TEXAS INSTRUMENTS

MSP430 32-kHz Crystal Oscillators

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ABSTRACT

Selection of the right crystal, correct load circuit, and proper board layout are important for a stable crystal oscillator. This application report summarizes crystal oscillator function and explains the parameters to select the correct crystal for MSP430 ultralow-power operation. In addition, hints and examples for correct board layout are given. The document also contains detailed information on the possible oscillator tests to ensure stable oscillator operation in mass production.

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1.1   The Crystal

For an ultralow-power design, only low-frequency crystals are usable, because with higher-frequency oscillators, the current consumption increases significantly. Tuning-fork crystals typically have a frequency range of 10 kHz to 200 kHz in fundamental mode and a maximum drive level of 1 μW. These parameters make them the first choice for the 32768-Hz ultralow-power crystal oscillator in MSP430 microcontrollers.

Every MSP430 has a built-in crystal oscillator that can be operated with a tuning-fork crystal at 32768 Hz (often called 32 kHz). The mechanical oscillation (see Figure 1) of a 32-kHz tuning fork crystal is converted into an electrical signal. The equivalent electrical circuit of a crystal (see Figure 2) gives these electrical characteristics:

- C_M motional capacitance
- L_M motional inductance
- R_M mechanical losses during oscillation
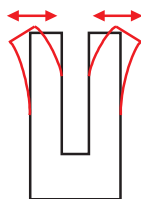- C_0 parasitic capacitance of package and pins

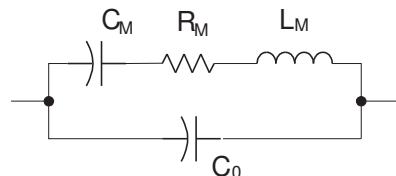**Figure 1. Mechanical Oscillation of a Tuning-Fork Crystal**

Figure 2. Equivalent Circuit of a Crystal

The series-resonance circuit consisting of C_M, L_M, and R_M represents the electrical equivalent of the mechanical resonance of the tuning fork. The frequency characteristics of a crystal's reactance are shown in Figure 3 and give two special frequencies:

- F_S (series resonance frequency) solely depends on C_M and L_M and gives a very stable frequency value.

$$F_s = \frac{1}{2\pi\sqrt{L_M C_M}}$$

- F_A (anti-resonance or parallel-resonance frequency), in addition, also depends on C_0, the parasitic capacitance of package and pins, which is not as precise as the other parameters, C_M and L_M. Hence, F_A gives a less well-defined frequency than F_S.

$$F_A = \frac{1}{2\pi\sqrt{L_M C_M}}\sqrt{1 + \frac{C_M}{C_0}}$$

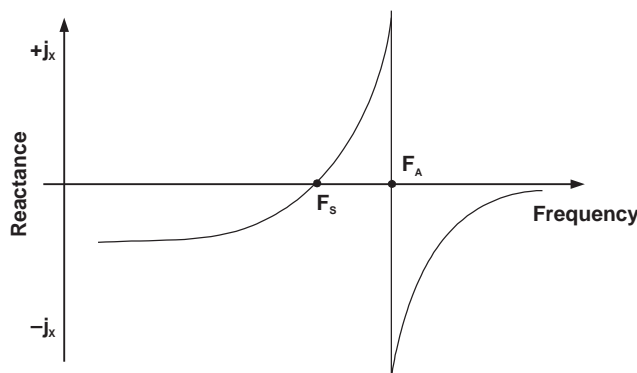**Figure 3. Reactance of a Crystal**

The equivalent series resistance (ESR) can be calculated with the formula in Equation 1 from the equivalent circuit in Figure 2:

$$ESR = R_M \left(1 + \frac{C_0}{C_L} \right)^2$$

(1)

C_0 is shown in Figure 2 and given by the crystal's data sheet, as is R_M or ESR. C_L is the required load capacitance of a crystal and is also given by the crystal's data sheet.

