Short Tutorial on Quartz Crystals and Oszillators

Contents

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1 Quartz crystals

This manual provides a brief summary of the Quartz crystal basics, the common terminology and most important parameters used for circuit designs based on crystals.

The design basics are verified with the GEYER Y-Design App, which allows the design and optimization of an oscillator circuit and helps you to select the appropriate crystal.

The Y-Design App is available for Free download from Google or Apple Playstore or as Windows version at https://www.geyer-electronic.de/en/design-test-center/design-support/.

Based on a modern and user-friendly menu navigation, the App provides:

- A graphical and numerical representation of the input/output parameter
- Simple input or upload of existing circuits
- The selection of desired component packages
- The import of design specific templates
- A direct sample inquiry and a link to the GEYER Online Shop

1.1 Equivalent circuit of a quartz crystal

A crystal oscillator is an electric oscillator type circuit that uses a piezoelectric crystal, as its frequency-determining element.

The mechanical oscillation, piezo-electrically excited by an alternating electrical field of suitable frequency, corresponds with the equivalent circuit in Figure 1, which consists of a series resonant circuit together with a capacitance in parallel. Common parameters are the motional capacitance C_1, the motional inductance L_1, the motional resistance R_1 representing the so-called motional (dynamic) branch, and the shunt (static) capacitance C_0.

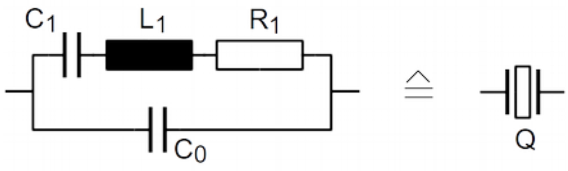

Figure 1
Equivalent circuit of a quartz crystal

The motional capacitance C_1 represents the mechanical elasticity and the motional inductance L_1 corresponds to the mechanical mass. The motional resistance R_1 combines losses of internal friction, dampening effects of the surrounding atmosphere and the mounting arrangement. Finally, the electrode areas on the crystal surface are responsible for most of the static capacitance C_0.

On the basis of this equivalent circuit, the series resonance f_S of the motional branch with C_1 und L_1 can be calculated, as well as the so-called parallel resonance f_p of the circuit consisting of C_0 and, in this case, the inductive branch of C_1 and L_1.

The series resonant frequency f_s of the quartz crystal is defined by the series resonance of the motional branch

$$f_S = \frac{1}{2\pi\sqrt{C_1 L_1}}$$

The parallel resonant frequency f_p is defined by

$$f_P = \frac{1}{2\pi\sqrt{\frac{C_1 C_0}{C_1+C_0}L_1}} = f_s\sqrt{1+\frac{C_1}{C_0}}$$

$$\approx f_s\left(1+\frac{C_1}{2C_0}\right) \quad \text{für } C_0 \gg C_1$$

For both frequencies the crystal impedance is not purely resistive, but also has a capacitive part.

1.2 Important quartz crystal manufacturing and designs parameters

The performance of a quartz crystal is a combination of the resonance frequency and resonance mode, the series resistance, the load capacitance, drive level and very important the frequency stability of the desired temperature range. All these parameters are part of the manufacturer datasheet of the individual crystal.

From the crystal equivalent circuit presented in Figure 1 we see that the motional capacitance C_1, the motional inductance L_1 and resistance R_1, as well as the shunt capacitance C_0, are parameters defined during the manufacturing process.

In the next chapters we will describe the individual crystal characteristics and will show the impact on the designs, using the GEYER Y-Design App for representing the circuits.

The App has 3 main parts: **Quartz** = input parameters (the specifications of the crystal), **Circuit** = the calculated output parameters and the **Graphical Display** of the gain and the phase.

1.3 Quartz crystal in 'series resonance ‘

The difference between the series and the parallel mode is that the resonant frequency of a parallel resonant crystal is slightly higher than that of a series resonant crystal. However, is important to have two different modes of resonance because they are optimized to the design of the oscillator circuit.

