Sine Wave Oscillators

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March 8, 2009, rev. April 11, 2009

Introduction

A sine wave oscillator is an amplifier with positive feedback such that the system poles are on (or initially to the right) of the jw axis in the s-plane. Although there are a variety of circuits for achieving this, all of them work the same fundamental way. The Barkhausen criteria for oscillation is that the positive feedback loop gain be 1 (or more) and that the total phase change (including phase inversions) around the loop be either 0 or 360 degrees at the frequency of oscillation.

The oldest method for generating sine waves is to start with a resonant circuit consisting of an inductor and capacitor whose poles are almost on the jw axis on the s-plane. The addition of some electronic gain in a positive closed-loop network will move the poles rightwards to the jw axis. This method is still used today for radio frequency (RF) oscillators.

Another common method is to use a resistor-capacitor network that has a phase shift of either 0 or 180 degrees at a particular frequency. When such a network is inside a positive closed-loop system with the right amount of gain the system poles will be on the jw axis.

In either case the gain of the oscillator must be the exact amount that puts the system poles exactly on the jw axis. If the gain is even the slightest less then the poles are in the left s-plane and any sine wave decays to zero. If the gain is even the slightest more then the poles are in the right s-plane and the sine wave grows exponentially until the system amplitude limits are reached. It is impossible in reality to set the gain to the exact amount. Even if one could perfectly set the gain the amplitude of the sine wave would be indeterminate. The solution to this dilemma is to start with a system that has somewhat too much gain (i.e. system poles in the right s-plane) and then either to use some form of automatic gain control or some form of amplitude compression that results in an operating point of exactly the gain required and also a predictable amplitude.

In RF oscillators using inductor-capacitor resonators a common method is to employ peak detection to alter the bias of the transistor so that the gain is reduced as the amplitude grows thus producing a stable operating point. That method has a drawback in introducing some amount of phase noise on the generated signal and amplitude limiting is the preferred method where phase noise must be as small as possible. The details are beyond the scope of this introductory article.

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RC Oscillators

Wein Bridge

This is the famous oscillator that Bill Hewlett developed as part of a master's thesis project in 1938 at Stanford University in Palo Alto, California under Dr. Frederick (Fred) Terman. This became the first and very famous product, the model 200A, of the newly formed Hewlett-Packard Company in 1939 and oscillators based on that technique were sold until 1985. The circuit uses a bandpass RC network in the positive feedback path that has zero phase shift at the natural frequency and the positive resistance versus temperature characteristic of a tungsten filament in a light bulb to amplitude regulate the negative feedback path so that it equals that of the positive feedback path. Figure 1 shows a modern version of the circuit that oscillates at 1.6 kHz.