1.2 The Oscillator

The principle circuit of an oscillator is shown in Figure 4. Two basic parameters must be fulfilled to enable oscillation:

- Closed loop gain ≥ 1 for oscillator start up and
  closed loop gain = 1 for stable oscillation
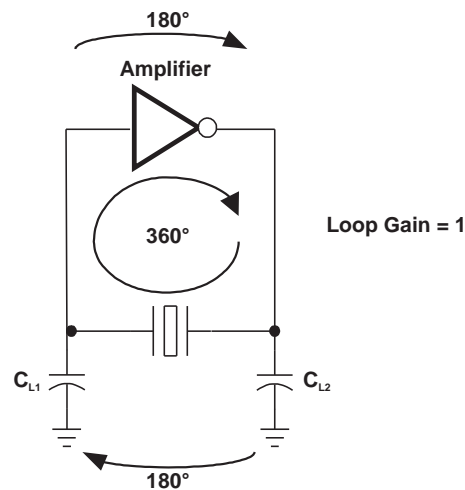- Closed loop phase shift = n × 360°

Figure 4. Principle Pierce Oscillator Circuit

Figure 4 shows the Pierce oscillator circuit, which takes advantage of the crystal's serial resonance frequency. The inverting amplifier gives a phase shift of approximately 180°. The feedback circuit consisting of a 32-kHz crystal and two load capacitors adds another 180° phase shift. This results in the required oscillator closed-loop phase shift of 360°. The closed-loop gain must be adjusted with the gain of the inverting amplifier. All MSP430 32-kHz crystal oscillators are Pierce oscillators.

2 Crystal Selection

The most important parameters when choosing a crystal are:

- Crystal's required effective load capacitance (for 32-kHz crystals, typically 6 pF to 15 pF)
- Crystal's ESR (for 32-kHz crystals, typically 30 kΩ to 100 kΩ)
- Tolerance (typically 5 ppm to 30 ppm)

All of these crystal parameters are given by the crystal data sheet but can be also measured at the real crystal using, for example, crystal impedance bridge, a vector voltmeter, or a network analyzer. It is very important to know these parameters, because otherwise it is not possible to design a stable oscillator.

2.1 *Effective Load Capacitance*

The Pierce oscillator (see Figure 4) uses two load capacitors, C_{L1} and C_{L2}, as load for the crystal. These capacitors generate, together with the crystal's inductance (L_M) (see Figure 2), the required 180° phase shift of the feedback loop. From the view of the crystal, these capacitors are a serial connection through GND. Hence, if using two equal capacitors, the values of these capacitors must be twice the required load capacitance. It is also important to consider all parasitic capacitances, such as PCB traces and MSP430 pin capacitance, for the calculation of the necessary capacitors according to the formula in Equation 2.

$$C_{Load} = \frac{C'_{L1} \times C'_{L2}}{C'_{L1} + C'_{L2}}$$

(2)

Where:

$C'_{L1} = C_{L1} + C_{L1Parasitic}$
$C'_{L2} = C_{L2} + C_{L2Parasitic}$

When using equal capacitors for C_{L1} and C_{L2} and a symmetric layout with equal parasitic capacitance on both crystal pins, the effective load capacitance is shown in Equation 3.

$$C_{Load} = \frac{C_{L1} + C_{Parasitic}}{2}$$

(3)

Example:

Crystal requires 12 pF load.
Parasitic capacitance per pin is 2 pF.
$C_{L1} = (2 \times C_{Load}) - C_{Parasitic} = (2 \times 12\ pF) - 2\ pF = 22\ pF$
$C_{L2} = C_{L1} = 22\ pF$

One result of choosing the wrong load capacitors, which can be easily measured, is an incorrect oscillation frequency. A typical curve, showing frequency vs load capacitance, is given in Figure 5.
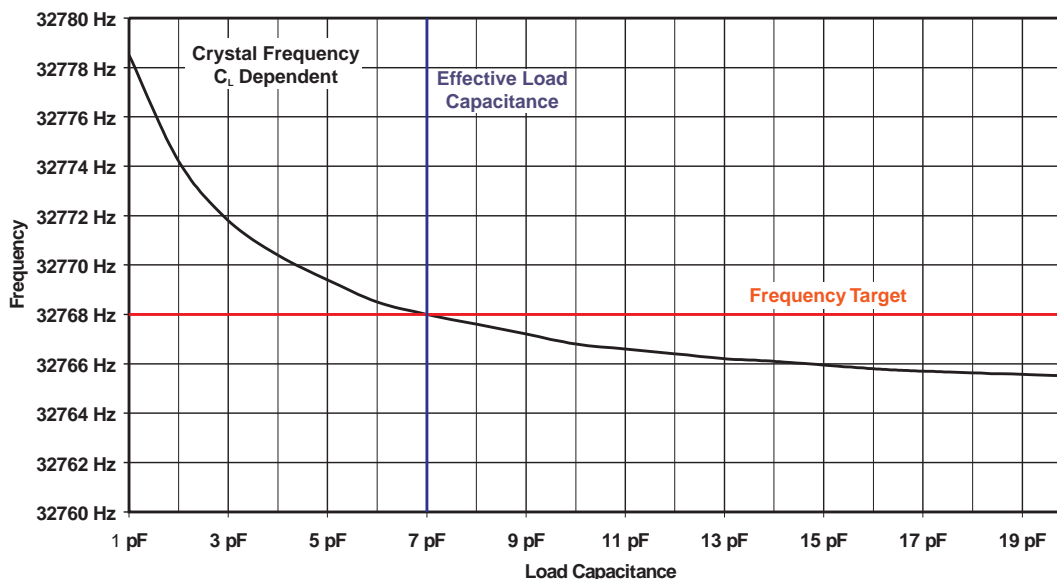
Figure 5. Frequency vs Load Capacitance for a 0-ppm Crystal