'Series resonant quartz crystal' means alignment of the resonator to the desired frequency during production without an additional load capacitance.

For series resonance oscillating crystals, activate the 'Series resonance' option. The nominal frequency is then obtained with the slider for C_L set to maximum (C_L short-circuit).
We simulate a quartz crystal as described in the equivalent circuit with the parameters C_1, L_1, R_1 (the so-called 'motional branch') and the 'static' shunt capacitance C_0 without any series (load) capacitance.

Note: Series resonant quartz crystals are not the normal case, crystals are much more often used with load capacitance.

While in Figure 2 you see the impedance view of this resonant mode, Figure 3 displays the admittance mode.

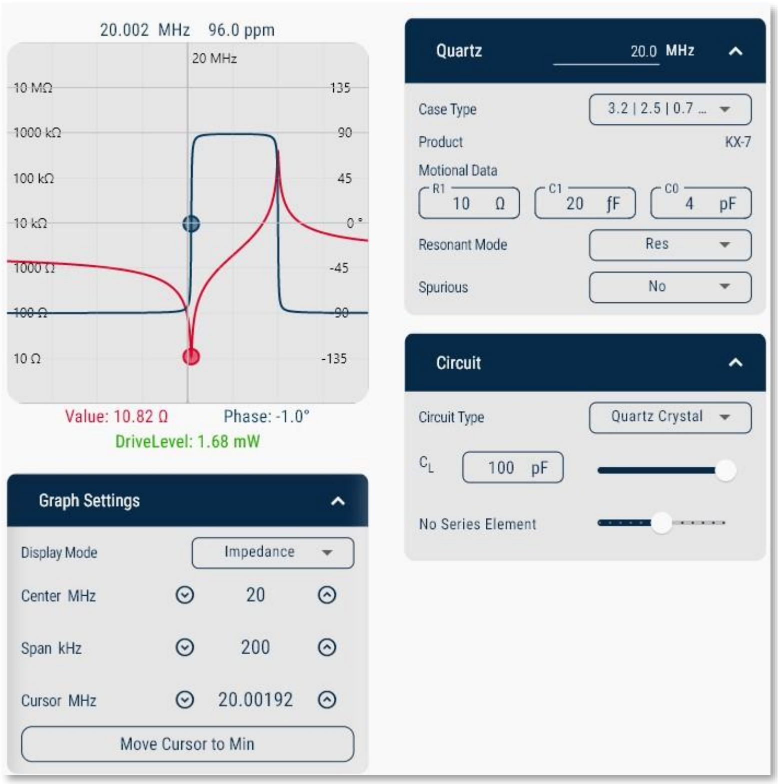

Figure 2
Crystal in series resonance, no C_L;
Impedance view

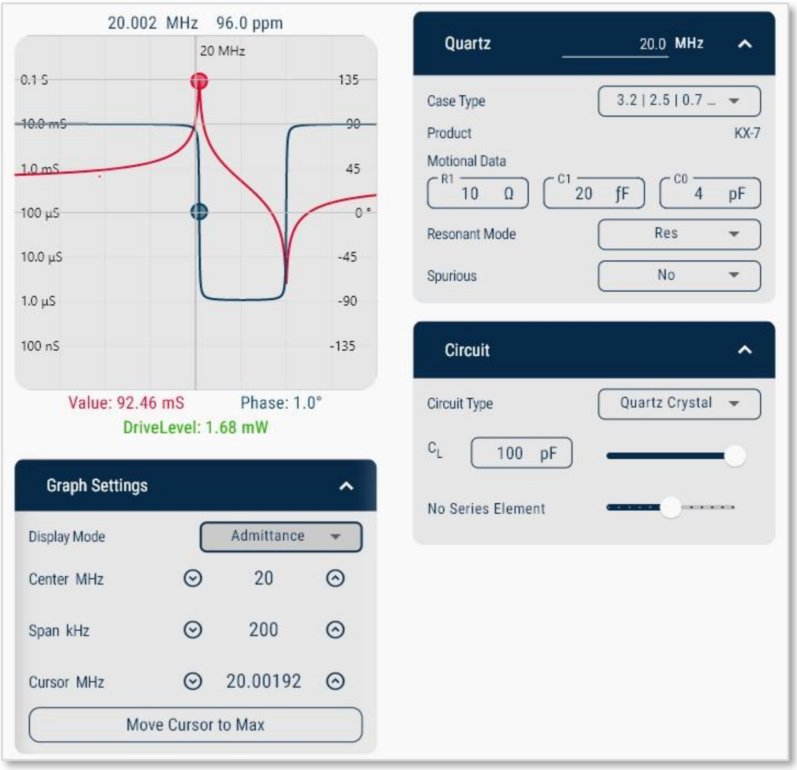

Figure 3
Crystal in series resonance, no C_L;
Admittance view

1.3.1 Shunt capacitance, high frequencies

The shunt capacitance C_0 is a static capacitance between the crystal terminals, measured in pF and is present whether the device is oscillating or not.

