Classification of Electrical Oscillators

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Chapter 1

Introduction

Electrical oscillators are used as timing references or waveform generators in computers, communication systems, test and measurement equipment, scientific experiments, and many other applications. While the sheer number of different oscillator circuits is impressive, all common electrical oscillators can be classified into just five groups with common fundamental operating mechanisms and shared important characteristics such as the ability for wide frequency tuning or the potential for low noise. In this article I discuss a classification scheme, the fundamental properties of the five common oscillator classes, and several practical oscillator circuits.

The classification system discussed in this article is based on the book *Oscillators and Oscillator Systems: Classification, Analysis and Synthesis* by Jan R. Westra, Chris J. M. Verhoeven, and Arthur van Roermund (Springer, 1999). In this article I reformulate the for me important concepts in an application- and circuit-oriented fashion. The scope of this article is confined to the classification and properties of single oscillators while the book also includes a chapter on oscillator systems, that is circuits with multiple oscillators synchronized to each other. Also I limit the main scope of this article to oscillator classes that find broad practical use.

The remainder of the article is structured as follows: Chapter 2 discusses the basic oscillator classification scheme and the fundamental properties of the different oscillator classes. The following chapters 3 to 5 show examples of practical oscillator architectures that are in common use. Finally the article is summarized in chapter 6.

Chapter 2

Oscillator Classification

The book *Oscillators and Oscillator Systems: Classification, Analysis and Synthesis* groups electrical oscillators according to two main criteria: the oscillation mechanism and the pole-zero pattern. The first two sections will discuss these two criteria. Later sections will then show the oscillator classes that are of broad practical interest and investigate their fundamental tuning and noise properties.

2.1 Oscillation Mechanism

There are two fundamentally different oscillation mechanisms: relaxation oscillation and harmonic oscillation. Relaxation oscillators rely on nonlinear feedback and produce waveforms rich in harmonics, usually either a triangular, sawtooth, or RC step response waveform. Because of the nonlinear feedback, the oscillation frequency of relaxation oscillators depends directly on the oscillation amplitude. The operation of harmonic oscillators, on the contrary, can be largely described with a linear feedback model and their waveforms may be purely sinusoidal. While a harmonic oscillator always requires a nonlinear mechanism to stabilize its amplitude, the oscillation frequency is in principle not affected by the oscillation amplitude.

Relaxation oscillators require three fundamental functions for their operation: time-to-amplitude transfer, level discrimination, and state memory.

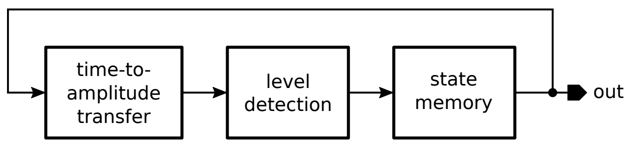

Figure 2.1: Block diagram showing the three fundamental functions required for relaxation oscillators: time-to-amplitude transfer, level detection, and state memory.

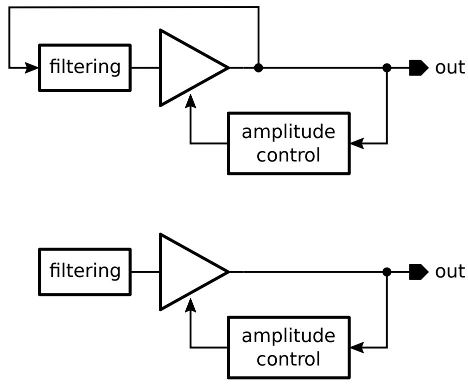

Figure 2.2: Block diagram showing the three fundamental functions required for harmonic oscillators: filtering, amplification, and amplitude control. The top drawing shows an oscillator with a two-port filter and the bottom drawing an oscillator with a one-port filter.

A block diagram illustrating these functions and their connection is shown in figure 2.1. The time-to-amplitude transfer makes time an electronically measurable quantity by generating a time-variant signal. For example, this function can be implemented as a capacitor that is charged with a DC current. As the voltage across the capacitor increases linearly with time, time is now electronically measurable by observing the voltage across the capacitor. The level discriminator, the second fundamental function of relaxation oscillators, senses the amplitude of the time-variant signal and changes the state of the oscillator when the time-variant signal exceeds or falls below a certain threshold. Changing the state of the oscillator is what generates a periodic signal out of the time-variant signal, and what constitutes the nonlinear feedback of relaxation oscillators. In the example given above where the time-to-amplitude transfer is implemented as a capacitor charged by a DC current, changing the oscillator state can be realized by switching the sign of the DC current. Changing the sign of the DC current also changes the direction of the voltage ramp, thereby creating a periodic signal with bounded amplitude. If we shift the thresholds at which the level detector changes the oscillator state, both the oscillator amplitude and the time between state changes varies. This is why the frequency of relaxation oscillators depends directly on their amplitude. The third fundamental function, the state memory, is required to keep the state of the oscillator until the next state change. There is only a discrete set of oscillator states: usually just two, in our example *ramping up* and *ramping down.* The state memory is thus implemented as a digital circuit, for example a latch. In practical relaxation oscillators, level detection and state memory are often implemented together in a single circuit, for example using a comparator with hysteresis.