All MSP430 32-kHz oscillators have built-in load capacitors, C_{L1} and C_{L2}. In some MSP430 versions, these load capacitors are fixed; in other MSP430 versions, the internal load capacitor values can be programmed or external capacitors can be used. For details, see the data sheets and MSP430 family user's guides. The various MSP430 families have the following load capacitor configuration:

- MSP430x1xx: 6 pF (fixed effective capacitance with 12 pF per pin), external capacitors are not recommended
- MSP430F2xx: 0 pF to 12.5 pF (programmable effective capacitance), external capacitors are possible
- MSP430F4xx: 0 pF to 10 pF (programmable effective capacitance), external capacitors are possible

2.2 ESR Value

The ESR value is an electrical representation of losses of the mechanical crystal oscillation. A larger crystal loses less energy during oscillation, and this results in a lower ESR value. Small crystals, especially SMD crystals, tend to have higher ESR. A higher ESR value reflects the higher losses of a crystal.

The oscillator becomes unstable and stops oscillation if the ESR becomes too high. Hence, each oscillator has maximum limits of the ESR value. The lower the ESR than the recommended maximum value, the better the oscillator start up and stability.

A common test for oscillator stability is the negative resistance method (see Section 4.2). For this test, ESR must be increased with an external resistor. The maximum value of this increased ESR is called the oscillation allowance (OA). With this OA value, it is possible to make a judgment of the oscillator safety factor (SF) margin. It is good practice to do the negative resistance test, to avoid oscillator problems in high-volume applications.

Table 1 lists typical OA values for the 32-kHz oscillators of various MSP430 families.

Note: If oscillation allowance for LF crystals (OALF) values are specified in an MSP430 data sheet, this table does not apply, and only the data sheet values are valid.

Table 1. Typical Oscillation Allowance Values for the 32-kHz Oscillator

	MSP430x1xx	MSP430x2xx		MSP430x4xx	
	C_{L1} = 6 pF	C_{L1} = 6 pF	C_{L1} = 12.5 pF	C_{L1} = 6 pF	C_{L1} = 12.5 pF
V_{CC} = 3 V	185 kΩ	500 kΩ	200 kΩ	460 kΩ	180 kΩ
V_{CC} = 2.2 V	88 kΩ	500 kΩ	200 kΩ	440 kΩ	170 kΩ

Refer to crystal manufacturer recommendation for 32-kHz crystals operating with MSP430 oscillators.

