Quartz Crystal Resonators
- Brief overview -

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Quartz Crystal Resonators

Quartz Crystals, Cut Angles

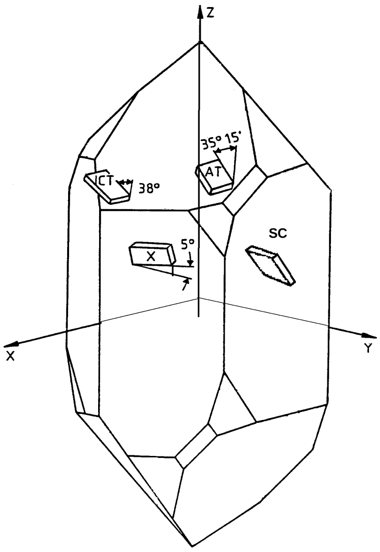

Figure 1: Orientation of different cuts in a natural quartz crystal

Piezoelectric materials, especially quartz , have the property to transform electrical energy into mechanical energy and vice versa.

In technical applications this effect is utilised by applying an alternating electrical field, which will cause the material to vibrate and subsequently resonate mechanically.

This electrical reaction permits usage as an electrical resonator with a very high figure of merit Q and a low temperature coefficient.

Different quartz crystal cuts can be made possessing different properties.

Cuts are defined by two rotation angles phi and theta around the crystallographic axes.

Most common cuts are the single rotation AT- cut (phi = 0°) and the double rotation SC-cut (phi = 22°) . The theta angle in both cases is around 34°.

Other double rotated cuts like MSC-, IT-, FC-, LD- for special applications also exist.

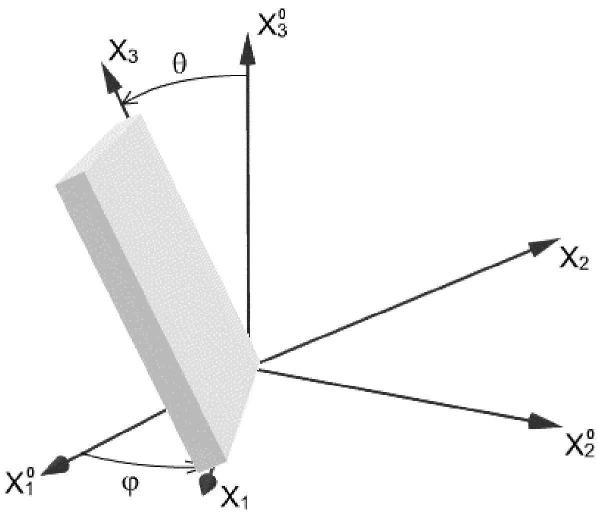

Figure 2: φ and θ cut angles

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Quartz Crystal Resonators

Quartz Resonators

The active component of the crystal resonator is a mechanically vibrating plate (“crystal element”) cut from mono-crystalline quartz with a precise orientation to the crystallographic axes. The resonator is plated under high vacuum with aluminium, silver or gold electrodes and hermetically sealed into a suitable enclosure either with a cold-weld or resistance weld process .

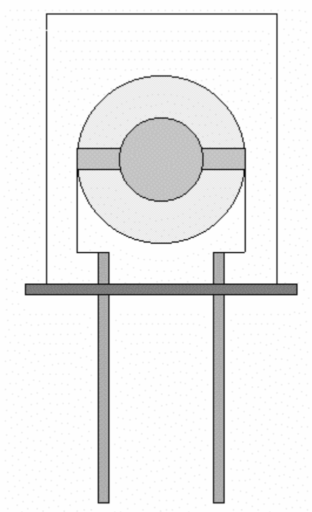

Figure 3: Crystal unit

The physical dimensions of the element and its orientation to the axes will determine in particular the resonance frequency, its initial accuracy, its electrical properties and the temperature coefficient.

KVG produces AT- and SC-Cut crystals (and others), which are the most widely used cuts providing a frequency range from 800kHz up to 300MHz and excellent frequency-temperature characteristics.

The frequency of crystals is inversely proportional to the thickness of the element . For mechanical processing, this results in an upper frequency limit of about 50MHz for crystals operating on the fundamental mode.