In harmonic oscillators we can again identify three fundamental functions: filtering, amplification, and amplitude control. These three functions and their connection are shown in figure 2.2. The filtering function gives the circuit selectivity such that the oscillation frequency is determined. If the filtering is realized as a two-port filter, the amplifier is configured as a feedback system around the filter such that at the oscillation frequency sufficient gain for positive feedback is available to start and sustain oscillation. If the filtering is realized as a one-port filter, the amplifier is configured as a negative-resistance generator that cancels the loss of the filter. In this case the positive feedback required to start oscillation is embedded inside the amplifier to generate the negative resistance. In any case the oscillation occurs because the amplifier drives the system poles into the right hand plane such that the circuit becomes unstable and oscillation can start. As the amplitude grows, the amplitude control will reduce the gain of the amplifier which moves the poles back towards the imaginary axis. Once the poles lay exactly on the imaginary axis, the oscillator has reached its steady state. As both the filter and the amplifier can be implemented as circuits with high linearity, the frequency of harmonic oscillators can be independent from the amplitude.

Often some of the three fundamental functions of harmonic oscillators are combined in one circuit. In particular the filter may be realized as an active filter and thereby combines filtering with amplification, or the gain compression of the amplifier limits the oscillator amplitude and thus combines amplification with amplitude control.

2.2 Pole-Zero Pattern

Besides the oscillator mechanism, the pole-zero pattern of an oscillator circuit is useful to group oscillators into classes with similar fundamental properties. First of all it should be noted that oscillator circuits apply feedback that modifies the pole-zero pattern, for example a real pole pair may be transformed into a complex pole pair, or the pole position might be horizontally shifted from the left half plane to the imaginary axis. The fundamental properties of the oscillator, however, are determined by the pole-zero pattern *before* the application of feedback. Thus the classification considers the open-loop pole-zero pattern only.

Although theoretically oscillators can be built with any pole-zero pattern, most common oscillators use either just real poles or just complex poles. So a first broad pole-zero pattern classification can be done based on whether the oscillator uses real or complex poles. A more detailed pole-zero pattern classification also considers the number of poles. The number of poles determines the *order* of the oscillator. So, for example, an oscillator with two poles is called a *second-order oscillator.* As most common oscillators do not depend on zeros for their operation, I do not consider zeros in the pole-zero pattern for the classification.

In oscillators using lumped elements, the pole-zero pattern is directly formed by capacitors, inductors, resistors, and transconductances. With lumped elements, oscillators of any finite order and both with real or complex poles can be built. Alternatively distributed elements may be used. Locally around the desired mode, distributed elements that resemble a bandpass filter function can be approximated as an equivalent lumped inductance-capacitance resonator. As such a lumped resonator results in a complex pole pair, oscillators using a distributed resonator with bandpass filter function are classified as *second-order complex pole oscillators.* Distributed elements that resemble a delay line can be approximated as a low-pass filter formed by a high number of lumped inductance-capacitance sections in series. Ideally the approximation would use an infinite number of sections to fully model a pure time delay. Oscillators using a distributed element with delay line characteristics are therefore classified as *infinite-order complex-pole oscillators.*

2.3 Common Oscillator Classes

Not every combination of oscillation mechanism and pole-zero pattern can be used to build oscillators or finds broad practical use. In particular harmonic oscillators require at least two poles and relaxation oscillators are in practice built with one pole only. Overall, only oscillators from five different classes are common:

- first-order real pole relaxation oscillators;
- second-order real pole harmonic oscillators;
- higher-order[1] real pole harmonic oscillators;
- second-order complex pole harmonic oscillators;
- infinite-order complex pole harmonic oscillators.

Figure 2.3 illustrates the classification of electrical oscillators into these five groups.

2.4 Noise and Tuning Properties

Low noise and wide frequency tuning are often desired oscillator characteristics. To understand the fundamental properties of an oscillator class with

[1] *Higher-order* means a finite number of three or more poles.

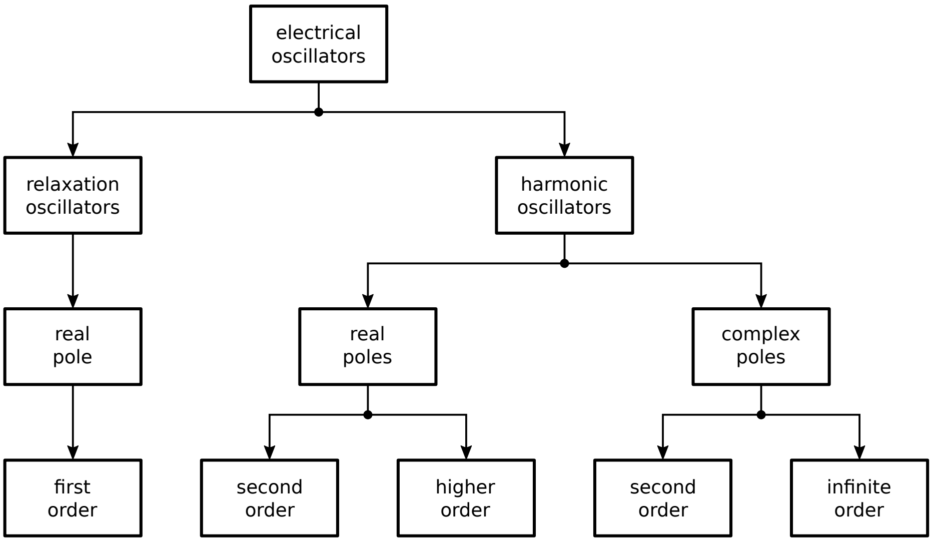

Figure 2.3: Classification of common electrical oscillators into five groups.

respect to these two characteristics the concept of *energy flow* is very useful. In oscillators, we can identify three relevant energy flow mechanisms:

- Energy is dissipated because of the loss in capacitors, inductors, or distributed passive elements, that is electrical energy is converted into heat.
- Energy is supplied to or withdrawn from capacitors, inductors, or distributed passive elements through active circuits.
- Energy is exchanged between capacitors and inductors, or within different regions of distributed passive elements.