C_0 depends on the dielectric of the quartz, the area of the crystal electrodes, and the capacitance presented by the crystal holder.

If we increase the simulated value of the shunt capacitance C_0 to a not very realistic value of 40 pF, the high-impedance resonance f_a moves closer to the low-impedance frequency f_r. The effects are shown in Figure 4.

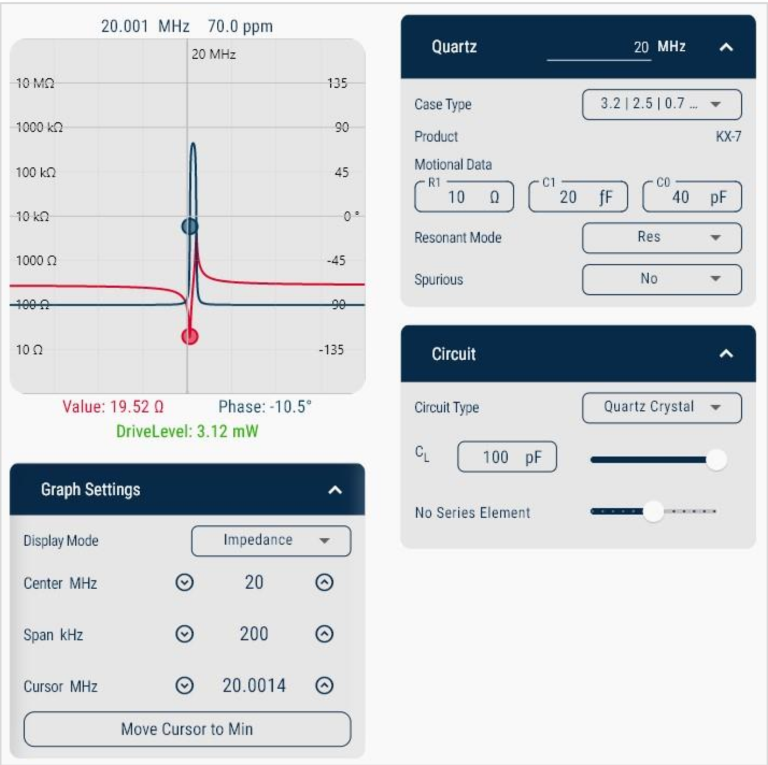

Figure 4
Series resonant crystal
with extremely large C_0

At very high frequencies, like in Figure 5, the effect of the shunt capacitance is compensated by an inductive C_0, both in production during alignment as well as in the application circuit.

For the following analysis of the resonator quality factor, we reset the equivalent parameters of the resonator to the values R_1 = 10 Ω, C_1 = 2 fF, C_0 = 4 pF

Figure 5
Series resonant crystal
with high frequency

1.3.2 Series resistance, motional capacitance, quality factor

The two major advantages of quartz crystals are very good frequency stability over temperature and the high quality of the oscillation, i.e. the sharpness of the resonance.