To reach higher frequencies in the fundamental mode KVG also produces chemically etched inverted-mesa crystals where the central part of the resonator is etched to have a thickness of as low as ten microns.

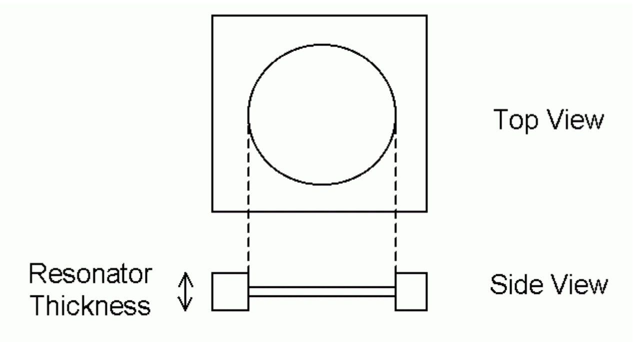

Figure 4: inverted – mesa resonator

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Resonator Design

Many different parameters have an influence on the final resonator properties. Thickness and diameter of the element , electrode diameter, electrode material but also holders, sealing method etc.

Crystal elements can be manufactured plano-parallel or contoured (with bevels, plano-convex or bi-convex) .

Contouring is necessary to prevent edge effects . A radius of curvature can be manufactured on one or both sides of the crystal element to trap the energy in the center of the resonator. Trapping can also be performed through mass loading.

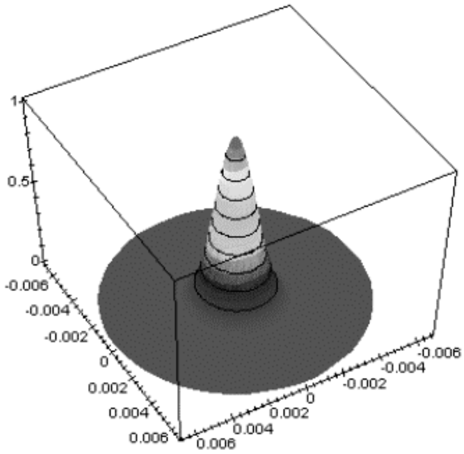

Figure 5: amplitude of vibration in the plate plan in a plano-convex resonator

Fundamental mode and overtone mode

High frequency crystals vibrate in the thickness-shear vibration, which can be excited in fundamental or odd overtone modes.

The motional capacitance C_{1n} of an overtone-crystal decreases with the order n of the overtone and is approximately given by

$$C_{1n} \approx \frac{C_{11}}{n^2} .$$

Therefore the ratio C_O/C_1 is much larger for overtone crystals than for crystals operating in fundamental mode and the pulling range is reduced by a factor of approximately n^3. Crystals used in VCXOs, where wide pulling range is required, therefore operate in fundamental mode

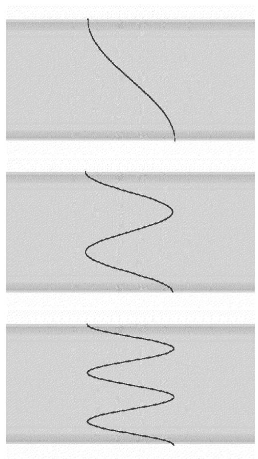

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Figure 6: 1st, 3rd and 5th thickness shear overtones

Unwanted Response and Inharmonics (spurious modes)

All crystal resonators produce for each overtone a main mode which is a thickness shear vibration and also unwanted responses, which are inharmonic thickness shear modes above the resonance frequency.
Besides the commonly used thickness shear C-mode another thickness shear mode named B-mode exsists. It has a higher frequency and commonly lower motional resistance than the C-mode but a larger temperature coefficient . Sometimes it becomes necessary to filter this mode for the oscillator to work on the C-mode.

Further unwanted modes are shear-, flexure-, thickness- and twist vibrations, which can appear above and below the required resonance frequency. With correct oscillator design the unwanted modes rarely cause problems. Unwanted modes close to the resonance frequency affect the start up behaviour of oscillators, or cause shifting to the wrong frequency during operation.

Other undesired effects are frequency and resistance dips over temperature caused by unwanted modes.
Spurious modes are generally specified as the ratio of resonance resistance of the inharmonic modes to the main mode resistance.
KVG must have detailed information about the test circuit (e.g. pi-network or measurement bridge) and about the frequency range of the spurious modes .

