. As the output voltage gets large, the negative swing turns the diode on and the sample is stored on C_1, which provides a dc potential to the gate of Q_1. Resistor R_1 limits the current and establishes the time constant for charging C_1, which should be much greater than f_{OSC}. When the output voltage drifts high, R_{DS} increases, lowering the gain to a minimum of 2.87 ($1+R_F/R_{G1}$). The output stabilizes when the gain reaches 3. The distortion of the AGC is 0.8%, which is due to slight clipping at the positive rail.

The circuit of Figure 15–12 is biased with V_{REF} for a single-supply amplifier. A zener diode can be placed in series with D1 to limit the positive swing of the output and reduce distortion. A split supply can be easily implemented by grounding all points connected to V_{REF}. There are a wide variety of Wien bridge variations that exist to more precisely control the amplitude and allow selectable or even variable oscillation frequencies. Some circuits use diode limiting in place of a nonlinear feedback component. The diodes reduce the distortion by providing a soft limit for the output voltage.
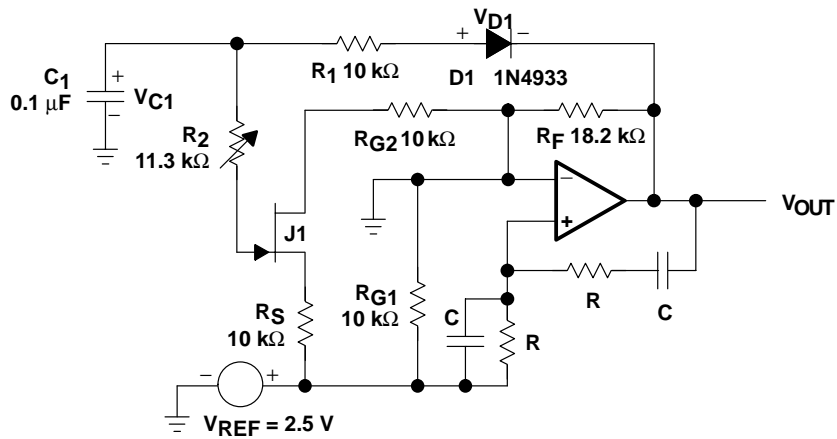
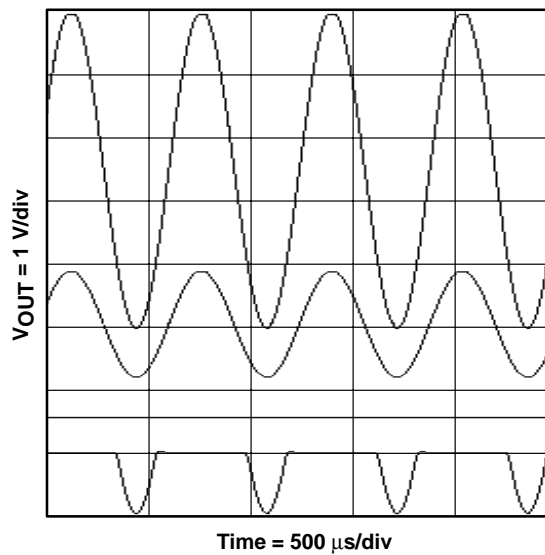*Figure 15–12. Wien Bridge Oscillator with AGC*