Both the dissipation of energy and the process of supplying or withdrawing energy through active circuits is associated with noise. Thus for low noise these energy flow mechanisms should be minimal. The exchange of energy between passive reactive elements, on the other hand, is a noiseless mechanism and therefore the preferred energy flow for low noise oscillators.

In real pole oscillators only the first two energy flow mechanisms are present. As loss in passive reactive elements is usually negligible in such oscillators, this means that essentially the full energy flow from and to passive reactive elements takes place through active circuits and a comparably high amount of noise is generated. In complex pole oscillators the third mechanism is the dominant one. The first two mechanisms are present too because of the loss in the passive reactive elements which has to be compensated through active circuits to keep the oscillator in steady-state, but the third mechanism usually transports at least ten times more energy. Therefore complex pole oscillators can have comparably low noise.

With respect to tuning, a similar clear distinction between real pole and complex pole oscillators exists. Most common oscillator tuning schemes change the speed at which energy flows either between or to and from passive reactive elements. As in oscillators with real poles the energy is supplied and withdrawn from passive reactive elements through active circuits, changing the speed of the energy flow is comparably easy by changing the gain (for example the transconductance) of the active circuits. In most cases such a tuning mechanisms can be implemented with negligible noise penalty and tuning ranges as wide as several decades may be achieved.

In complex pole oscillators the active circuitry usually supplies energy only to compensate the loss in passive reactive elements. This mechanism is not associated with the oscillation frequency and thus can not be used to tune an oscillator. Instead the passive elements themselves have to be changed to influence the speed of the energy flow between the passive elements. Changing passive elements in an oscillator often introduces significant additional loss that increases noise. Also parasitic capacitance introduced by the tuning elements lowers the maximum oscillation frequency. In practice the tuning range of complex pole oscillators is therefore usually limited to an octave or less, and circuits with narrow tuning range tend to have lower noise than oscillators with wide tuning range.

Amplitude bounce from tuning is another important consideration in some applications. In relaxation oscillators, the strong nonlinear operation of the level detector stabilizes the amplitude of the oscillator instantaneously. For harmonic oscillators, amplitude bounce may or may not be present depending on the design details of the tuning mechanism. Real pole oscillators can be tuned by changing the value of either resistors or transconductances. Such tuning can be implemented so that only very little amplitude bounce occurs. On the other hand, if the value of passive reactive elements is changed to tune the oscillator, not only the speed of the energy flow is changed but also the internal states of the oscillator may be disturbed. As bringing the internal oscillator states back to their steady-state energy distribution takes time, the oscillator amplitude does not stabilize immediately and some bounce occurs. To avoid this behavior, the tuning of the oscillator can be timed such that it only occurs at the moment where a reactive element has zero instantaneous energy stored. If the value of a capacitor, for example, is changed when the voltage across the capacitor is zero, no amplitude bounce results. Particularly for oscillators operating at high frequency, implementing such a timed tuning mechanism is, however, often impractical.

Chapter 3

Real Pole Relaxation Oscillators

This chapter covers real pole relaxation oscillators. In practice, these circuits are built as first-order oscillator only, and the pole is realized with a capacitor and a current source or a capacitor and a resistor. For relaxation oscillators where a current source and a capacitor realize the pole, tuning is remarkably easy by just changing the DC current of the current source. Such a tuning scheme can be very linear over several decades.

3.1 First-Order

Figure 3.1 shows a first-order relaxation oscillator which is usually called an *astable multivibrator.* The square wave output signal is fed back to the negative input of the comparator through a RC low-pass filter, and to the positive input of the comparator through a resistive voltage divider. The combined action of positive and negative feedback makes the circuit unstable and defines the oscillation frequency. As discussed in section 2.1, a relaxation oscillator requires three fundamental functions for operation: time-to-amplitude transfer, level detection, and state memory. Here, the RC low-pass filter implements the time-to-amplitude transfer while the comparator with positive feedback through the resistive voltage divider realizes the level detection and state memory.

Note that while the circuit uses the square wave from the comparator as output, the actual oscillator signal, a RC step response, is situated at the negative comparator input. The square wave at the positive comparator input sets the threshold at which the comparator output switches. If we change the attenuation of the resistive voltage divider, the comparator will switch at a different point in the RC step response of the oscillator waveform. Switching at a different point in the RC step response simultaneously affects both the amplitude and frequency of the oscillator waveform. As discussed

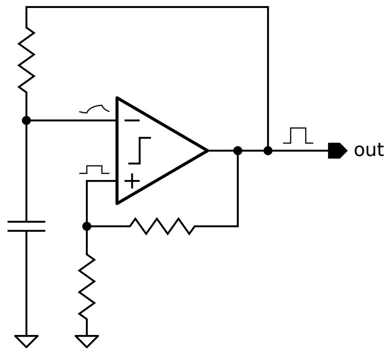

Figure 3.1: Astable multivibrator, a first-order relaxation oscillator

in section 2.1, this direct coupling of oscillator amplitude and frequency is a fundamental property of relaxation oscillators. The oscillation frequency, however, is independent from the amplitude of the output square wave. That is because both the square wave and the RC step response signal at the comparator inputs proportionally track the amplitude of the output square wave, and the comparator senses the relative amplitude difference between its two inputs only.