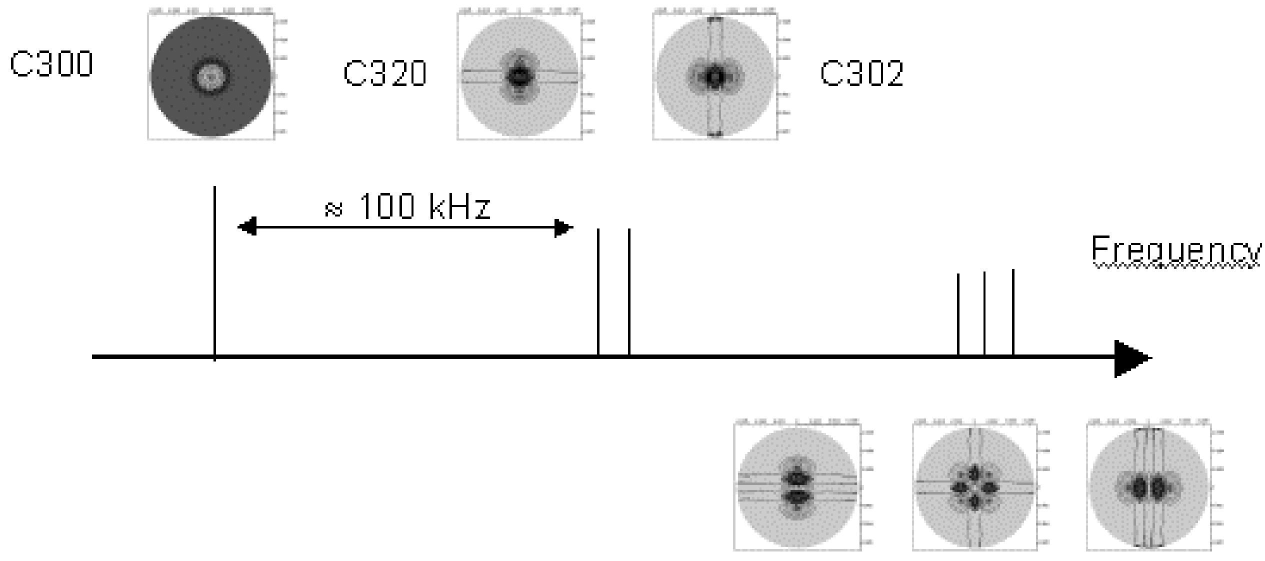

Figure 7 : Anharmonics of an SC-cut resonator on 3rd overtone

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Equivalent electrical circuit

Near to the resonance frequency the crystal unit is represented by an electrical two pole shown in figure 8 .

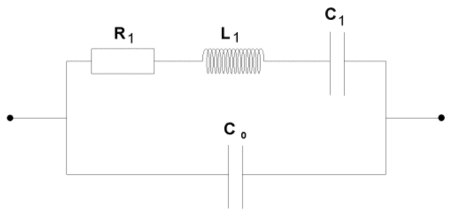

Figure 8: Equivalent electrical circuit

C_O: shunt capacitance (capacitance between the electrodes, crystal holder, leads and case)
C_1: motional capacitance (represent mechanical elasticity)
L_1: motional inductance (represent mechanical inertia)
R_1: motional resistance (represents mechanical losses)

Figure 9 shows the response in amplitude and phase vs frequency around resonance.

The resonance frequency is given by:

$$fr \approx fs = \frac{1}{2p\sqrt{L_1 C_1}}$$

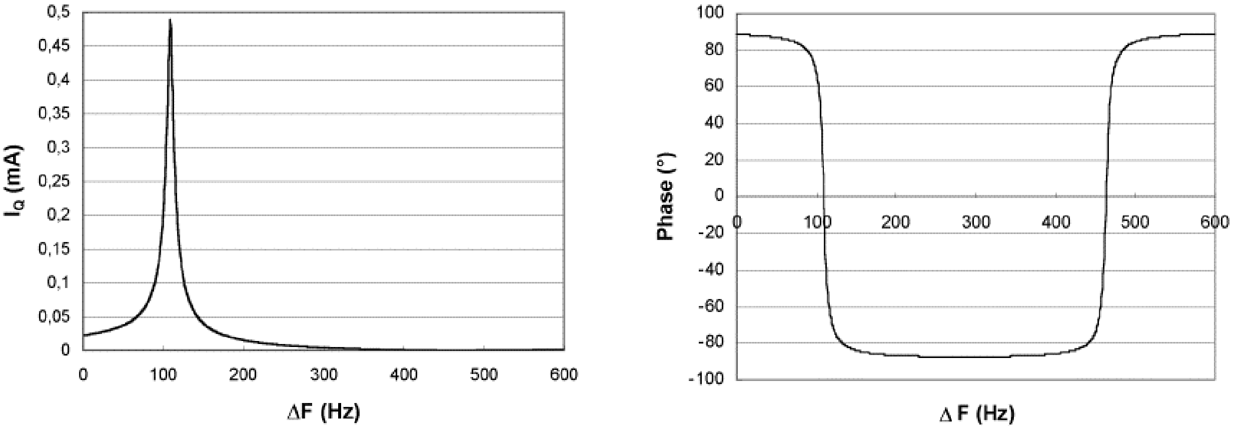

Figure 9: Resonance and phase curves

Pulling

With a load capacitance in series or parallel to the crystal the resonance frequency is shifted according to :

$$f_{LS} \approx fs \cdot \left(1 + \frac{C_1}{2 \cdot (C_O + C_{LS})}\right)$$

and the resistance at resonance becomes:

$$R_{LS} = R_1 \cdot \left(1 + \frac{C_O}{C_{LS}}\right)^2$$

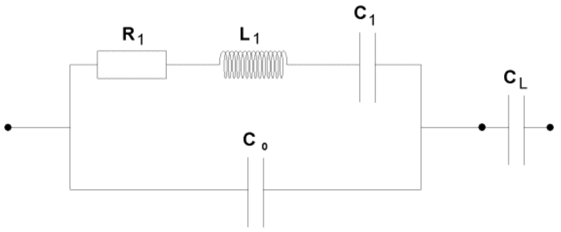

Figure 10: Load capacitance in series

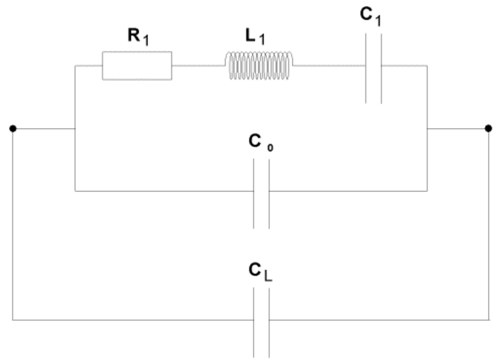

Figure 11: Load capacitance in parallel

Frequency-Temperature characteristics

The temperature characteristics of AT- and SC-cuts crystals are described by a 3rd order parabola.
It is then possible to describe the relative change of frequency:

$$\frac{\Delta f}{f} = A_i \Delta T + C_i \Delta T^3$$

with $\Delta T = T - T_i$ and T_i is the inflection temperature.

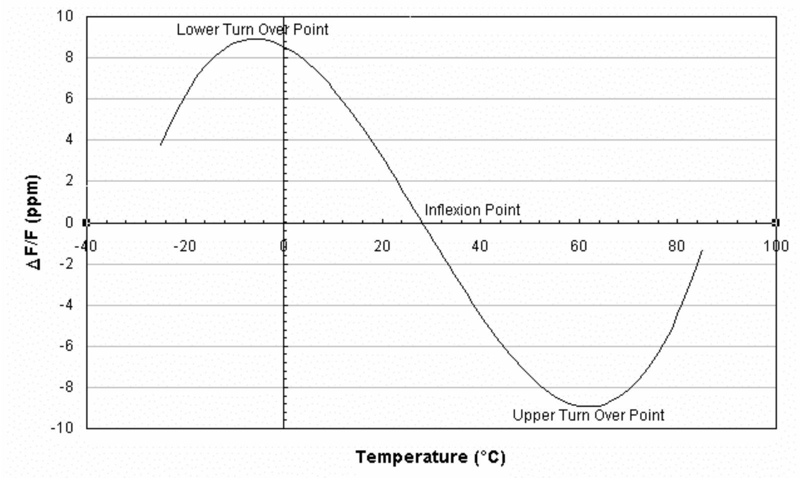

Figure 12: Typical frequency-temperature curve (AT-cut)