Time = 500 μs/div

Figure 15–13. Output of the Circuit in Figure 15–12

15.7.2 Phase Shift Oscillator, Single Amplifier

Phase shift oscillators have less distortion than the Wien bridge oscillator, coupled with good frequency stability. A phase shift oscillator can be built with one op amp as shown in figure 15–14. Three RC sections are cascaded to get the steep $d\phi/d\omega$ slope as described in Section 15–3 to get a stable oscillation frequency. Any less and the oscillation frequency is high and interferes with the op amp BW limitations.
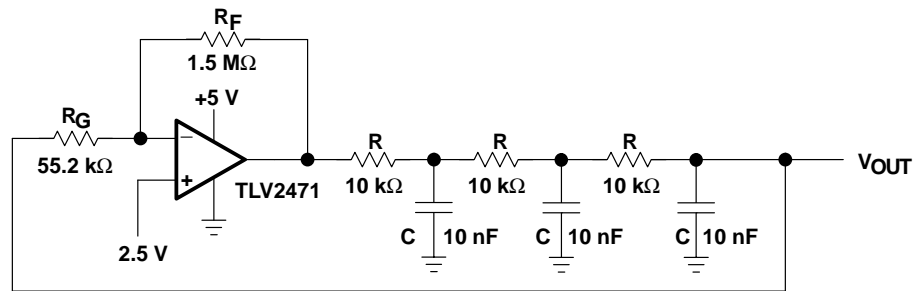
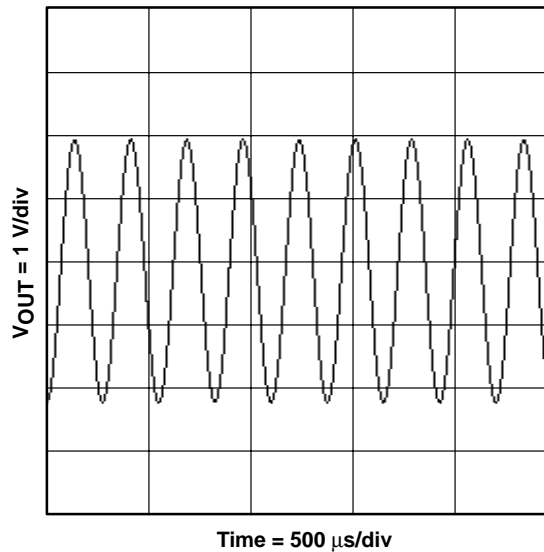*Figure 15–14. Phase Shift Oscillator (Single Op Amp)*

Time = 500 μs/div

Figure 15–15. Output of the Circuit in Figure 15–14

$$A\beta = A\left(\frac{1}{RCs + 1}\right)^3 \tag{15–10}$$

The normal assumption is that the phase shift sections are independent of each other. Then Equation 15–10 is written. The loop phase shift is $-180°$ when the phase shift of each section is $-60°$, and this occurs when $\omega = 2\pi f = 1.732/RC$ because the tangent of $60° = 1.732$. The magnitude of β at this point is $(1/2)^3$, so the gain, A, must be equal to 8 for the system gain to be equal to one.

The oscillation frequency with the component values shown in Figure 15–14 is 3.76 kHz rather than the calculated oscillation frequency of 2.76 kHz as shown in Figure 15–14. Also, the gain required to start oscillation is 27 rather than the calculated gain of 8. These

discrepancies are partially due to component variations, but the biggest contributing factor is the incorrect assumption that the RC sections do not load each other. This circuit configuration was very popular when active components were large and expensive. But now op amps are inexpensive, small, and come four in a package, so the single op amp phase shift oscillator is losing popularity. The output distortion is a low 0.46%, considerably less than the Wein bridge circuit without amplitude stabilization.

15.7.3 Phase Shift Oscillator, Buffered

The buffered phase shift oscillator is much improved over the unbuffered version, the cost being a higher component count. The buffered phase shift oscillator is shown in Figure 15–16 and the resulting output waveform in Figure 15–17. The buffers prevent the RC sections from loading each other, hence the buffered phase shift oscillator performs closer to the calculated frequency and gain. The gain setting resistor, R_G, loads the third RC section. If the fourth buffer in a quad op amp buffers this RC section, the performance becomes ideal. Low-distortion sine waves can be obtained from either phase shift oscillator design, but the purest sine wave is taken from the output of the last RC section. This is a high-impedance node, so a high impedance input is mandated to prevent loading and frequency shifting with load variations.
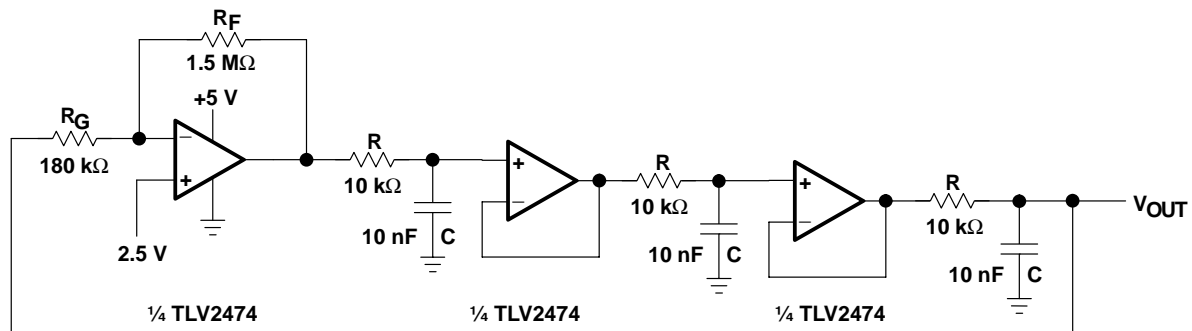

