Design of op amp sine wave oscillators
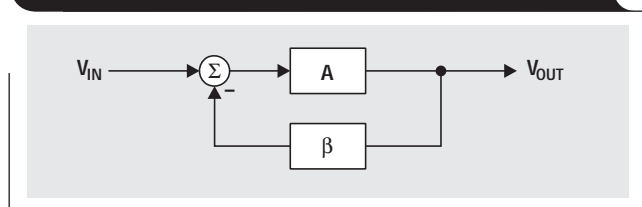
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Criteria for oscillation

The canonical form of a feedback system[1] is shown in Figure 1, and Equation 1 describes the performance of any feedback system (an amplifier with passive feedback components constitutes a feedback system).

Figure 1. Canonical form of a feedback circuit

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

Oscillation results from an unstable state; i.e., the feedback system can't find a stable state because its transfer function can't be satisfied. Equation 1 becomes unstable when $(1+A\beta) = 0$ because $A/0$ is an undefined state. Thus, the key to designing an oscillator is to insure that $A\beta = -1$ (called the Barkhausen criterion), or using complex math the equivalent expression is $A\beta = 1\angle-180°$. The $-180°$ phase shift criterion applies to negative feedback systems, and $0°$ phase shift applies to positive feedback systems.

The output voltage of a feedback system heads for infinite voltage when $A\beta = -1$. 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, non-linearity in saturation or cutoff can cause the system to become stable and lock up. Second, the initial charge can cause the system to saturate (or cut off) 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.

All oscillator circuits were built with TLV247X op amps, 5% resistors, and 20% capacitors; hence, component tolerances cause differences between ideal and measured values.
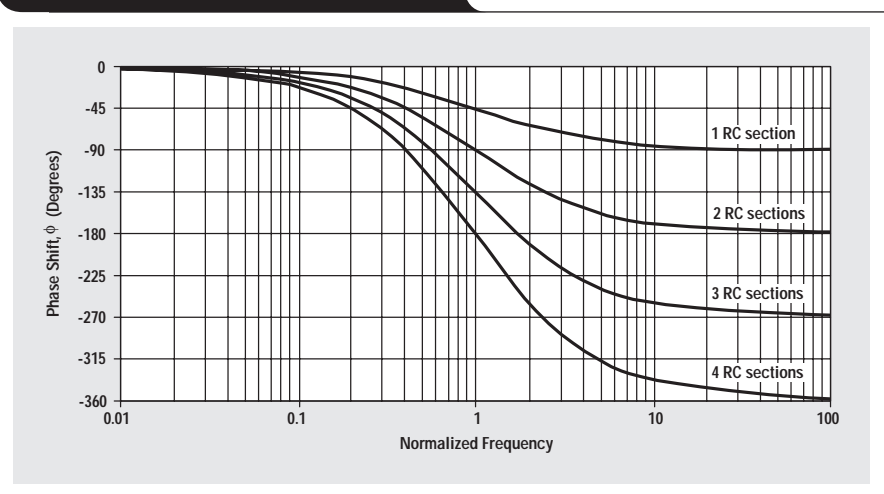
Phase shift in oscillators

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.

A single pole RL or RC circuit contributes up to 90° phase shift per pole, and because 180° is required for oscillation, at least two poles must be used in 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 non-ideal. 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, $d\phi/dt$, 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 2).

Figure 2. Phase plot of RC sections

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Although two cascaded RC sections provide 180° phase shift, dϕ/dt at the oscillator frequency is low, thus oscillators made with two cascaded RC sections have poor frequency stability. Three equal cascaded RC filter sections have a higher dϕ/dt, and the resulting oscillator has improved frequency stability. Adding a fourth RC section produces an oscillator with an excellent dϕ/dt, thus this is the most stable oscillator configuration. Four sections are the maximum number used because op amps come in quad packages, and the four-section oscillator yields four sine waves that are 45° phase shifted relative to each other, so 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/dt resulting from their non-linear 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 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 and count down the output to obtain a low frequency than it is to use a low-frequency resonator.

Gain in oscillators

The oscillator gain must equal one ($A\beta = 1\angle -180°$) at the oscillation frequency. The circuit becomes stable when the gain exceeds one and oscillations cease. When the gain exceeds one with a phase shift of –180°, the active device non-linearity reduces the gain to one. The non-linearity 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 one 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.