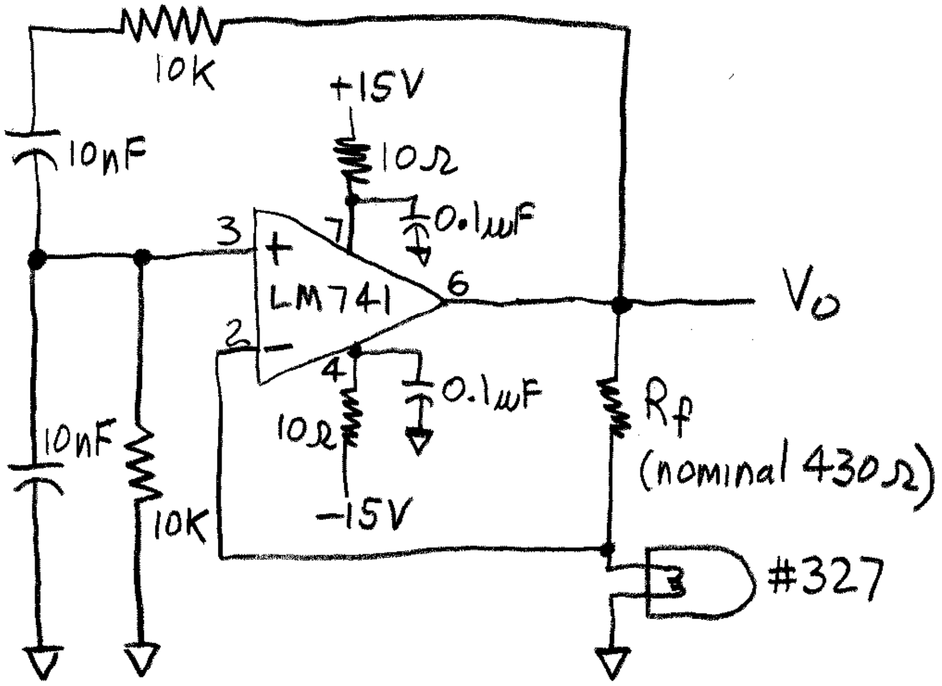

Figure 1: Wein Bridge Oscillator

At the natural frequency, the RC bandpass filter has a transfer function of 0.333 with a phase shift of zero degrees. At the stable operating point, the negative feedback path as determined by the voltage divider, Rf and the resistance of the lamp is also 0.333 thus making the non-inverting voltage gain equal to 3.000. This results in a net positive loop gain of 1.000 thus satisfying the Barkhausen criteria. The room temperature (~300 K) of an unpowered type 327 bulb is around 100 ohms. The non-inverting gain of the amplifier using 430 ohms (as used by Jim Williams at Linear Technologies Corporation) for Rf is 5.3 which is more than needed, thus at start-up the system poles are in the right s-plane and the amplitude of oscillation grows exponentially as expected. However, as the amplitude of oscillation grows the lamp filament begins receiving power and heats thus raising its resistance and lowering the gain. This negative thermal feedback process continues until the output signal amplitude is such that the resistance of the lamp filament has risen to nominally 215 ohms thus bringing the bringing the positive loop gain to exactly 1.000 and the output sine wave amplitude is stable and undistorted at an amplitude of around 4.5 Vrms. One very important thing to note is that the time period of oscillation must be much shorter than the thermal time constant of the filament. Otherwise the resistance of the filament will vary as a function of the time in the sine wave cycle and distortion will be introduced.

From s-plane analysis the magnitude of oscillation is indeterminate when the poles are on the jw axis. Some other function must establish that. So in addition to stabilizing the gain, the lamp also stabilizes the level of oscillation based on its physical characteristics related to the feedback resistor. For proper operation, the lamp must be operated at relatively low temperatures where the change in resistance versus applied power is greatest.

Figure 2 shows the relative resistivity of tungsten versus temperature. Since the room temperature resistance of a type 327 lamp is around 100 ohms then working the plot backwards from the final value of 215 ohms indicates that the lamp temperature is around 600 K which is too low to produce visible light. Thus, in normal operation the lamp is not glowing and has an extremely long life. Normal operating temperatures for a lamp emitting visible light are in the 2000 to 3000 K range.

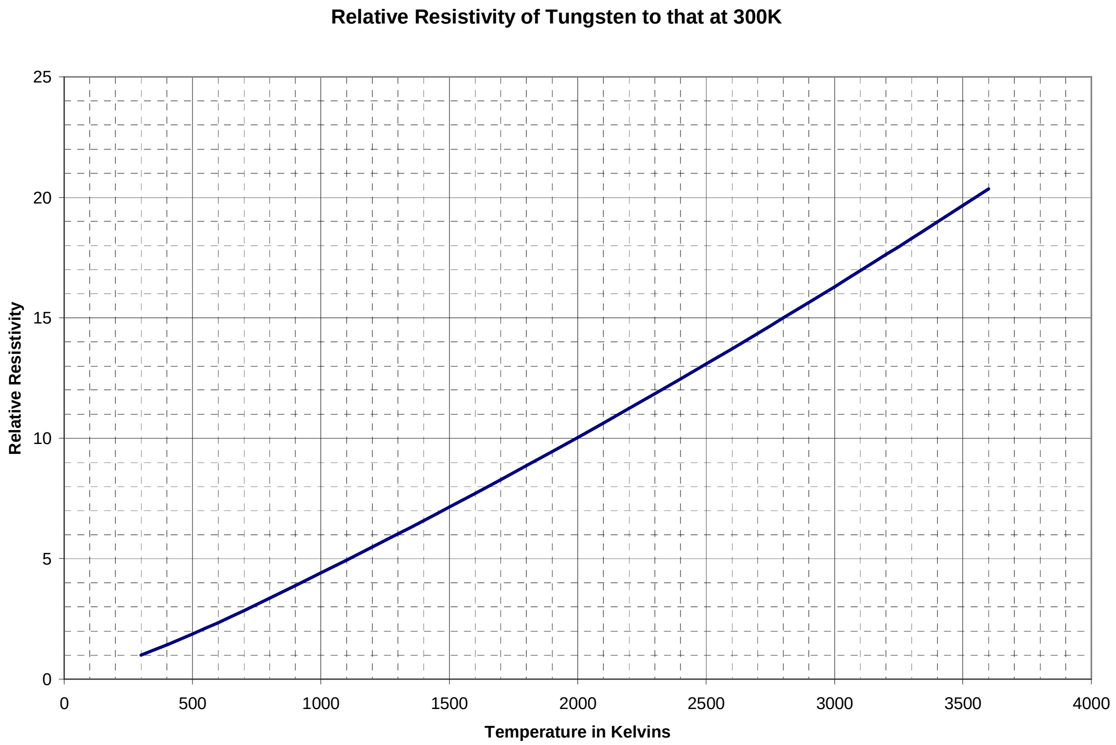

Figure 2: Relative Resistivity of Tungsten

Figure 3 shows a plot of actual data of the stable output level of the oscillator as set by the value of the feedback resistor. At low feedback resistances the thermal loop that ultimately stabilizes the operating point is very unstable in of itself and the start-up transient is significant and in some cases may never settle. This problem diminishes at the higher resistances because amplifier clipping is not much above the final operating point thus preventing the transient from being excessively large.