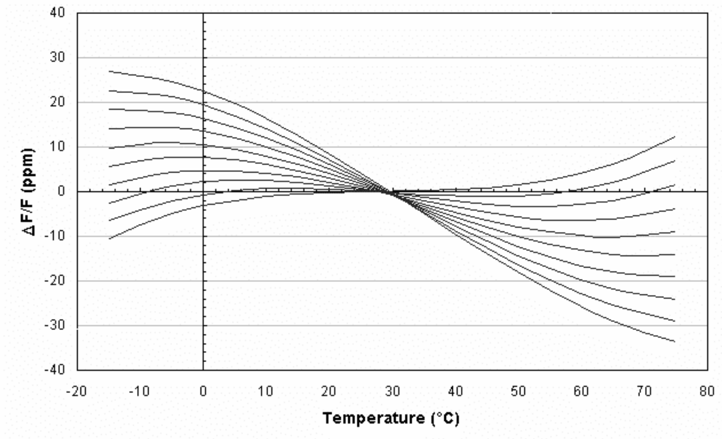

Figure 13: Frequency-Temperature characteristics of AT-cut for different values of θ

The frequency-temperature characteristic is primaraly determined by the the cut angle. For a given cut the parameter which changes the most with θ angle is A_i.

C_i is almost constant and T_i varies between +25°C and +35°C for the AT-cut and between +85°C and +95°C for the SC-cut , depending on the dimensions of the crystal element.

Since the inflection point of the SC-cut is close to 90° it is very suitable for ovenized oscillators because a TOP around 80° leads to very low dependency of frequency against temperature. (Note the different scale between Fig. 13 and 14)

Moreover SC-cut crystals are less sensitive to mechanical and thermal stress and provide lower aging and higher Q compared to the AT-cut.

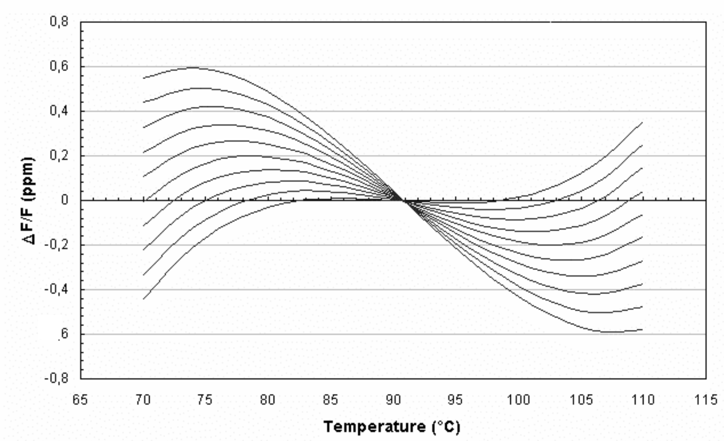

Figure 14: Frequency-Temperature characteristics of SC-cut for different values of θ

Aging

Aging is the change in crystal frequency with time (generally an inverse logarithmic function of the time). The aging performance is affected by the fabrication technology, pre-aging, the level of drive, the design of the oscillator and the environmental conditions.

Typical aging values:

RW enclosures : 1 - 5 ppm / 1st year
CW enclosures: 0.05 - 1 ppm / 1st year

RW = Resistance weld
CW = cold weld

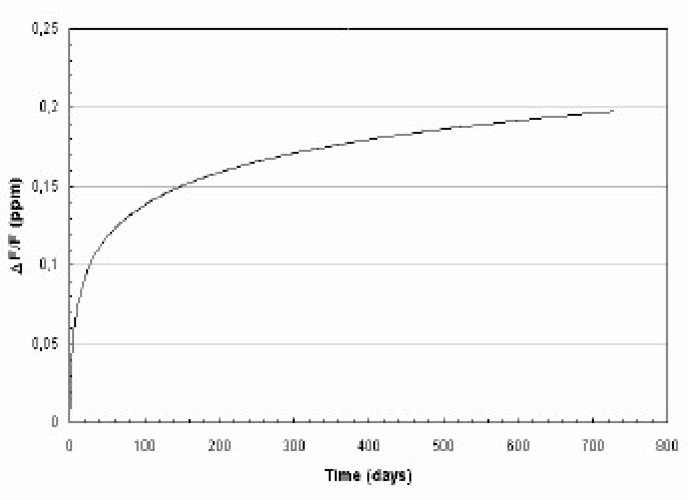

Figure 15: Typical aging curve

Drive Level Dependance

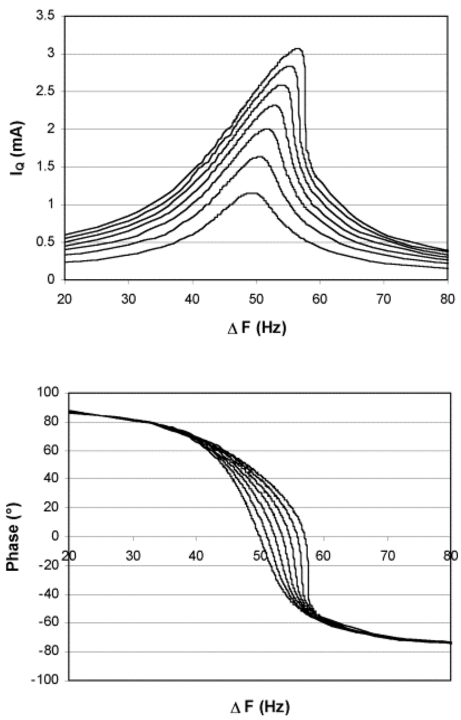

Figure 16: Resonance and phase curves for different drive levels

Drive level dependance is the frequency dependancy on the power through the resonator.

Varying the drive level will change the resonance and phase curves. Typically the dependance is linear with the power.

The effect is of the order of some $10^{-9}/\mu$Watt and is typically lower for the SC-cut than for the AT-cut.
It can be a problem when drive level fluctuates or drifts over time.

Crystals should be used at the level of drive for which they were designed. Higher drive levels excite unwanted modes of vibration, cause serious degradation of the frequency-temperature characteristic, accelerate aging and can shift the frequency due to overheating of the resonator.

The test drive level of KVG for standard crystals is 0.1mW.

Thermal Hysteresis

Hysteresis can occur when the crystal is subjected to temperature cycling.
After going through a temperature cycle as in fig. 18 , the difference between the frequency at the beginning and the end of the cycle can be higher than 1 ppm .
It is typically a problem in TCXO applications where the external temperature can vary in a quite large range.
By correct design of the crystal hysteresis can be minimized .