Some circuit configurations (Wien-bridge) or low-distortion specifications require an auxiliary circuit to adjust the gain. Auxiliary circuits range from inserting a non-linear

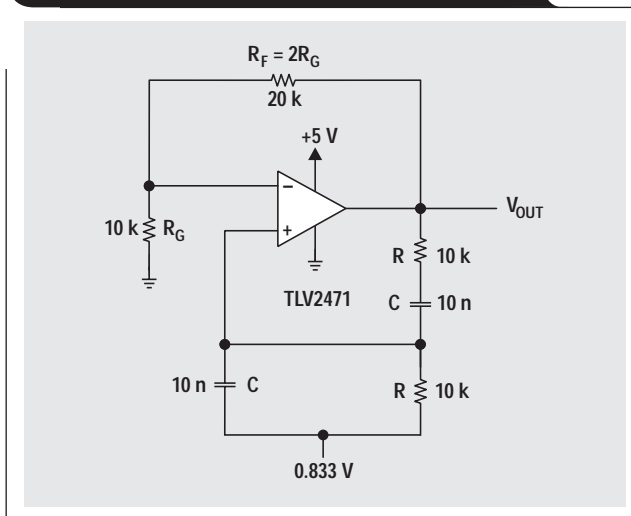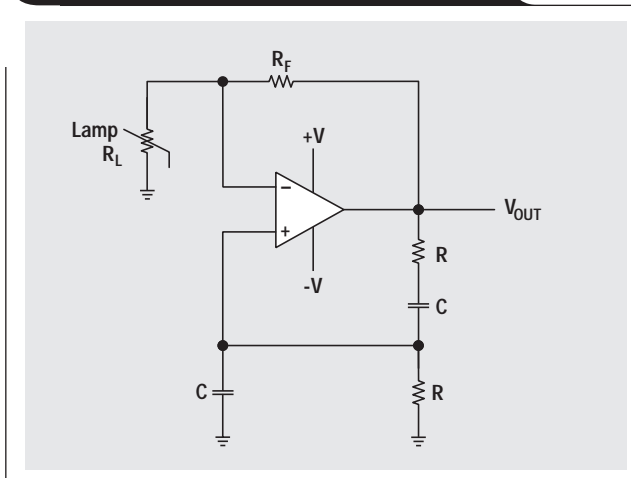Figure 3. Wien-bridge circuit schematic

Figure 4. Wien-bridge oscillator with non-linear feedback

component in the feedback loop, to automatic gain control (AGC) loops, to limiting by external components.

Wien-bridge oscillator

Figure 3 gives the Wien-bridge circuit configuration. The loop is broken at the positive input, and the return signal is calculated in Equation 2 below.

When $\omega = 2\pi f = 1/RC$, the feedback is in phase (this is positive feedback), and the gain is 1/3, so oscillation requires an amplifier with a gain of 3. When $R_F = 2R_G$, the amplifier gain is 3 and oscillation occurs at $f = 1/2\pi RC$. The circuit oscillated at 1.65 kHz rather than 1.59 kHz with the component values shown in Figure 3, but the distortion

$$\frac{V_{RETURN}}{V_{OUT}} = \frac{\dfrac{R}{RCs+1}}{\dfrac{R}{RCs+1}+R+\dfrac{1}{Cs}} = \frac{1}{3+RCs+\dfrac{1}{RCs}} = \frac{1}{3+j\left(RC\omega - \dfrac{1}{RC\omega}\right)}, \qquad \textbf{(2)}$$

where $s = j\omega$ and $j = \sqrt{-1}$.

is noticeable. Figure 4 shows a Wien-bridge circuit with non-linear feedback. The lamp resistance, R_L, is nominally selected as half the feedback resistance, R_F, at the lamp current established by R_F and R_L. The non-linear relationship between the lamp current and resistance keeps output voltage changes small.

Some circuits use diode limiting in place of a non-linear feedback component. The diodes reduce the distortion by providing a soft limit for the output voltage. AGC must be used when neither of these techniques yields low distortion. A typical Wien-bridge oscillator with an AGC circuit is shown in Figure 5.