For tuning, at least one passive component has to be changed. As there are other relaxation oscillator architectures that are more easily tuned, the astable multivibrator is primarily used for uncritical timing applications that tolerate a fixed frequency with comparably high production spread.

Figure 3.2 shows a relaxation oscillator that is implemented as a fully differential circuit. In this oscillator, two current sources periodically charge and discharge a differentially connected capacitor. The resulting triangular waveform is buffered and sensed by a comparator. At the output of the comparator, a square wave drives the gates of CMOS switches which alternately steer the current sources to one or the other side of the capacitor. The amplitude of the oscillation signal, the triangular wave, is set by the internal hysteresis of the comparator. Changing the magnitude of the hysteresis affects both the amplitude and frequency of the oscillator, which we recognize as the fundamental coupling mechanism always found in relaxation oscillators. In this circuit, the current sources and the capacitor implement the time-to-amplitude transfer, the first fundamental function required for the operation of a relaxation oscillator. The comparator with internal hysteresis realizes the other two fundamental functions, level detection and state memory.

Mismatch between the two current sources results in a symmetry error, that is a difference in slope between the rising and falling edge of the triangular wave. In the shown circuit, common-mode feedback forces the bottom current source to track the top current source. That way the oscillator can be tuned over several decades by adjusting the top current source while maintaining

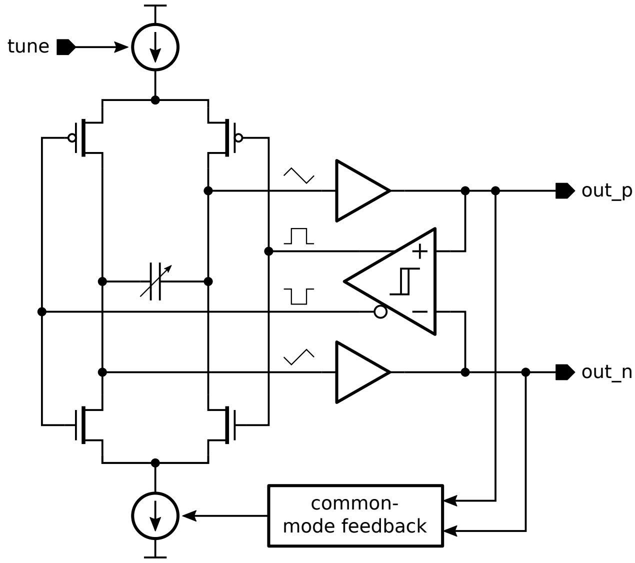

Figure 3.2: Differential first-order relaxation oscillator

excellent waveform symmetry. To further increase the tuning range, the capacitor is often made switchable in decadic steps.

This oscillator is an excellent candidate for function generators. Besides the triangular wave, a square wave is already available and can be used as an alternative output waveform. Furthermore, a sine shaper is usually added to convert the triangular wave into a sine wave.

Chapter 4

Real Pole Harmonic Oscillators

This chapter discusses the class of real pole harmonic oscillators. In real pole harmonic oscillators, either transconductances and capacitors, or resistors and capacitors form the pole-zero pattern. Theoretically inductors could be used as reactive elements too, but capacitors are preferred because of their lower cost, size, and loss. Typically real pole harmonic oscillators offer multiple output phases and can be tuned over a wide range. The first section of this chapter discusses second-order real pole harmonic oscillators. Higher-order real pole harmonic oscillators are covered by the second section.

4.1 Second-Order

Figure 4.1 shows a second-order real pole harmonic oscillator where two main transconductances and two shunt capacitors form two integrators in series. This type of oscillator is called a *g_m-C oscillator* and offers quadrature phase outputs at the two integrator nodes. By changing the two main transconductances simultaneously, a $\mathrm{g_m}$-C oscillator can achieve linear and bounce-free tuning over several decades. Two additional transconductances are configured with positive feedback to generate negative resistance at the output nodes of the main transconductances. To stabilize the oscillator amplitude, an amplitude control loop adjusts the negative resistance until the integrator losses are exactly compensated.

Figure 4.2 shows another second-order real pole harmonic oscillator. In this circuit, resistors, capacitors, and operational amplifiers realize two integrators and an inverter that is required for correct loop polarity. As this type of oscillator is derived from a state-variable low-pass filter, it is called a *state-variable RC oscillator.* As for the $\mathrm{g_m}$-C oscillator, the two integrator outputs are in quadrature and changing the time constants of the two integrators simultaneously results in a linear tuning characteristics.