The quality factor Q can be expressed with a formula including the motional resistance R_1 and the motional capacitance C_1 relative to the motional inductance L_1:

$$Q = \frac{1}{2\pi f C_1 R_1} = \frac{2\pi f L_1}{R_1}$$

Higher C_1 as well as higher R_1 mean a reduction of the quality factor. In addition, higher C_1 results in a large distance between series and parallel resonance.

Figure 6 shows the summary of the graphs for R_1 = 10 Ω and R_1 = 40 Ω superimposed. The resonance peaks are flattened with R_1 being bigger: The quality factor is lower.

Figure 6
Influence of R_1

With larger motional capacitance C_1, the quality factor would also decrease, but to stay realistic with the C_1 value, Figure 7 shows the effect of four times smaller C_1 of 5 pF: The resonances are sharper, the quality factor increases.

However, we also see that the distance betwen the serial and parallel resonance is reduced according to the reduction of C_1 by a factor of 4.

Figure 7
Influence of C_1

1.4 Quartz crystal aligned with load capacitance

As mentioned before, the usual requirement is a quartz crystal with load capacitance. The reason is simple: oscillator circuits generally offer a capacitive load component to the resonator at this connection points. Usually this is due to capacitors ensuring oscillation as part of the feedback network of an oscillator circuit.

To resonate on the right frequency, the crystal has to "see" its correct load capacitance.
The pulling sensitivity is directly linked to the behaviour of the oscillator, indicating how sensitive the frequency reacts to changes of the outer design parameters.

$TS = C_1 x 10^6 / 2x(C_0+C_L)^2$ (ppm/pF)

The load capacitance C_L is not an inherent crystal feature, but rather a design parameter.
The C_L consists of the capacitors C_a und C_b, the PCB's stray capacitance C_{stray} and the pin capacitances of the oscillator amplifier:

$C_L = (C_a \times C_b)/C_a + C_b + C_{stray} + C_{chip}$

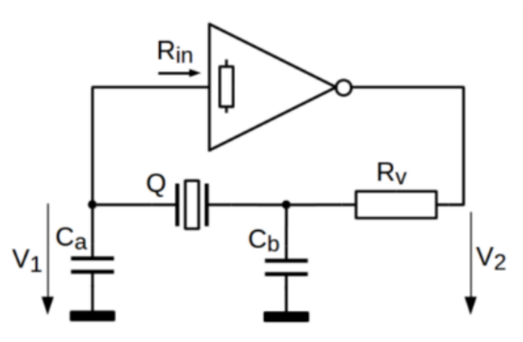

Figure 8
Pierce oscillator

C_a = capacitor at the input of the oscillator amplifier
C_b = capacitor at the output of the oscillator amplifier|
C_{stray} = stray capacitance (average 5 pF, range 3 pF ~ 10 pF)

When choosing the load capacitance, one must evaluate the individual requirements.
A low C_L leads to a lower power consumption and thus a lower rise time, it increases however the sensitivity of the design with respect to component tolerances – refer to TS.

	C_L high	C_L low
Power consumption of the oscillator circuit	higher	lower
Rise time of the oscillator	longer	shorter
Sensitivity with respect to component tolerances	low	high

Often the IC manufacturer recommends C_L values, purely based on experience.

For the dimensioning of C_a und C_b, with a given C_L one can choose either the classical method or an alternative approach:

Classical approach
(equal values for both capacitors):

$C_a = C_b = 2x\ C_L - C_s$

Alternative Approach
(capacitors with different values):
$C_a = 1{,}1\text{~}1{,}2x\ C_L - C_s$
$C_b = 4x\ C_L - C_s$

The alternative approach has the advantage of higher oscillation margin, faster startup, lower stress for the crystal.

However, in some cases the ICs demand **equal values for** the capacitors and so an alternative approach is not possible.