The negative sine wave is sampled by D_1, and the sample is stored on C_1. R_1 and R_2 are chosen to center the bias on Q_1 so that $(R_G + R_{Q1}) = R_F/2$ at the desired output voltage. When the output voltage drifts high, Q_1 increases resistance, thus decreasing the gain. In the oscillator shown in Figure 3, the 0.833-volt power supply is applied to the positive op amp input to center the output quiescent voltage at $V_{CC}/2 = 2.5$ V.

Phase-shift oscillator (one op amp)

A phase-shift oscillator can be built with one op amp as shown in Figure 6.

The normal assumption is that the phase-shift sections are independent of each other. Then Equation 3 is written:

$$A\beta = A\left(\frac{1}{RCs+1}\right)^3 \qquad \textbf{(3)}$$

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 60° = 1.73. 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 1.

The oscillation frequency with the component values shown in Figure 6 is 3.76 kHz rather than the calculated

Figure 5. Wien-bridge oscillator with AGC
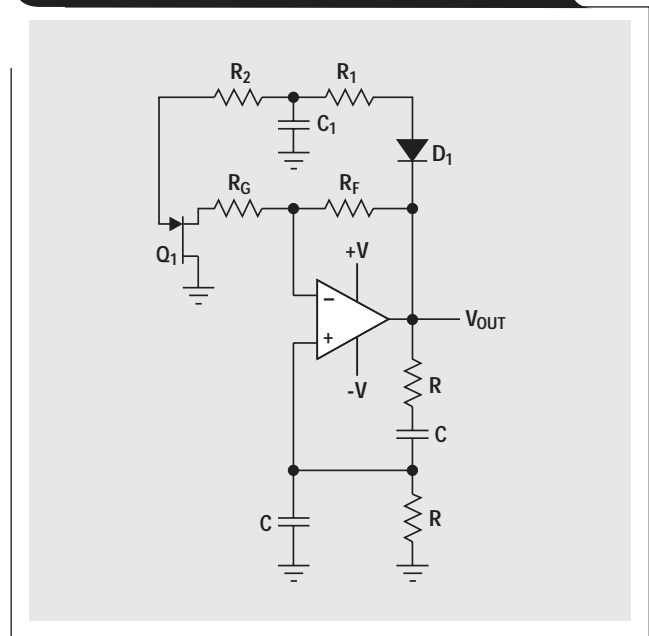
oscillation frequency of 2.76 kHz. Also, the gain required to start oscillation is 26 rather than the calculated gain of 8. These discrepancies are partially due to component variations, but the biggest contributing factor is the incorrect assumption that the RC sections do not load each other. This circuit configuration was very popular when active components were large and expensive, but now op amps are inexpensive and small and come four in a package, so the single op amp phase-shift oscillator is losing popularity.