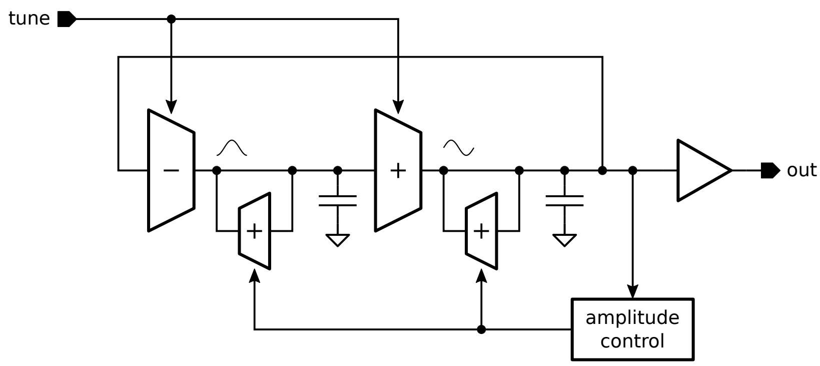

Figure 4.1: A second-order g_m-C oscillator

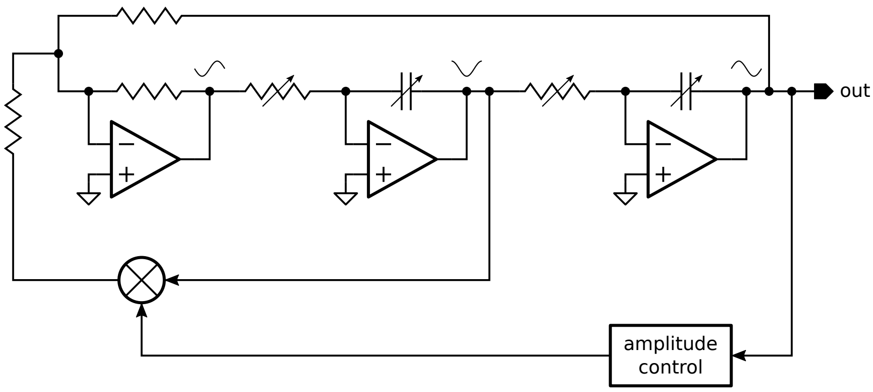

Figure 4.2: A second-order state-variable RC oscillator

Typically the capacitors are switched to select decadic ranges and the resistors are switched for fine tuning within a decade. Switching the resistors of the integrators is a bounce-free tuning mechanism. Switching the capacitors, on the other hand, disturbs the internal states of the oscillator and results in amplitude bounce.

The amplitude control loop adjust the Q of the state-variable filter with a multiplier. If the Q is set to infinity, the oscillator poles lay exactly on the imaginary axis and the amplitude is stable. As all elements of the state-variable RC oscillator can be realized with very low harmonic distortion, the output waveform can have very low harmonic distortion too. The state-variable oscillator is thus a common choice as source for low-frequency harmonic distortion measurements.

Figure 4.3 shows a typical implementation of the Wien-bridge oscillator. The Wien-bridge is a classic RC oscillator that can be implemented with very few elements. The oscillation frequency is determined by a RC bridge that is wired to give positive feedback. In this particular implementation, a thermistor in the feedback network of the operational amplifier provides the amplitude control function. Initially at power up, the gain of the amplifier

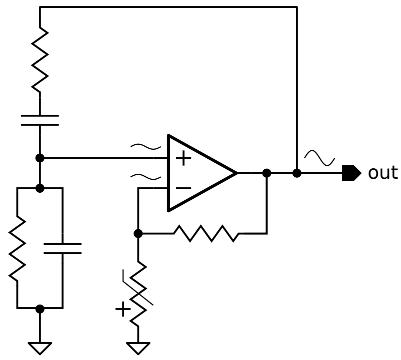

Figure 4.3: A Wien-bridge oscillator

is high such that oscillation starts. As the amplitude of the oscillation grows, the thermistor dissipates more power and thus heats up. Because of the positive temperature coefficient of the thermistor, the amplifier gain is reduced until it matches the loss of the RC bridge and the oscillator amplitude stabilizes. At high oscillation frequencies where the thermal time constant of the thermistor is large compared to the period of the oscillation, this amplitude control scheme adds little harmonic distortion. At low frequencies, the resistance of the thermistor is dynamically modulated by the signal and significant harmonic distortion may be generated.

4.2 Higher-Order

The by far most common higher-order real pole harmonic oscillator is the *ring oscillator.* Ring oscillators are convenient for integration and they offer multiple output phases. Figure 4.4 shows a typical implementation where CMOS inverters form a ring of g_m-C integrators. The oscillator is tuned by adjusting the transconductance of the inverters through a common current source. To reduce high-frequency ripple on the supply voltage of the inverters, a bypass capacitor shunts the current source to ground. The oscillator amplitude is stabilized by the nonlinearity of the inverters. As the amplitude increases, the output swing of the inverters approaches the supply voltage. The resulting increase in inverter output conductance limits the amplitude and ensures essentially bounce-free tuning. Additional amplitude limiting can result from transconductance compression.

The oscillator in figure 4.4 is built from three inverters and thus classifies as third-order oscillator. Increasing the order is possible by adding more inverters. To maintain correct loop polarity, an odd number of inverters has to be used in a single-ended oscillator. In differential ring oscillators, an even number of inverters can be realized though because cross-coupling structures can prevent latch-up. Figure 4.5 shows such a differential ring oscillator. Compared to figure 4.4, the schematic omits the current source, supply