In any case**, it is indispensable** to verify the dimensioning of the capacitors on a prototype, as the calculated values are only orientative.

Hint for Fine-tuning: frequency too high– increase C_b. Frequency too low– reduce C_a

During the production cycle of the crystal, the C_L plays a role for the frequency fine tuning.

For each package type we recommend in the datasheet a certain “standard” load capacitance value, as well as alternative values. The range usually is between 6 – 20 pF.

However, if in order to maintain the pullability the C_L is reduced for a small package size, you need to pay attention to other factors such as stray capacity and tolerances that might impact the frequency accuracy.

Therefore, we recommend once more the verification of all parameters on a prototype board.

The load capacitance C_L used in the manufacturing process resp. the alignment procedure of the manufacturer must then comply with this capacitance in the user circuit and is therefore an important specification parameter together with the load resonant frequency f_L, which is defined as the low impedance resonance of the circuit in Figure 9.

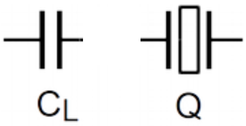

Figure 9
Quartz resonator with series (load) capacitor

The relationship between f_S and f_L is given by

$$f_L \approx f_S\left(1+\frac{C_1}{2(C_0+C_L)}\right)$$

Figure 10
Quartz crystal with series (load) capacitor

As shown in Figure 10, the distance to the parallel resonance is reduced in comparison to the series resonant quartz crystal (Figure 2). The reason is simple: The load resonant quartz crystal has already been drawn in this direction according to equation 5 with the C_L of 15 pF. Shorted series capacitance C_L under 'Circuit' thus results again in the old distance from Figure 2 (Figure 11).

Figure 11
Quartz crystal with load) capacitance
Position of load resonant freqzency f_L
and series resonant frequency f_S

Using load resonant resonators, the user can apply a frequency correction in both directions by modifying the circuit load capacitance (pulling of the crystal). With a series resonant resonator and without additional inductances only an increase in frequency is possible.
By increasing the effective load capacitance in the circuit, the load resonant frequency f_L can be reduced down to the actual series resonance frequency f_s. Conversely it can be increased up to the parallel resonance frequency f_p by decreasing the effective series capacitor. The possibility of change to either side not only allows compensation for manufacturing tolerances, but is also the base for the specific frequency change in voltage-controlled oscillators. It should be noted that very low series (load) capacitances reduce stability drastically. In addition, the load resonant resistance increases to very high values.

This new total resistance of the series resonant circuit is the load resonant resistance R_L

$$R_L \approx R_1 \left(1+\frac{C_0}{C_L}\right)^2$$

R_L is also known as 'transformed R1' and is larger than the actual resonant resistance Rr of the quartz crystal without load capacitance. Without the circuit capacitance (circuit C_L set to large) we return to the non-transformed resonance resistance of 10 Ω. The value can be determined with better accuracy by reducing the span.

The relative difference between the resonant frequency and load resonant frequency is being called load resonant frequency offset D_L

$$D_L \approx \frac{C_1}{2(C_0+C_L)}$$

The differential pullability S is

$$S = \frac{1}{f_S}\frac{\delta f_L}{\delta C_L} = -\frac{C_1}{2(C_0+C_L)^2}$$

In summary:
Since a change with external adjustment capacitance is possible in only one direction (upwards) for a series resonant quartz crystal, whereas manufacturing inaccuracies usually go in both directions, the need arises to specify the nominal frequency together with a load capacitance for the manufacturing process. The series resonant frequency is then, as shown at the beginning of the chapter, a little lower and a manufacturing tolerance range as well as the limited accuracy of circuit values can be completely compensated for by circuit tuning.
Likewise, it should be noted that a frequency change downwards can also be achieved with a load inductance. This possibility should only be used when big tuning ranges are required: Inductors usually lack the adjustability, the accuracy and the temperature stability of capacitors.
In addition, it is clear that for voltage-controlled oscillators with large pulling ranges a rather big C_1 value is desirable. On the other hand, high precision, high quality oscillators with high frequency stability should use resonators with small C_1 value.