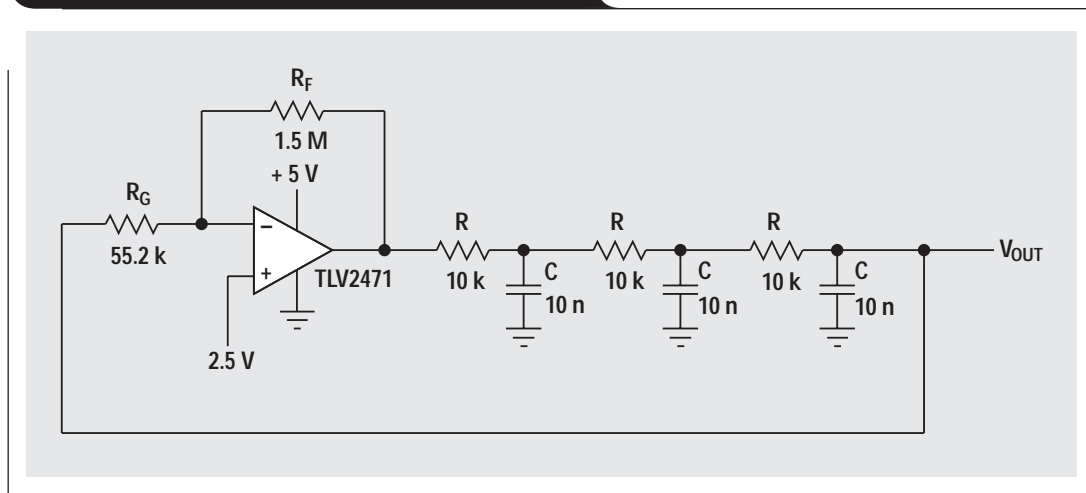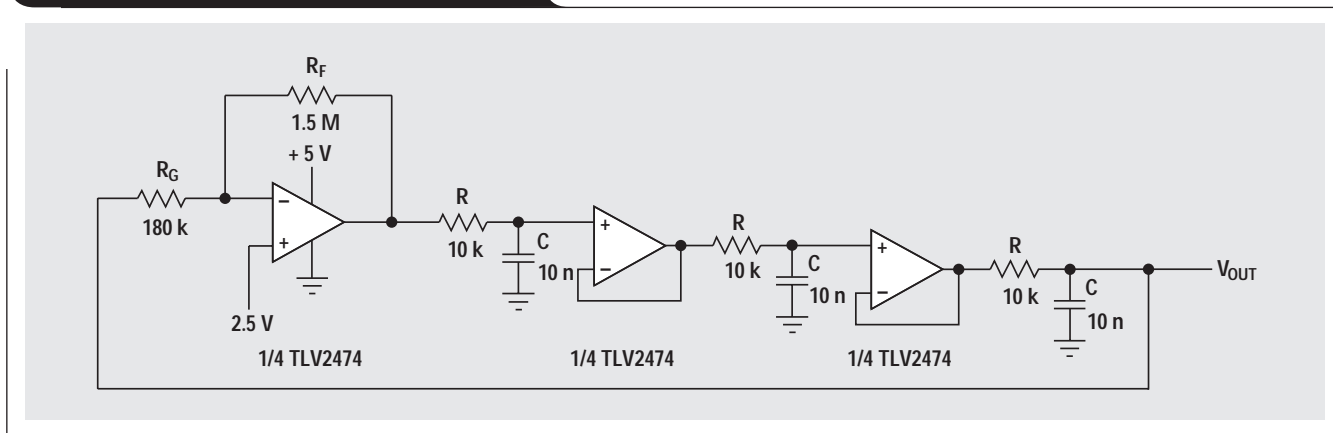Figure 6. Phase-shift oscillator (one op amp)

Figure 7. Buffered phase-shift oscillator

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Buffered phase-shift oscillator

The buffered phase-shift oscillator shown in Figure 7 oscillated at 2.9 kHz compared to an ideal frequency of 2.76 kHz, and it oscillated with a gain of 8.33 compared to an ideal gain of 8.

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, and if the fourth op amp 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, 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.

Quadrature oscillator

The quadrature oscillator is another type of phase-shift oscillator, but the three RC sections are configured so that each section contributes 90° of phase shift. The outputs are labeled sine and cosine (quadrature) because there is a 90° phase shift between op amp outputs (see Figure 8). The loop gain is calculated in Equation 4.
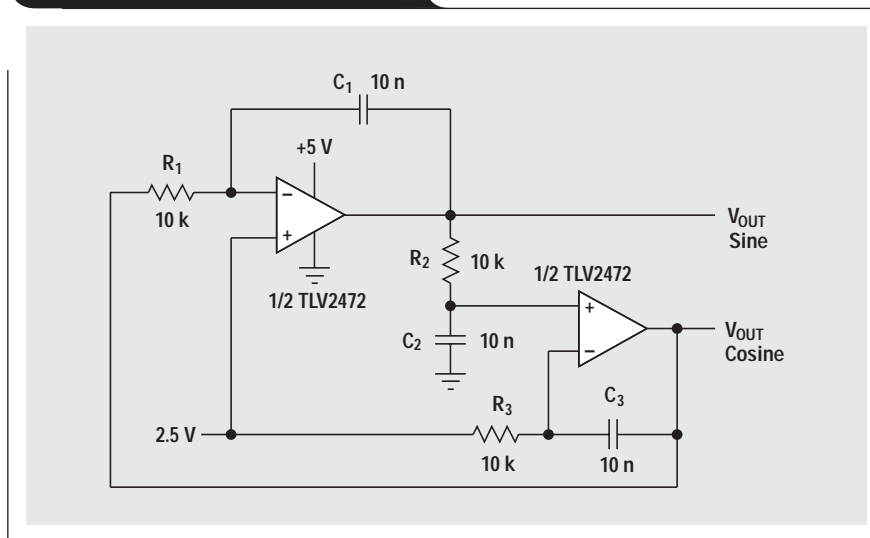
$$A\beta = \left(\frac{1}{R_1 C_1 s}\right)\left(\frac{R_3 C_3 s + 1}{R_3 C_3 s (R_2 C_2 s + 1)}\right) \qquad \textbf{(4)}$$