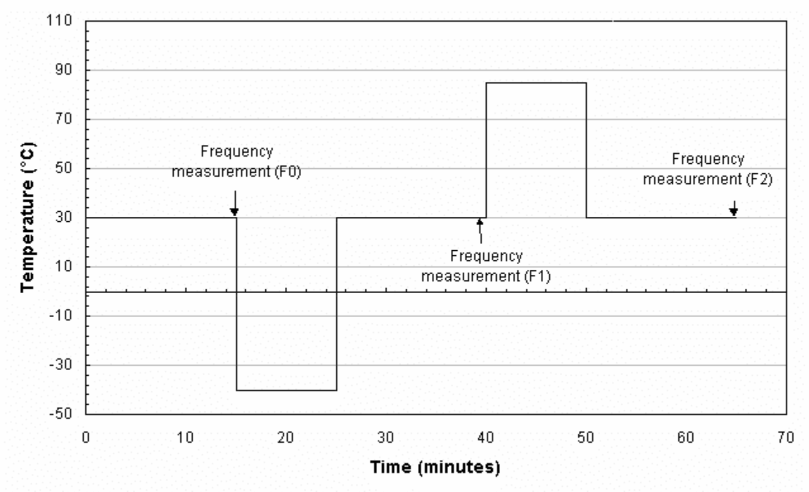

Figure 18: Temperature cycle

Activity Dips

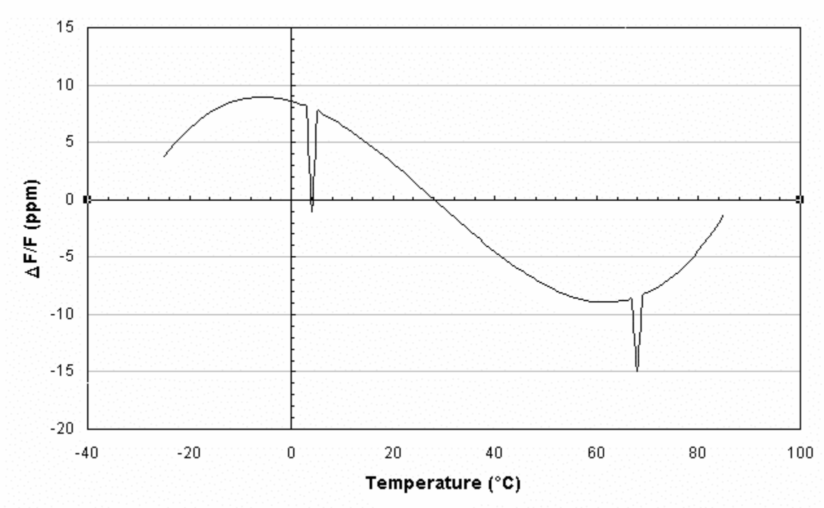

Figure 19: Activity dips

Dips can cause problems in crystals for VCXOs and TCXOs. A dip is characterized by deviation from the third order frequency-temperature curve.

It is caused by the excitation of unwanted modes through mechanical coupling.

Generally these modes have a strong temperature dependance so they appear as perturbations at discrete temperatures .

Dips are influenced by resonator design , drive level and oscillator circuit conditions.

Quartz Crystal Resonators

G-sensitivity

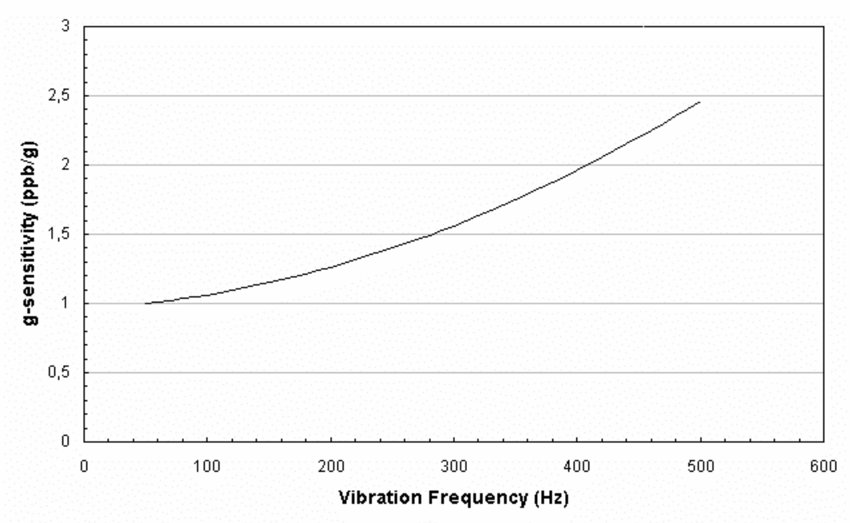

Figure 20: G-sensitivity vs vibration frequency

G-sensitivity is the frequency dependancy on the acceleration of the device.

Principally due to the stress in the crystal element it can lead to problems when the crystal is subjected to acceleration or vibration .

G-sensitivity can be minimized by appropriate mounting of the crystal element in the holder .

Ordering information

Minimum ordering information:

1. Crystal enclosure
2. Frequency
3. Fundamental - or overtone mode
4. Load capacitance C_L
5. Adjustment tolerance
6. Temperature stability over a specified temperature range

How to order the standard catalogue crystals:

The most crystal designations consist of XS and four figures. The first two figures define the crystal enclosure and frequency the last two figures define the stability of the crystal.

Example: Enclosure: HC-52
Frequency: 81.25MHz, 3.OT
Frequency stability in the temperature range of -20°C to +70°C: ± 10ppm
Calibration tolerance: ±10ppm

Þ Type: **XS 7114, 81.25MHz**

For special requirements please use the data sheets on our web-page: www.kvg-gmbh.de.

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