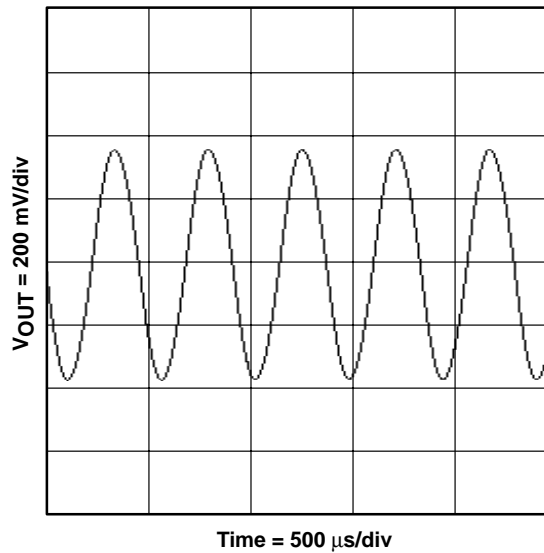*Figure 15–16.   Phase Shift Oscillator, Buffered*

Time = 500 μs/div

Figure 15–17.   Output of the Circuit Figure 15–16

15.7.4 Bubba Oscillator

The bubba oscillator in Figure 15–18 is another phase shift oscillator, but it takes advantage of the quad op amp package to yield some unique advantages. Four RC sections require 45° phase shift per section, so this oscillator has an excellent dφ/dt resulting in minimized frequency drift. The RC sections each contribute 45° phase shift, so taking outputs from alternate sections yields low impedance quadrature outputs. When an output is taken from each op amp, the circuit delivers four 45° phase shifted sine waves. The loop equation is given in Equation 15–11. When ω = 1/RCs, Equation 15–11 reduces to Equations 15–12 and 15–13.

$$A\beta = A\left(\frac{1}{RCs + 1}\right)^4 \qquad (15\text{–}11)$$

$$|\beta| = \left|\left(\frac{1}{j + 4}\right)^4 = \frac{1}{\sqrt{2}^4} = \frac{1}{4}\right| \qquad (15\text{–}12)$$