2.3 Tolerance

The ppm tolerance value given in the data sheet expresses the possible frequency deviation of the resulting oscillator frequency, assuming that all other frequency-affecting parameters, such as effective capacitive load, temperature, etc., are at recommended values.
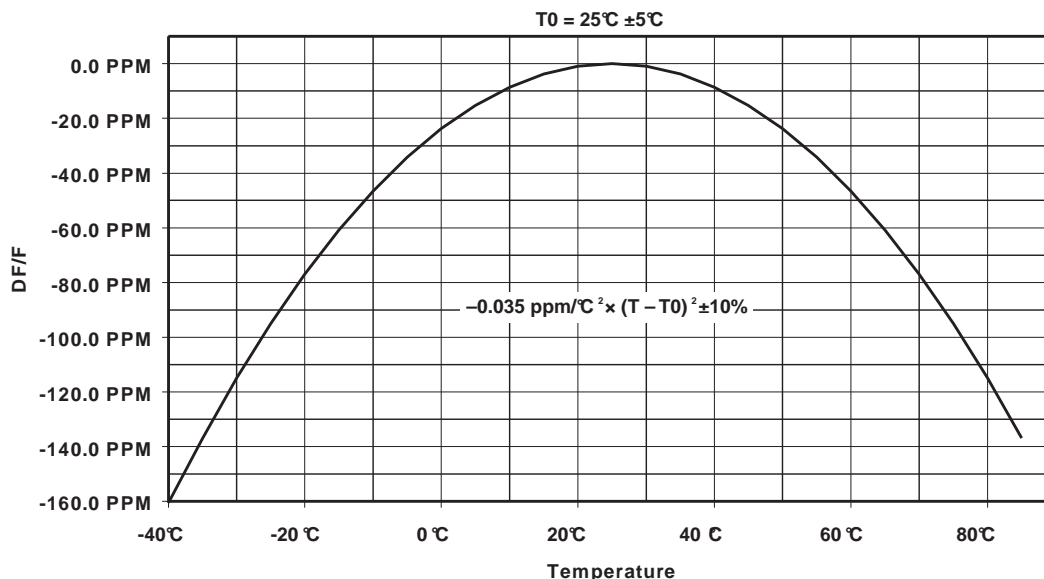

Figure 6. Frequency Deviation of a Tuning-Fork Crystal Over Temperature

It should be considered that the amount of the frequency variation due to temperature depends very much on the crystal cut and the crystal shape. In comparison to some other crystal cuts, 32-kHz tuning-fork crystals exhibit a relative high frequency drift over temperature. Figure 6 shows the typical frequency deviation of a 0-ppm tuning-fork crystal over temperature. The ±ppm tolerance value, given in the crystal data sheet, shifts the graph of the tuning-fork crystal up and down.

In case the 32-kHz crystal oscillator frequency is used for precision measurements over a wide temperature range, software can improve the measurement results by correcting the measured values according to the curve in Figure 6. In this case, the real curve for the used crystal should be obtained from the crystal manufacturer.

A test for oscillator frequency and a method to adjust the oscillator frequency is explained in Section 4.1.

2.4 *Start-Up Time*

When initially energized, the only signal in the circuit is noise. That component of noise whose frequency satisfies the phase condition for oscillation is propagated around the loop with increasing amplitude. The amplitude continues to increase until the amplifier gain is reduced either by nonlinearities of the active elements ("self-limiting Pierce", MSP430x1xx) or by some automatic level control ("controlled Pierce" with AGC circuitry, MSP430x2xx and MSP430x4xx).

Start-up times between several hundred milliseconds and a few seconds are normal values for low-frequency tuning-fork crystals, like 32768-Hz crystals. The start-up time of a crystal oscillator depends on various factors:

- The oscillator frequency influences the start-up time. A 32-kHz crystal oscillator starts relatively slowly, compared to a crystal oscillator with a high frequency, e.g., above 1 MHz.
- High Q-factor crystal oscillators typically start slower than crystal oscillators with higher frequency tolerance.
- Crystal with low load capacitance typically start faster than crystals requiring high load capacitance.
- Crystals with low ESR start more quickly than high ESR crystals.
- Oscillators with high OA (Oscillation Allowance) start faster than low OA crystal oscillators.

3 PCB Design considerations

The MSP430 LFXT1 32-kHz crystal oscillator is designed for ultralow-power consumption. According to the data sheets, most MSP430 derivatives consume less than 1 μA when the 32-kHz oscillator, the clock signal (ACLK), and a timer are running. Hence, the current flowing between the MSP430 pins, the crystal and, if used, the external capacitors is extremely low. Long signal lines make the oscillator very sensitive to EMC, ESD, and crosstalk. Even the best components cannot solve problems caused by a poor layout.

The crystal oscillator is an analog circuit and must be designed according to analog-board layout rules:

- Signal traces between the MSP430 pins, the crystal and, if used, the external capacitors must be as short as possible. This minimizes parasitic capacitance and sensitivity to crosstalk and EMI. The capacitance of the signal traces must be considered when dimensioning the load capacitors.
- Keep other digital signal lines, especially clock lines and frequently switching signal lines, as far away from the crystal connections as possible. Crosstalk from digital signals may disturb the small-amplitude sine-shaped oscillator signal.
- Reduce the parasitic capacitance between XIN and XOUT signals by routing them as far apart as possible.
- The main oscillation loop current is flowing between the crystal and the load capacitors. This signal path (crystal to C_{L1} to C_{L2} to crystal) should be kept as short as possible and should have a symmetric layout. Hence, both capacitors' ground connections should always be as close together as possible. Never route the ground connection between the capacitors all around the crystal, because this long ground trace is sensitive to crosstalk and EMI.
- Guard the crystal traces with ground traces (guard ring). This ground guard ring must be clean ground. This means that no current from and to other devices should be flowing through the guard ring. This guard ring should be connected to AVSS of the MSP430 with a short trace. Never connect the ground guard ring to any other ground signal on the board. Also avoid implementing ground loops.

