Oscillators

Oscillators are electronic circuits that produce a constant oscillating signal that can be a sinusoid, a square wave or a triangular wave.

Oscillators are classified as *linear* or *harmonic* oscillators if their output is a sinusoidal waveform.

1. Feedback
   a. RC
      Wien bridge
      Phase-shift
      Twin-T
      Quadrature
      Robinson
   b. LC
      Armstrong/Meissner
      Hartley
      Colpitts
      Gouriet/Clapp
      Vackář
      Cross-coupled
      Meacham bridge
      Seiler
   c. Crystal
      Pierce
      Butler

2. Negative resistance

Oscillators are classified as *nonlinear* or *relaxation* oscillators if their output is a square, a sawtooth or a triangular waveform.

1. Multivibrators
   a. Astable
   b. Monostable
   c. Bistable
2. Ring
3. Pearson-Anson or neon lamp
4. Delay line
5. Royer

Some oscillators are simply classified as *generators* and their output is a square and/or a triangular waveform:

6. Generator I
7. Generator II
8. Generator III
9. Generator IV
Notes:

- Oscillators such as Hartley, Colpitts and Gouriet/Clapp can be configured to be Voltage-Controlled Oscillators (VCO). The frequency of the oscillators depends on the input voltage.

- The Vackář oscillator is described as a Variable-Frequency Oscillator (VFO). Its frequency can be tuned with a variable capacitor. Its output is nearly constant over its frequency range of operation.

- Crystal oscillators were developed in the 1920s and 1930s and provided better frequency stability than tuned oscillators because they are affected by temperature to a much lower degree (they are more stable).

- The Tri-tet oscillator is described as an Electron-Coupled Oscillator (ECO).
**RC oscillators**

RC oscillators contain resistors and capacitors. They are typically used for low frequency (audio range or up to 20kHz).

**Wien bridge oscillator I**

The circuit was first conceived by Prussian physicist Max Wien in 1891. Because of limitations during his time, the circuit was not constructed until American engineer William Hewlett revisited it in 1939 for his master’s degree thesis. Shortly after that, Hewlett-Packard was founded and one of the company’s first products was a sine-wave oscillator based on the Wien bridge circuit. The final product proved to be very successful and it became very popular because it was stable and inexpensive.

The Wien bridge oscillator uses positive feedback which is provided by a bandpass filter made up by two RC circuits, one in parallel ($R_1$ and $C_1$) and one in series ($R_2$ and $C_2$). $R_4$ is a variable resistor and $R_3$, at the time of Hewlett, was a light bulb.

**Transient response of the Wien bridge oscillator**
The ideal set of parameters is the following:

\[ R_1 = R_2 = R \quad C_1 = C_2 = C \quad \frac{R_4}{R_3} = \frac{2}{1} \]

R₃, the light bulb, has a selected resistance:

\[ R_3 = 57\Omega \]

The value for R₄ can be easily calculated:

\[ R_4 = 2 \cdot R_3 = 114\Omega \]

The gain is given by the following expression:

\[ A = \frac{V_o}{V_i} = 1 + \frac{R_4}{R_3} = 1 + \frac{114\Omega}{57\Omega} = 3 \]

The oscillation frequency is:

\[ f = \frac{1}{2\pi RC} = \frac{1}{2\pi \cdot 1k\Omega \cdot 22nF} = 7.234kHz \]

The oscillation frequency from the simulation is 6.896kHz.

*Note: modern Wien bridge oscillators use other nonlinear elements such as diodes, thermistors, field effect transistors or photocells in place of light bulbs.*
Wien bridge oscillator II

This is a variation of the classic Wien bridge oscillator. It adds a JFET, a diode and an RC circuit.

The Wien bridge oscillator uses positive feedback which is provided by a bandpass filter made up by two RC circuits, one in parallel (R₁ and C₁) and one in series (R₂ and C₂).

Transient response of the Wien bridge oscillator
The ideal set of parameters is the following:

\[ R_1 = R_2 = R \quad C_1 = C_2 = C \quad \frac{R_4}{R_3} = \frac{2}{1} \]

R\(_3\) has a selected resistance:

\[ R_3 = 4.8k\Omega \]

The value for R\(_4\) can be easily calculated:

\[ R_4 = 2 \cdot R_3 = 9.6k\Omega \to 10k\Omega \]

R\(_4\) is rounded up to 10k\(\Omega\) to provide a gain of at least 2 which is going to start the oscillator.