$$\phi = \tan^{-1}(1) = 45° \qquad (15\text{–}13)$$

Figure 15–18. Bubba Oscillator

Time = 500 μs/div

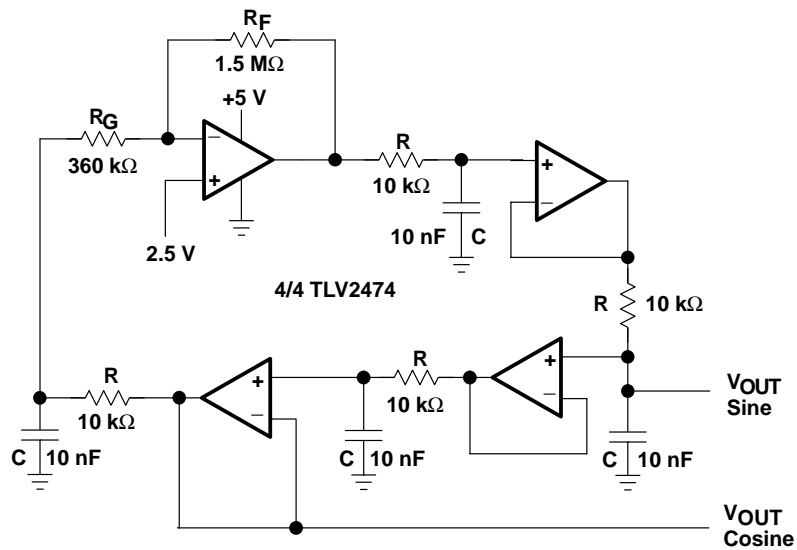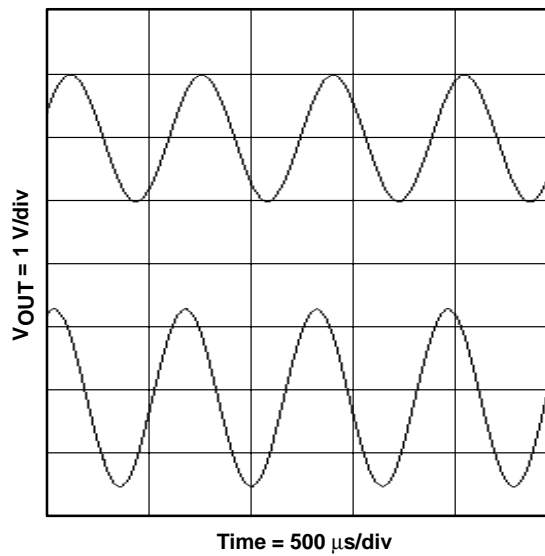*Figure 15–19. Output of the Circuit in Figure 15–18.*

The gain, A, must equal 4 for oscillation to occur. The test circuit oscillated at 1.76 kHz rather than the ideal frequency of 1.72 kHz when the gain was 4.17 rather than the ideal gain 4. The output waveform is shown in Figure 15–19. Distortion is 1% for $V_{OUTSINE}$ and 0.1% for $V_{OUTCOSINE}$. With low gain, A, and low bias current op amps, the gain setting

resistor, R_G, does not load the last RC section, thus ensuring oscillator frequency accuracy. Very low distortion sine waves can be obtained from the junction of R and R_G. When low-distortion sine waves are required at all outputs, the gain should be distributed between all of the op amps. The noninverting input of the gain op amp is biased at 0.5 V to set the quiescent output voltage at 2.5 V for single supply operation, and should be ground for split supply op amps. Gain distribution requires biasing of the other op amps, but it has no effect on the oscillator frequency.

15.7.5 Quadrature Oscillator

The quadrature oscillator shown in Figure 15–20 is another type of phase shift oscillator, but the three RC sections are configured so each section contributes 90° of phase shift. This provides both sine and cosine waveform outputs (the outputs are quadrature, or 90° apart), which is a distinct advantage over other phase shift oscillators. The idea of the quadrature oscillator is to use the fact that the double integral of a sine wave is a negative sine wave of the same frequency and phase. The phase of the second integrator is then inverted and applied as positive feedback to induce oscillation [6].

The loop gain is calculated in Equation 15–14. When $R_1C_1 = R_2C_2 = R_3C_3$, Equation 15–14 reduces to Equation 15–15. When $\omega = 1/RC$, Equation 15–14 reduces to $1\angle-180$, so oscillation occurs at $\omega = 2\pi f = 1/RC$. The test circuit oscillated at 1.65 kHz rather than the calculated 1.59 kHz, as shown in Figure 15–21. This discrepancy is attributed to component variations. Both outputs have relatively high distortion that can be reduced with a gain stabilizing circuit. The sine output had 0.846% distortion and the cosine output had 0.46% distortion. Adjusting the gain can increase the amplitudes. The cost is bandwidth.

$$A\beta = A\left(\frac{1}{R_1C_1s}\right)\left(\frac{R_3C_3s + 1}{R_3C_3s(R_2C_2s + 1)}\right) \tag{15–14}$$