1.5 Undesired resonances of quartz crystals

Spurious resonances

With this option an additional branch with motional parameters C_{1n}, L_{1n} und R_{1n} can be added in parallel to the quartz crystal with C_1, L_1 and R_1: a so-called spurious resonance of the crystal.

When the temperature changes, these “secondary resonances” can move across the main resonance because of their much larger temperature coefficient. There are three secondary resonance resistors to choose from. The secondary resonance C_1 is always C_1 /10 in the respective simulations.

In Figure 12 the option 'R_{1n} = 10 x R' is selected; appropriate setting of the 'Temperature' slider results in a small peak beneath the main resonance fr.
Incidentally, the parallel resonant frequency is now about 10% higher: In the simulation the C_{1n} of the spurious is assumed to be at 10% of the C_1 of the main resonance, thus contribuing to the distance series / parallel resonance according to equation 2 (but only if the main and the disturbing series resonance are almost at the the same frequency!).

These undesired resonances usually show a big temperature dependency compared to the desired resonance. You can change the 'temperature' in the simulation and thus the frequency of the spurious by moving the slider.
If a quartz crystal with load capacitance is used, the influence of spurious resonances can increase substantially (Figure 13).
Depending on the value of the interfering parameters, the resonant resistance can significantly increase, the correct resonance can shift or even two equally strong resonance points can result.

Figure 12
Series resonant quartz crystal with spurious resonance

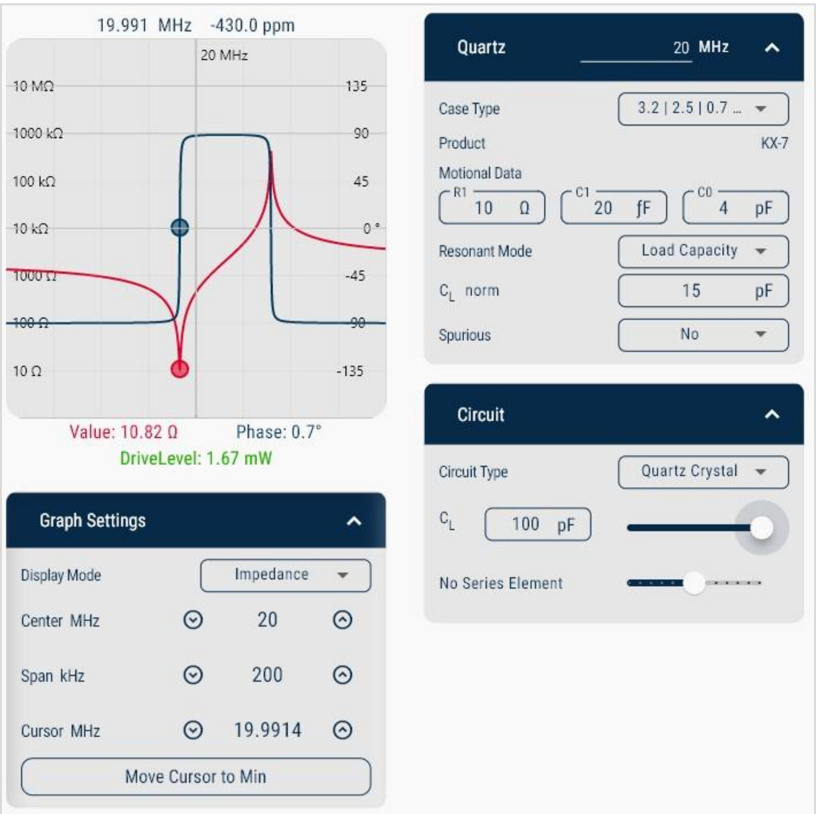

Figure 13
Quartz crystal with load capacitance stronger influence of a spurious resonance

2 Quartz Crystal Oszillators

2.1 Pierce oscillator with inverting amplifier

In most microprocessors a crystal oscillator in pierce configuration is used as clock. The active part is taken by an inverter. Within the menu 'Structure' it is possible to select and simulate the feedback network of such a pierce oscillator.