The gain is given by the following expression:

\[ A = \frac{V_o}{V_i} = 1 + \frac{R_4}{R_3} = 1 + \frac{10k\Omega}{4.8k\Omega} = 3.083 \]

The oscillation frequency is:

\[ f = \frac{1}{2\pi \cdot R \cdot C} = \frac{1}{2\pi \cdot 10k\Omega \cdot 10nF} = 1.591k\text{Hz} \]

The oscillation frequency from the simulation is 1.582kHz.
Phase shift oscillator I

This circuit produces a sinusoidal oscillation and a phase shift by means of a series of RC circuits, each of them providing a 60° phase shift.

The circuit is implemented with a BJT.

The resistors and the capacitors for the RC circuits have the same values so $R_1=R_2=R_3=R$ and $C_1=C_2=C_3=C$.

The oscillation frequency from the simulation is 7.194kHz.
Phase shift oscillator II

This circuit produces a sinusoidal oscillation and a phase shift by means of a series of RC circuits, each of them providing a 60° phase shift.

The circuit is implemented with an op-amp.

The equation for the oscillation frequency is very complex. When $R_1=R_2=R_3=R$ and $C_1=C_2=C_3=C$ the equation is much simpler and it becomes:

$$f = \frac{1}{2\pi RC\sqrt{2} \cdot N} = \frac{1}{2\pi \cdot 10k\Omega \cdot 1nF \cdot \sqrt{2} \cdot 3} = 6.497\,kHz$$

where $N$ is the number of RC stages (3 in this case).

The gain of the op-amp is typically 26 to 30 (28 in this case).

The oscillation frequency from the simulation is 6.06kHz.
Quadrature oscillator

This circuit uses positive and negative feedback to generate two sinusoidal waves of similar properties, one of them being a sine and the other one being a cosine. C₁ through C₃ must be matched. All resistors should also be matched, except for R₁ which must be slightly less than R₂ and R₃ to cause the circuit to oscillate. D₁ through D₄ avoid clipping at the outputs (breakdown voltage is 8.1V).

The oscillation frequency is:

\[ f = \frac{1}{2\pi RC} = 159\text{Hz} \]

where R=R₂=R₃ and C=C₁=C₂=C₃.

The oscillation frequency from the simulation is 161Hz.
LC oscillators

LC oscillators contain inductors and capacitors. They are typically used for high frequency (radio range or above 20kHz).

Hartley oscillator

This circuit was invented by American engineer Ralph Vinton Lyon Hartley in 1915. The oscillation frequency of this circuit depends on $L_1$, $L_2$ and $C_1$. The Hartley oscillator is the dual circuit of the Colpitts oscillator which follows next.

![Hartley oscillator circuit diagram]

Hartley oscillator

![Transient response of the Hartley oscillator]

Transient response of the Hartley oscillator
If the inductors are *not coupled*, \( L \) is given by:

\[
L = L_1 + L_2
\]

If the inductors are *coupled*, \( L \) is given by:

\[
L = L_1 + L_2 + k \sqrt{L_1 L_2}
\]

where \( k \) is the coupling coefficient, a number between 0 and 1.

The oscillation frequency for the circuit is given by:

\[
f = \frac{1}{2\pi \sqrt{LC_1}} = \frac{1}{2\pi \sqrt{158.3 \mu H \cdot 4nF}} = 200.009 kHz
\]

The oscillation frequency from the simulation is 200kHz.
Colpitts oscillator

This circuit was invented by American engineer Edwin Henry Colpitts in 1918. The oscillation frequency of this circuit depends on C₁, C₂ and L₁. The Colpitts oscillator is the dual circuit of the Hartley oscillator discussed above.
The oscillation frequency for the circuit is given by:

\[ f = \frac{1}{2\pi \sqrt{\frac{L}{C_1 + C_2}}} = \frac{1}{2\pi \sqrt{\frac{17.41 \mu H}{40nF + 400nF}}} = 200.026kHz \]

The oscillation frequency from the simulation is 200kHz.
Gouriet/Clapp oscillator

This circuit was independently discovered and first published by American electrical engineer James Kilton Clapp in 1948. However, the circuit was invented by Geoffrey George Gouriet and it was used as early as 1938 at the BBC but this was not made public until after World War II due to the fact the circuit was kept secret.

Essentially, the Gouriet-Clapp oscillator is a Colpitts oscillator with an additional capacitor in series with the inductor.

Note: \( R_5 \) is placed to force PSpice A/D to start.