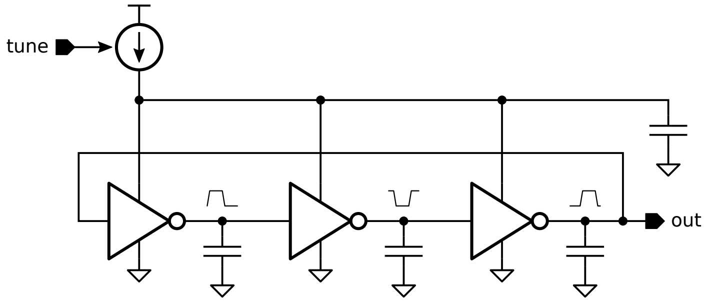

Figure 4.4: A third-order CMOS ring oscillator

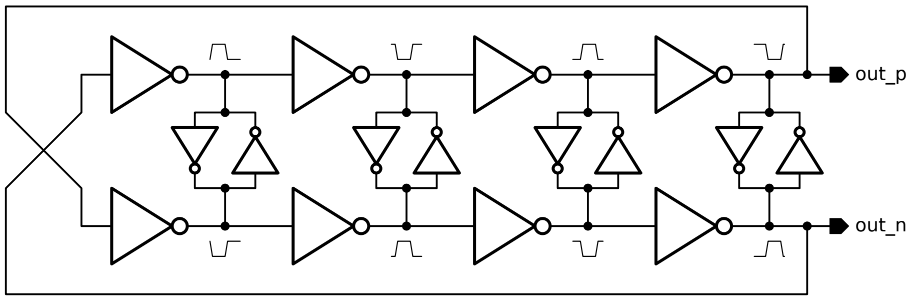

Figure 4.5: A fourth-order differential CMOS ring oscillator

decoupling, and load capacitances for clarity, but a practical implementation would probably include these elements too.

Apart from using CMOS inverters, it is also common to build ring oscillators from current-mode logic (CML) stages. Figure 4.6 shows such an oscillator. Here the oscillator has third-order, but thanks to the common-mode rejection of CML stages, even-order oscillators are realizable without any particular additional circuitry. The oscillation frequency is determined primarily by the transconductance and the input capacitance of the CML stages. Tuning can be achieved by adjusting the tail current sources and thus the transconductance, or by adding explicit load capacitance at every stage. Gain compression of the CML stages stabilizes the oscillation amplitude.

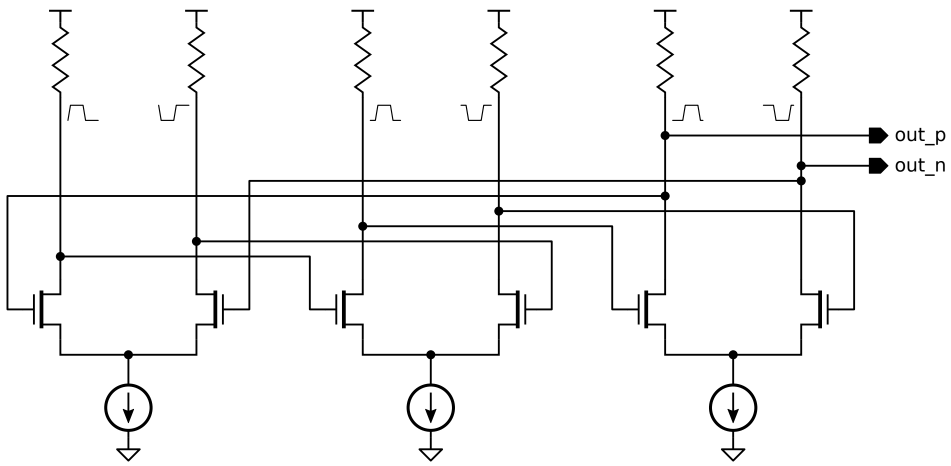

Figure 4.6: A third-order CML ring oscillator

Chapter 5

Complex Pole Harmonic Oscillators

In this chapter, we will discuss harmonic oscillators with complex poles. In these circuits, the poles are formed by lumped or distributed passive reactive elements. In contrast to the real pole oscillators discussed in the previous two chapters, resistive or active elements are not involved in forming the poles. This property gives complex pole harmonic oscillators the potential for very low noise but makes tuning more difficult. The first section of this chapter discusses second-order oscillators. Infinite-order oscillators are discussed in the second section.

5.1 Second-Order

Figure 5.1 shows a differential oscillator architecture that is often used in integrated circuits. A center-tapped inductor, a switchable capacitor, and two series-connected varactor diodes form a LC tank. The parallel resonance of this LC tank sets the complex pole pair that determines the oscillation frequency. The loss of the tank is canceled by two N-FETs that are configured to generate a differential negative resistance between their drains by means of positive feedback. For biasing, the drains of the transistors are connected to the supply through the center tap of the inductor and the sources to a current source. As the oscillator amplitude increases after startup of the circuit, the transistors are driven into gain compression. This stabilizes the oscillator amplitude. Switchable capacitors provide coarse and varactor diodes fine tuning of the oscillator frequency.

The quality factor of the LC tank is crucial for the noise performance of such an oscillator. To minimize loading of the tank, buffers are added to isolate the load. As varactors tend to have a poor quality factor, as much of the tuning range as possible is usually realized with the switched capacitors.

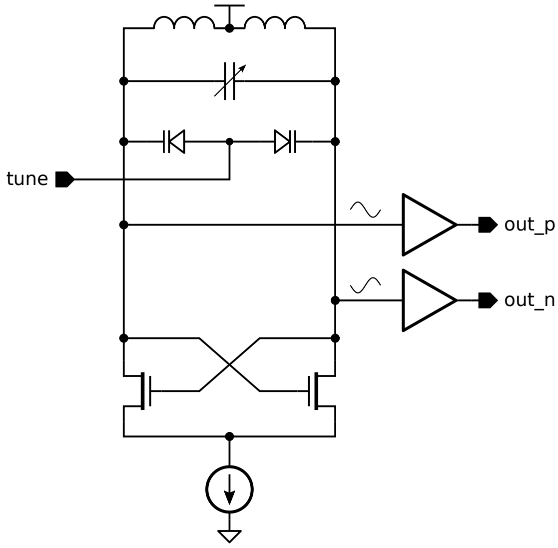

Figure 5.1: Differential second-order LC oscillator

The tuning linearity of the oscillator is usually poor because of the strong nonlinearity of the varactors.