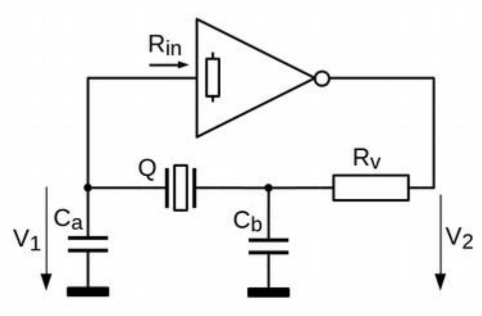

Figure 14
Pierce oscillator with inverter and feedback network for crystals in fundamental mode

The output resistance of the inverter together with the resistor R_v and the Pi- Element C_b / Resonator / C_a constitute a narrow band pass filter with frequency-dependent phase shift. The oscillation condition requires the total phase to be 360°. The inverter provides 180°, usually with a bit more because of additional semiconductor-related time delays. The external phase shift by the bandpass may therefore be slightly less than 180°.

The App simulates the transmission behavior of the Pi network formed by R_v, C_b, Q, C_a, according to gain (amplification), phase at f_L (center) and environment (span).

The aim is to have a:

- Gain (amplification) at f_L as high as possible.
- Phase at f_L as close to -180° as possible

Automatic optimization: Search, either manually or using the optimization button, the values for R_v, C_b, C_a, for which the target (see above) is maximized.

Choose the values of the external components such that both the amplitude and the phase component of the resonant condition is satisfied without exceeding the maximum crystal load; usually, a good compromise can be found. Choosing the same value for C_a and C_b, e.g., the double value of C_L, may work. The better solution is an impedance transformation by an 'unbalanced' configuration of the capacitors connected to the resonator. A first guess for C_a is 10 - 20% higher than the specified load capacitance, a first value for C_b is at least four times the C_a value.

R_v should be chosen large enough such that the allowed level of the crystal load will not be exceeded. With the sliders for R_v and C_b the transfer function should be optimized for the right resonator load and an optimum shape of the resonance curve. This setting is not necessarily the one with the highest voltage gain of the feedback network, given the inverter provides sufficient gain!

Figure 15
Pierce oscillator with asymmetrical choice of C_a and C_b (18/110 pF)

Figure 16
Pierce oscillator with symmetrical choice of C_a and C_b (24/24 pF)

As can be seen, the unbalanced configuration for C_a and C_b leads to a better resonance with higher quality factor.

The Pierce oscillator requires a quartz crystal with load capacitance, when no additional inductors are connected in series to the resonator.

A possible circuit for overtone resonators is shown in Figure 17.

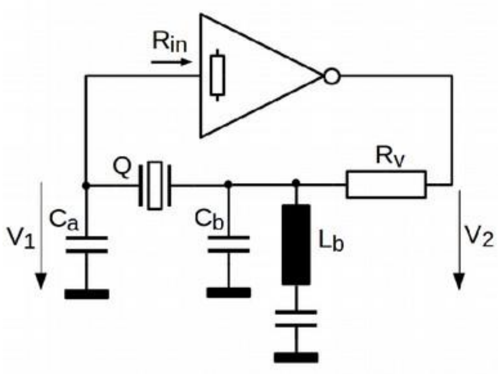

Figure 17
Pierce oscillator with inverter and feedback network for resonators in overtone mode

The GEYER App provides several other simulation options. For different types of crystals to be used in the simulation or other types of oscillators, like for ex. the colpitts oscillator, these can be provided on request.

For questions and suggestions, as well as new ideas, please contact us at any time at +49 89546868-0 or via the e-mail address app@geyer-electronic.de.