Transient response of the Gouriet-Clapp oscillator
The oscillation frequency for the circuit is given by:

\[
f = \frac{1}{2\pi} \sqrt{\frac{1}{L} \left( \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \right)} = \frac{1}{2\pi} \sqrt{\frac{1}{10 \mu F} \left( \frac{1}{100 n F} + \frac{1}{1 \mu F} + \frac{1}{1 \mu F} \right)} = 174.346 kHz
\]

The oscillation frequency from the simulation is 166.666kHz.
Vackář oscillator

This circuit was published in a paper by Czech engineer Jiří Vackář in 1949 but he attributed the invention of the oscillator that dates back to 1945 to a firm called Radioslava in Czechoslovakia.

![Vackář oscillator circuit diagram]

Transient response of the Vackář oscillator

The oscillation frequency from the simulation is 2MHz.
**Multivibrators**

Multivibrators are circuits designed to implement a two-state logic system and they can be of three types: astable, monostable and bistable. Astable multivibrators constantly oscillate between two states. Monostable multivibrators can be placed in a transient state by an external signal and return to the initial stable state after a specific time. Bistable multivibrators stay in either of two stable states and alternate between them depending on an external trigger.

**Astable multivibrator**

This circuit constantly oscillates between two states.

![Astable multivibrator circuit diagram](image)

**Transient response of the astable multivibrator**

![Transient response graph](image)
The astable multivibrator frequency depends on the values of $R_2$, $C_1$, $R_3$ and $C_2$:

$$f = \frac{1}{T} = \frac{1}{\ln(2) \cdot (R_2C_1 + R_3C_2)} = \frac{1}{\ln(2) \cdot (68k\Omega \cdot 100nF + 82k\Omega \cdot 150nF)} = 75.534\text{Hz}$$

The frequency from the simulation is 72.49Hz.

As shown in the simulation, the circuit oscillates between two states.

*Note: if $R_2$=$R_3$ and $C_1$=$C_2$ the duty cycle will be exactly 50%.*
Monostable multivibrator

This circuit can be placed in a transient state by an external signal and return to the initial stable state after a specific time.

![Monostable multivibrator circuit diagram]

**Transient response of the monostable multivibrator**

- **V1 = 0.7V**
- **V2 = 0V**
- **TD = 20ms**
- **TR = 10ns**
- **TF = 10ns**
- **PW = 30ms**
- **PER = 100ms**
- **V1 = 0.7V**
- **V2 = 0V**
- **TR = 10ns**
- **V(C1:1)**
- **V(R3:1)**
As shown in the simulation, Q2 is initially on and Q1 is off. External signal V2 brings the base of Q2 down to 0V which turns off Q2 and turns on Q1. When V2 goes back up to 0.7V the circuits goes back to its initial state.

The time the monostable multivibrator stays in the transient state depends on the values of R2 and C1:

\[ t = \ln(2) \cdot R_2 \cdot C_1 = \ln(2) \cdot 5k\Omega \cdot 600nF = 2.079ms \]

As shown above, the circuit goes back to the initial state after about 2ms.
Bistable multivibrator

This circuit stays in either of two stable states and it alternates between them depending on an external trigger. This circuit is also referred to as *flip-flop* because it can store 1 bit of information.
As shown in the simulation, at 0ms, Q1 and Q2 are initially on so the circuit is in an undetermined state. At 10ms a 20ms external trigger called Set brings the base of Q2 down to 0V which turns off Q2 and turns on Q1. At 30ms a 30ms external trigger called Reset brings the base of Q1 down to 0V which turns off Q1 and turns on Q2. The circuit alternates between two states. It is in one state at 10ms-30ms and 60ms-80ms. It is the opposite state at 30ms-60ms and 80ms-100ms.
Generator I

This circuit uses positive and negative feedback in order to generate a triangular and square waves.

\[ f = \frac{1}{2R_1C_1 \ln \left( \frac{2R_1}{R_2} + 1 \right)} = 326 \text{Hz} \]

The oscillation frequency from the simulation is 343Hz.
Generator II

This circuit generates square and triangular waveforms. U2 integrates the output of U1 and flips it.

The transient response of the generator is shown below.

The oscillation frequency is:

$$ f = \frac{1}{4RC} \frac{R_2}{R_3} = 250 \text{Hz} $$

The oscillation frequency from the simulation is 255Hz.
**Generator III**

This circuit generates square and triangular waveforms. The frequency of the outputs can be modulated by the input voltage so this circuit is a Voltage-Controlled Oscillator (VCO).

For this circuit the ratio $R_1/R_2$ must be fixed to 1/2. Reducing the value of $C_1$ by half doubles the frequency. Increasing the value of $V_1$ by two also doubles the frequency which confirms this is a VCO.