- With 2-layer boards, do not route any digital-signal lines on the opposite side of the PCB under the crystal area. In any case, it is good design practice to fill the opposite side of the PCB with clean ground and also connect this ground to AVSS of the MSP430.
- Connect the crystal housing to ground.
- In LF mode, the LFXT1 oscillator of MSP430x1xx requires a ≥ 5.1-MΩ resistor from XOUT to V_{SS} when $V_{CC} < 2.5$ V. This is used to increase the drive level of the MSP430 amplifier at low V_{CC}. Refer to the data sheet for details.

Making use of the MSP430 built-in capacitors gives a simple layout, with only the crystal connected to the XIN and XOUT pins of the MSP430. The traces between the MSP430 and the crystal should be as short as possible, and a ground area should be placed under the crystal oscillator area. When using external capacitors instead of the internal capacitors, the traces between the crystal and the capacitors and the trace between the two capacitors should be as short as possible. Examples for recommended layouts are shown in Figure 7. An additional ground guard ring could improve the performance.
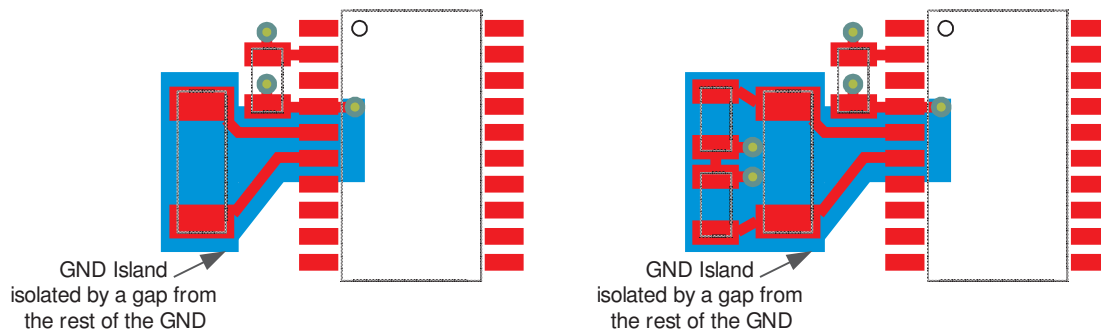

Figure 7. Layout Without and With External Load Capacitors
(XIN and XOUT Neighboring Pins Are Standard Function Pins)

Some of the MSP430 devices have NC (not connected) pins neighboring the XIN and XOUT crystal connection pins. In that case, it is recommended to make use of the situation and add a ground guard ring around the crystal signals. This ground guard ring should have a short connection to the MSP430 VSS pin. Layout examples for this scenario are shown in Figure 8. In all these examples, the section between crystal and the load capacitors is laid out symmetrically.
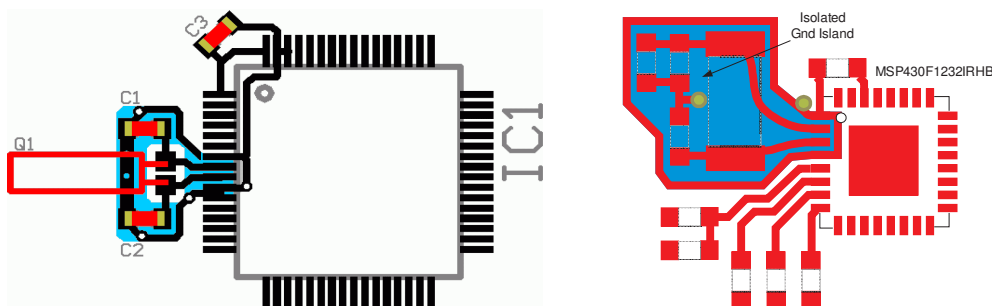