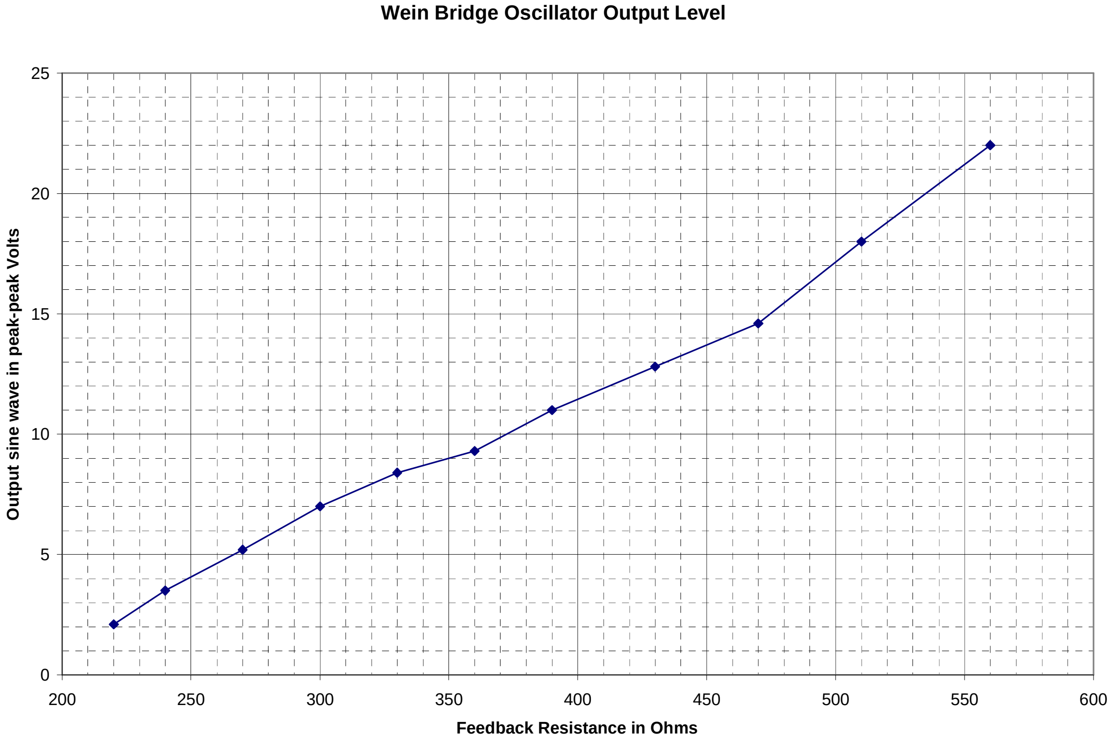

Figure 3: Wein Bridge oscillator output versus feedback resistance

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Phase Shift

The phase shift oscillator is based on feedback network consisting of three RC sections to achieve a phase shift of 180 degrees at a particular frequency. With an inverting gain of 29 the system poles are on the jw axis.

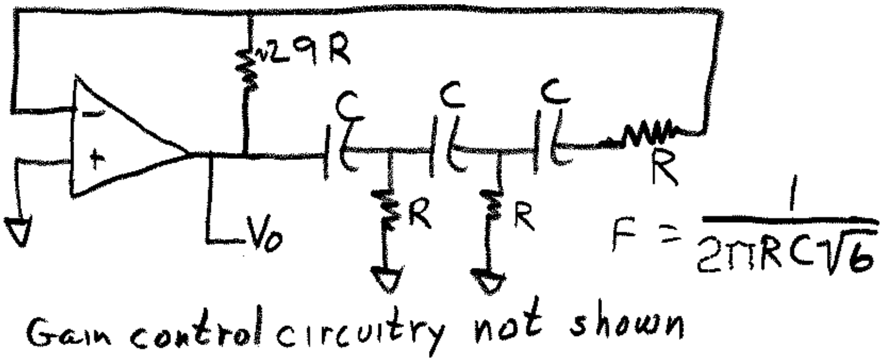

Figure 4: Phase Shift Oscillator

LC Oscillator Circuits

The first electronic oscillators were constructed using a resonant combination of inductance and capacitance. Such oscillators are still built to this day. The poles are already close to the jw axis and it only takes a small gain from an amplifier to move the poles to the jw axis. Since it is impossible to place the poles exactly on the jw axis the usual method is to design a small amount of excess gain that places the poles in the right s-plane (this also guarantees that the oscillator will start) and then amplitude limiting (a non-linear concept) is used to stabilize operation. There are three basic types of oscillators although there are numerous variations, some with different names. The names of the oscillators are in honor of the person credited with the first implementation. For simplicity all of the circuits are shown without the needed limiting mechanism. All of the circuits will self limit at some point but that is not the best way to operate them. LC oscillators work best if the loaded Q of resonance is high, preferably much greater than ten.