When $R_1 C_1 = R_2 C_2 = R_3 C_3$, Equation 4 reduces to Equation 5.

$$A\beta = \frac{1}{(RCs)^2} \qquad \textbf{(5)}$$

When $\omega = 1/RC$, Equation 5 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, and the discrepancy is attributed to component variations.

Figure 8. Quadrature oscillator

Bubba oscillator

The Bubba oscillator (Figure 9) 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 $d\phi/dt$ to minimize 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:

$$A\beta = A\left(\frac{1}{RCs+1}\right)^4 \qquad \textbf{(6)}$$

When $\omega = 1/RCs$, Equation 6 reduces to Equations 7 and 8.

$$|\beta| = \left|\left(\frac{1}{1+j}\right)^4\right| = \frac{1}{\sqrt{2}^4} = \frac{1}{4} \qquad \textbf{(7)}$$

$$Phase = Tan^{-1}1 = 45° \qquad \textbf{(8)}$$

The gain, A, must equal 4 for oscillation to occur. The test circuit oscillated at 1.76 kHz rather than the ideal frequency 1.72 kHz when the gain was 4.17 rather than the ideal gain of 4. With low gain, A, and low bias current op amps, the gain setting resistor, R_G, does not load the last RC section thus insuring 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 the op amps. The non-inverting input of the gain op amp is biased at 0.5 V to set the quiescent output voltage at 2.5 V. Gain distribution requires biasing of the other op amps, but it has no effect on the oscillator frequency.

Summary

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. The new current feedback op amps are very hard to use in oscillator circuits because they are sensitive to feedback capacitance. Voltage feedback op amps are limited to a few hundred kHz because they accumulate too much phase shift.

Figure 9. Bubba oscillator
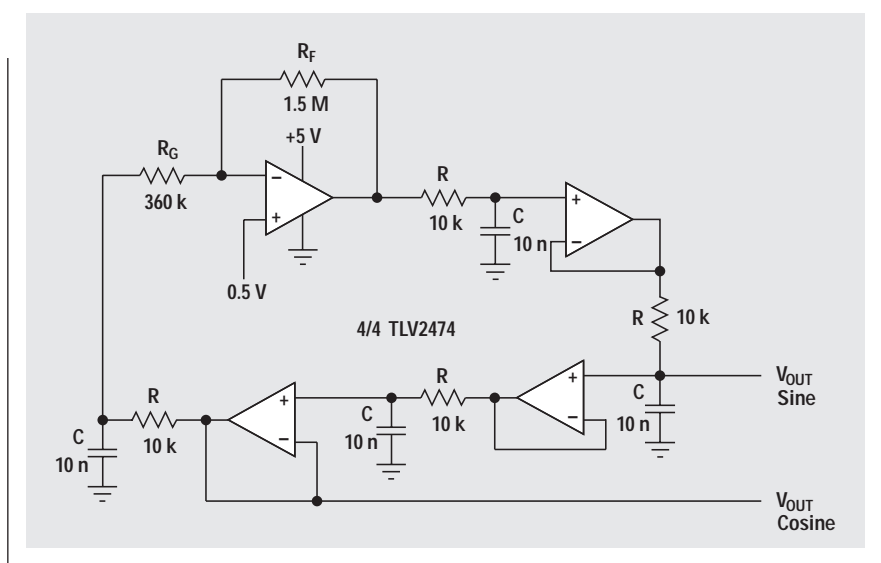
The Wien-bridge oscillator has few parts, and its frequency stability is good. Taming the distortion in a Wien-bridge oscillator is harder than getting the circuit to oscillate. The quadrature oscillator only requires two op amps, but it has high distortion. Phase-shift oscillators, especially the Bubba oscillator, have less distortion coupled with good frequency stability. The improved performance of the phase-shift oscillators comes at a cost of higher component count.

References

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Document Title   **TI Lit. #**

1. "Feedback Amplifier Analysis Tools" sloa017

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