Figure 5.2 shows another common LC oscillator architecture: the Colpitts oscillator. In the circuit shown, a bipolar transistor is configured as common-base amplifier. The operating point of the transistor is set by a resistive voltage divider connected to the base and an emitter resistor, and a capacitive voltage divider provides feedback from the collector to the emitter of the transistor. Together with the drain inductor, this capacitive voltage divider forms the parallel LC tank of this oscillator. As shown, the oscillator has no tuning mechanism. Where required, tuning can be provided by a varactor connected in parallel to the capacitive voltage divider. Gain compression of the transistor stabilizes the oscillator amplitude.

Many similar oscillator architectures exist. For example, the transistor can be configured as common-emitter or common-collector amplifier. Or, as in the Hartley oscillator, the feedback can be realized with a tapped inductor instead of the capacitive voltage divider.

Where high frequency accuracy is required, oscillators based on crystal resonators are often used. One of the many known circuits is the Butler common-collector oscillator, shown in figure 5.3. Here a bipolar transistor is configured as a common-collector amplifier, and made to oscillate by positive feedback from the emitter back to the base. The crystal is used in series resonance, such that at the oscillation frequency a low-impedance path allows positive feedback, and outside the crystal bandwidth a high impedance blocks positive feedback. After the crystal, the positive feedback path connects to the center point of a capacitive divider. The end of the capacitive voltage divider connecting to the base of the bipolar transistor resonates with an

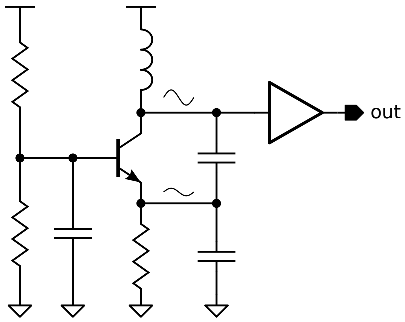

Figure 5.2: Colpitts common-base LC oscillator

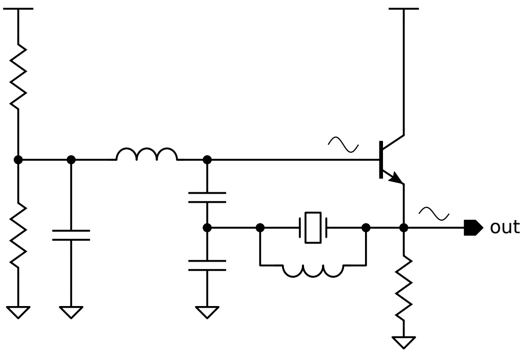

Figure 5.3: Butler common-collector crystal oscillator

inductor, such that the voltage gain between emitter and base is above unity and the positive feedback can start the oscillation. The LC resonance also serves as a filter that selects the desired crystal resonance. As the crystal is a distributed element, many modes exist that potentially can support oscillation. With the frequency selectivity of the LC resonance, the undesired modes are either attenuated such that not enough gain for oscillation exists, or shifted in phase such that at frequencies with gain above unity, the feedback system is stable. Across the crystal, an inductor is strapped to resonate out the package capacitance. The Butler oscillator is another example where a single transistor provides the double function of amplification and amplitude stabilization through gain compression. As for the Colpitts LC oscillators discussed in the previous paragraph, there is a family of related oscillators that deviate from the discussed Butler common-collector circuit for example by using a common-emitter or common-base transistor configuration, or by using an inductive rather than capacitive tap point for the crystal.

5.2 Infinite-Order

The probably most common infinite-order oscillator type is based on a surface acoustic wave (SAW) delay line. Similarly to crystal resonators, SAW delay

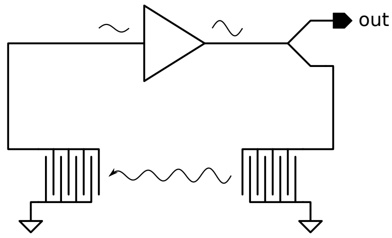

Figure 5.4: SAW delay line oscillator

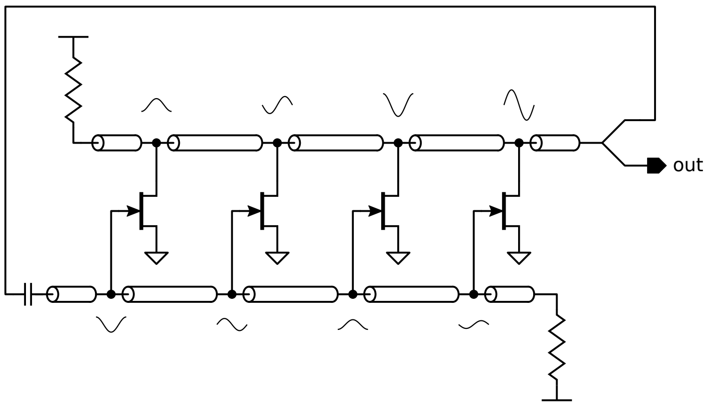

Figure 5.5: Traveling-wave oscillator

lines use transducers on a piezoelectric material to convert electrical energy to mechanical energy and vice versa. In the surface of the piezoelectric material, a mechanical wave forms that propagates signals between transducers. As shown in figure 5.4, the SAW delay line is placed in the feedback loop of an amplifier, whose output power is split between the output signal and the feedback path. At frequencies where the loop gain is above unity and the phase is an integer multiple of 360°, oscillation can potentially build up. To select a specific oscillation frequency, the SAW delay line includes a band-pass filter, such that at only one frequency with suitable phase condition there is gain above unity.