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Armstrong

The feedback mechanism is a coil that couples signal from the output of the amplifier back to the LC resonant circuit with the proper phase for positive feedback.

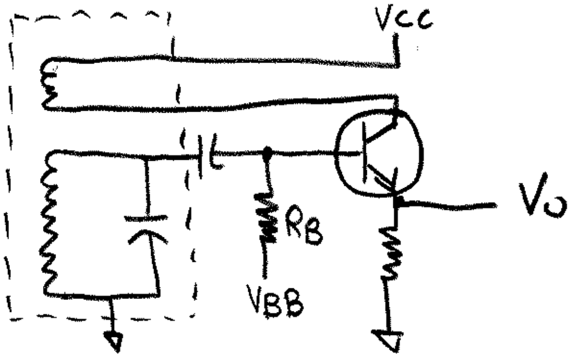

Figure 5: Simple Armstrong Oscillator

Hartley

The Hartley oscillator is a variation of the Armstrong that uses a tapped coil to couple energy rather than a second winding. The tap point is based on the needed impedance transformation. At resonance the signal at the top of the coil is in-phase with the signal at the tap so the phase response of the network is zero degrees. The amplifier provides zero phase shift and the net positive loop gain with limiting is one.

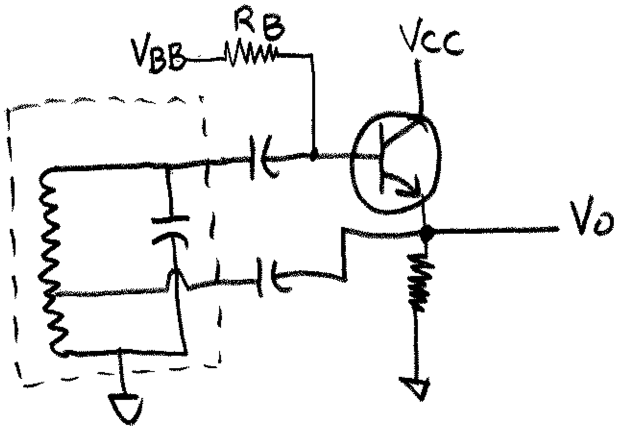

Figure 6: Simple Hartley Oscillator

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Colpitts

The Colpitts oscillator uses two series connected capacitors in the resonant circuit similar to the tap on the inductor in the Hartley circuit to couple energy. The tap point is based on the needed impedance transformation. At resonance in the circuit shown the phase of the transfer function is -180 degrees. The transistor amplifier provides phase inversion for a total of 360 degrees around the loop. The Colpitts oscillator is one of the most popular because it does not require either a second winding or tap on the inductor. The Colpitts oscillator is easily adaptable to oscillation at very high frequencies and there are numerous topologies optimized for various applications.

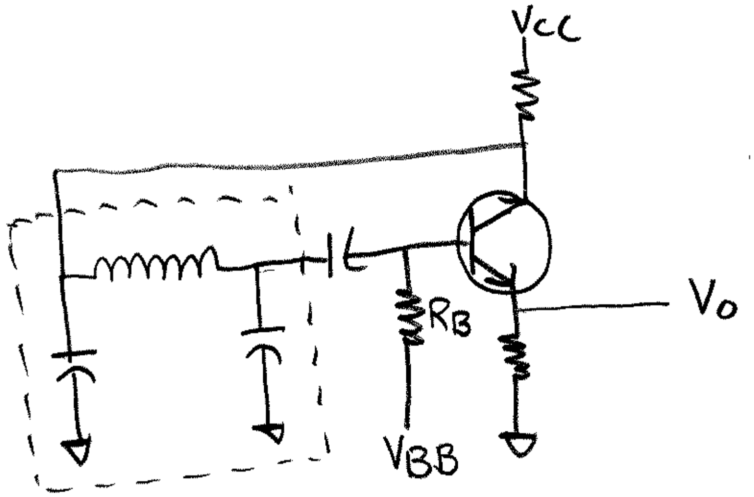

Figure 7: Simple Colpitts Oscillator