The oscillation frequency from the simulation is about 151Hz.

The circuit can be implemented with a MOSFET instead of a BJT.
Generator IV

This circuit generates triangle and square waveforms. R₂ and R₃ set the amplitude of the square waveform (R₃>>R₂). R₁ and C₁, along with the amplitude of the square waveform, set the oscillation frequency.

The oscillation frequency is:

\[ f = \frac{1}{4 \cdot V_{out\_tri} \cdot R₁ \cdot C₁} = \frac{1}{4 \cdot 1.839V \cdot 10kΩ \cdot 1nF} = 103.317kHz \]

where V_{out\_tri} is the peak-to-peak output of the triangular waveform.

The oscillation frequency from the simulation is 103.093kHz.
**555 timer IC**

The 555 timer IC was designed by Swiss electronics engineer Hans R. Camenzind in 1970 or 1971 and introduced on the market by Signetics in 1971.

It is a classical circuit and it can be configured to function just like a multivibrator, an oscillator or a flip-flop with the addition of a few external components such as capacitors and resistors. Internally, the IC can be implemented with BJTs or MOSFETs.

Depending on the manufacturer and the implementation, the 555 timer IC has transistors, resistors and diodes. The chip is available in an 8-pin configuration. The 556 version of the timer has 14 pins and it contains 2 555 chips. 558 and 599 versions come in 16-pin chips and they contain 4 modified 555 chips.

The NE555 was the first 555 timer IC chip, it was released by Signetics and it was designed for operation between 0°C and +70°C. The SE555 was designed for the military with a temperature range of -55°C to +125°C. A V suffix was used for a plastic package and a T suffix was used for the metal package so that, for example, the SE555T was a military metal packaged 555 timer IC.

The 555 timer IC has the following pins:

![555 Timer IC Diagram](image)

The chip can be configured to work in the following modes:

- **Astable or free-running mode**
- **Monostable or one-shot mode**
- **Bistable or Schmitt-trigger mode**

For the following simulations, the TLC555 by Texas Instruments is configured to work in the astable, monostable and bistable modes. Pin 5, the control pin, is always connected to a 10nF capacitor that goes to ground.
The internal schematic of the BJT implementation of the LM555 timer IC by Texas Instruments

The internal schematic of the CMOS implementation of the TLC555 timer IC by Texas Instruments
Astable mode

The astable or free-running mode produces an astable multivibrator. For this circuit, the only external components needed are 2 resistors and 2 capacitors.

The 555 timer IC in astable mode

The oscillation frequency is:

\[ f = \frac{1}{\ln(2) \cdot C_1 \cdot (R_1 + 2R_2)} = \frac{1}{\ln(2) \cdot 15nF \cdot (3.3k\Omega + 2 \cdot 1k\Omega)} = 18.174kHz \]

The on-time for the pulse is:

\[ t_{on} = \ln(2) \cdot C_1 \cdot (R_1 + R_2) = \ln(2) \cdot 15nF \cdot (3.3k\Omega + 1k\Omega) = 44.71\mu s \]

The off-time for the pulse is:

\[ t_{off} = \ln(2) \cdot C_2 \cdot R_2 = \ln(2) \cdot 15nF \cdot 1k\Omega = 10.40\mu s \]

The oscillation frequency from the simulation is 17.543kHz, the on-time is 46\mu s and the off-time is 11\mu s.
**Monostable mode**

The monostable or one-shot mode produces a monostable multivibrator. For this circuit the only external components needed are 1 resistor and 2 capacitors. Pin 2, the trigger pin, is active low. When the pin is brought low, it will initiate the pulse.

The 555 timer IC in monostable mode

![Circuit diagram](image)

Transit response for the 555 timer IC in monostable mode

The time of the pulse is:

\[
t_p = \ln(3) \cdot R_1C_1 = \ln(3) \cdot 3.3k\Omega \cdot 15nF = 54.38\mu s
\]

The pulse ends when the voltage across \(C_1\) is 2/3 of the supply voltage.

The time of the pulse from the simulation is 55.1\(\mu s\).
**Bistable mode**

The bistable or Schmitt-trigger mode produces a bistable multivibrator. For this circuit the only external component needed is 1 capacitor. Pin 2, the trigger pin, is active low. When the pin is brought low, it will set the output to a high state. Pin 4, the reset pin, is also active low. When the pin is brought low, it will reset the output to a low state.

The 555 timer IC in bistable mode

Transient response for the 555 timer IC in bistable mode