As is typical for high-frequency oscillators, gain compression of the amplifier stabilizes the oscillation amplitude. The frequency of a SAW oscillator is usually tuned by inserting a phase shifter in series with the amplifier. As sufficient gain has to be available at the oscillation frequency, the tuning range will be limited to the pass band of the SAW delay line.

A traveling-wave (or distributed) oscillator, shown in figure 5.5, is another infinite-order oscillator. As in traveling-wave (or distributed) amplifiers, transmission line sections absorb the input and output capacitances of the transistors such that particularly high operating frequencies can be achieved. In the gate line, the signal level drops as the wave travels along the path as part of the power is absorbed by transmission line and gate losses. In the drain line, the signal level increases towards the output as the output power of the individual transistors sums up. To create oscillation, a part of the output power is coupled back to the input. Oscillation is now potentially possible at frequencies where the phase is an integer multiple of 360° and the gain above unity. As this type of oscillator is usually used at very high frequencies, losses in the transmission lines and the intrinsic bandwidth limitation of the transistors restrict gain above unity and thus oscillation to the lowest frequency with suitable phase condition. Alternatively a bandpass filter may be used to select a specific oscillation mode.

In the particular oscillator shown in figure 5.5, metal–semiconductor field-effect transistors (MESFETs) or high electron mobility transistors (HEMTs) are used to achieve high operating frequency. As usually these transistors are manufactured as depletion-mode devices, a negative gate bias is required—here provided by tying the termination of the gate line to a negative supply voltage. As for the other oscillators discussed in this section, gain compression of the transistors stabilizes the oscillator amplitude. Tuning of traveling-wave oscillator is difficult, which limits the applicability of this oscillator type.

Chapter 6

Summary

In this article, I reformulated and summarized the for me important concepts from the book *Oscillators and Oscillator Systems: Classification, Analysis and Synthesis* by Jan R. Westra, Chris J. M. Verhoeven, and Arthur van Roermund (Springer, 1999). The shown oscillator classification system groups oscillators according to their oscillation mechanism, whether the circuit has real or complex poles, and the number of poles.

Relaxation oscillators are based on nonlinear feedback. The nonlinearity leads to oscillation waveforms rich in harmonic content—for example a triangular wave—and to a direct coupling of oscillator amplitude and frequency. Relaxation oscillators require three fundamental functions: time-to-amplitude transfer, level detection, and state memory. In many relaxation oscillators, level detection and state memory are combined in one circuit, for example a comparator with hysteresis.

Harmonic oscillators, on the other hand, are based primarily on linear feedback. Therefore their waveforms can be sinusoidal with very low harmonic content and the oscillation frequency independent from the oscillation amplitude. Filtering, amplification, and amplitude control are the three required functions to realize a harmonic oscillator. While the amplitude control is necessarily a nonlinear circuit, the filtering and amplification functions can in principle be purely linear operations. In some harmonic oscillators, active filters are used which combine the filtering and amplification functions in one circuit. In other harmonic oscillators, gain compression of the amplifier stabilizes the oscillation amplitude, therefore combining amplification and amplitude control in one circuit.

Oscillators with real poles have fundamentally different tuning behavior and noise characteristics compared to oscillators with complex poles. While real pole oscillators can often be easily tuned over a wide frequency range and with a very linear tuning characteristics, they tend to have high noise. Complex pole oscillators, on the other hand, can usually be tuned over a relative narrow frequency range only and tend to have nonlinear tuning characteristics. But they can have very low noise.

These fundamentally different characteristics can be explained by the different energy transfer mechanisms. In real pole oscillators, the dominant energy flow during an oscillation cycle is between active components and passive reactive components, for example between a transconductance amplifier and a capacitor. By adjusting the transconductance of the amplifier the oscillator is easily tuned, but the energy transfer through the amplifier is associated with high noise. In complex pole oscillators, the dominant energy flow is between passive reactive elements, for example between an inductor and a capacitor. This is a noiseless energy flow mechanism, but the oscillator becomes difficult to tune as usually the value of at least one passive reactive component must be changed. In complex pole oscillators, active circuits are used only to replace the energy dissipated by the losses of the passive reactive elements. As the energy dissipated during an oscillation cycle is much smaller than the energy exchanged between reactive components, the noise contribution from active circuits can be low.

Of broad practical relevance are only five oscillator classes: first-order real pole relaxation oscillators, second-order real pole harmonic oscillators, higher-order real pole harmonic oscillators, second-order complex pole harmonic oscillators, and infinite-order complex pole harmonic oscillators. For each of these five classes, I have discussed at least two oscillator circuits that are in common use:

- first-order real pole relaxation oscillators: astable multivibrator and differential waveform generator;
- second-order real pole harmonic oscillators: g_m-C, state-variable RC, and Wien-bridge oscillator;
- higher-order real pole harmonic oscillators: CMOS and CML ring oscillator;
- second-order complex pole harmonic oscillators: differential LC, Colpitts LC, and Butler crystal oscillator;
- infinite order complex pole harmonic oscillators: SAW delay line and traveling-wave oscillator.

The discussed oscillator classification system helps us understanding and highlighting the fundamental reasons for the specific merits of each oscillator type. This understanding is an essential advantage for a designer when selecting an architecture for a specific application, optimizing a circuit for a specific context, or searching for novel solutions surpassing existing designs in certain key aspects.