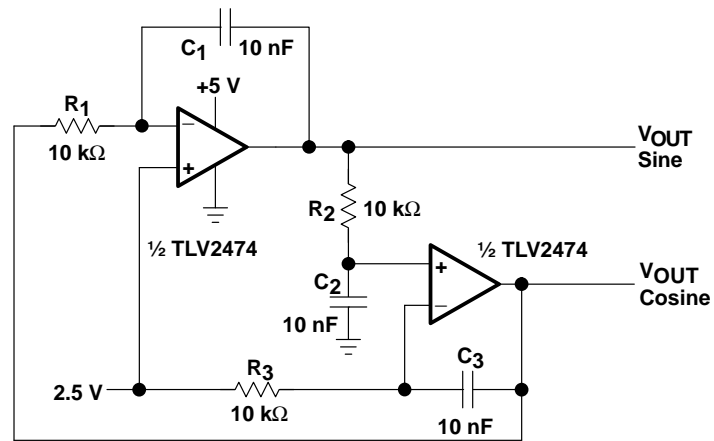$$A\beta = A\left(\frac{1}{RCs}\right)^2 \tag{15–15}$$

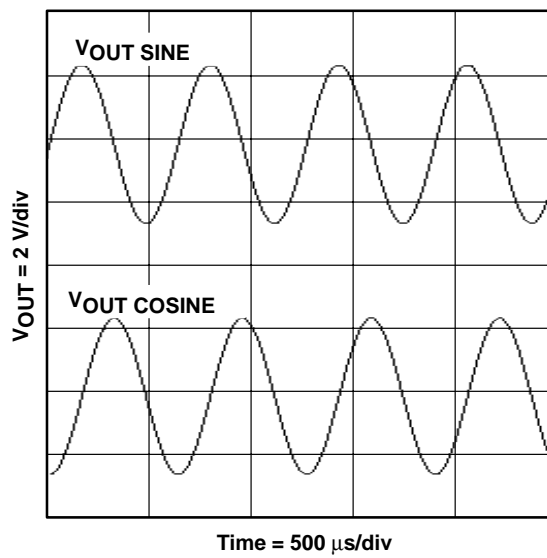*Figure 15–20.   Quadrature Oscillator*

Figure 15–21.   Output of the Circuit in Figure 15–20

15.7.6 Conclusion

Op amp oscillators are restricted to the lower end of the frequency spectrum because they do not have the required bandwidth to achieve low phase shift at high frequencies. The new current-feedback op amps have a much greater bandwidth than the voltage-feedback op amps, but are very difficult to use in oscillator circuits because of their sensitivity to feedback capacitance. Voltage-feedback op amps are limited to tens of Hz (at the most!) because of their low frequency rolloff. The bandwidth is reduced when op amps are cascaded due to the multiple contribution of phase shift.

The Wien bridge oscillator has few parts and good frequency stability, but the basic circuit has a high output distortion. AGC improves the distortion considerably, particularly at the lower frequency range. Nonlinear feedback offers the best performance over the mid and upper frequency ranges. The phase shift oscillator has lower output distortion and, without buffering, requires a high gain, which limits the use to very low frequencies. Decreasing cost of op amps and components has reduced the popularity of the phase shift oscillators. The quadrature oscillator only requires two op amps, has reasonable distortion, and offers both sine and cosine waveforms. The drawback is the low amplitude, which may require a higher gain and a reduction in bandwidth, or an additional gain stage.

May your oscillators always oscillate, and your amplifiers always amplify.

15.8 References

[1] Gottlieb, Irving M., *Practical Oscillator Handbook*, Newnes, 1997.

[2] Kennedy, E. J., *Operational Amplifier Circuits, Theory and Applications,* Holt Rhienhart and Winston, 1988.

[3] Graeme, Jerald, *Optimizing Op Amp Performance*, McGraw Hill Book Company, 1997.

[4] Philbrick Researches, Inc., *Applications Manual for Computing Amplifiers*, Nimrod Press, Inc., 1966.

[5] Graf, Rudolf F., *Oscillator Circuits*, Newnes, 1997.

[6] Graeme, Jerald, *Applications of Operational Amplifiers, Third Generation Techniques*, McGraw Hill Book Company, 1973.

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third–party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Mailing Address:

Texas Instruments
Post Office Box 655303
Dallas, Texas 75265