Figure 8. Layout With External Capacitors and Ground Guard Ring
(XIN and XOUT Neighboring Pins Are NC Pins)
Examples for MSP430F41x and MSP430F1232IRHB

4 Testing the Crystal Oscillator

The following measurements help to verify the crystal oscillator stability:

- Oscillator frequency vs load capacitance
- Negative resistance method (Oscillation Allowance test)
  - Start allowance
  - Stop allowance

4.1 Oscillator Frequency vs Load Capacitance

As shown in Figure 5, the crystal oscillator frequency is very much dependent on the load capacitance that is connected. Hence, measuring the oscillator frequency gives a good indication if the load capacitors that are used match the crystal requirements. This measurement also automatically includes the parasitic PCB and pin capacitances of the application. The graph in Figure 5 shows typical 32-kHz crystal characteristics. The characteristics (pullability curve) of the crystal should be provided by the crystal manufacturer.

It is strongly recommended not to measure the oscillator frequency directly at the crystal pins. The capacitance at the crystal pins is in the range of 10 pF, and the impedance on this signal line is several megaohms. A typical passive probe has a capacitance in the range of 10 pF and an input impedance of about 10 MΩ. Both values are in the range of the oscillator characteristics and heavily influence the behavior of the crystal oscillators. The MSP430 internal digital ACLK clock signal always carries the clock signal of the 32-kHz crystal oscillator. All MSP430 devices have the capability to output ALCK at one of the I/O pins. Measuring at this digital ACLK output does not influence the crystal oscillator in any way. ACLK still gives all necessary information to determine the stability and performance of the setup.

A frequency counter with a resolution and accuracy of at least 0.1 ppm in the targeted frequency range should be used to measure the 32768-Hz clock signal. If, for example, the tolerance of the crystal is given with $\pm$30 ppm, the 32768-Hz clock frequency should be $\pm$0.9 Hz accurate at room temperature. For a $\pm$5-ppm crystal, the frequency should be within $\pm$0.16 Hz when the correct capacitive load is connected.

Assuming the crystal itself has no tolerance, too low a capacitive load results in a higher oscillator frequency than expected and, vice versa, the frequency is lower than the nominal value, if the load is too high. Hence, if the oscillation frequency is too high, the value of load capacitors must be increased. When a too low frequency is measured, it is necessary to decrease the value of the load capacitors. Comparing the finally optimized capacitors with the crystal data sheet value for load capacitance gives the parasitic capacitance added by the PCB layout and pins.

4.2 Negative Resistance Method

The negative resistance method is also called the Oscillation Allowance test or safety margin test. With this test, the ESR safety factor is measured. As already stated in previous sections, the ESR value in the equivalent circuit of a crystal (see Figure 2) represents the losses. These losses must be compensated by the amplifier in the MPS430. If the losses exceed the drive capabilities of the amplifier, the oscillation amplitude starts decreasing until it finally dies away, or the oscillator does not even start up. The ESR value of a crystal increases with temperature. Thus, the oscillator may be working fine at room temperature but may fail at higher temperatures. Also, higher humidity can increase the losses in the oscillator, due to lower parasitic resistive values. To avoid time-consuming oscillator tests over all possible environmental situations, the negative resistance test has been established. It gives a SF (Safety Factor) value that allows the designer to assess, relatively easily, the safety margin of a particular oscillator setup.

For the negative resistance test, an additional resistor is added in series with the crystal, as shown in Figure 9. The additional serial test resistance, R_Q, is increased until the oscillator does not start up or a running oscillation stops. It is good practice to lower the resistance until the oscillator works again, to determine the critical value. This can be done using an SMD potentiometer that is suitable for RF, to add as few parasitic values as possible. Because all parameters and the parasitic values of this potentiometer contribute to the resulting parameters of the oscillator circuit, the final value of R_{Qmax} should be verified with an SMD resistor.
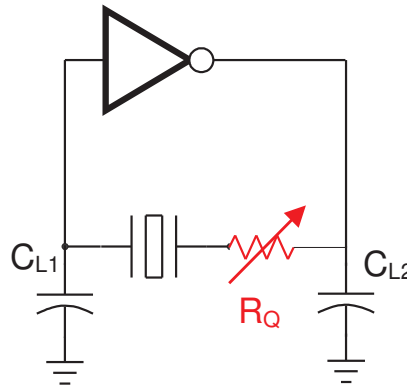
Figure 9. Negative Resistance Method With Added Resistor R$_Q$

The test can be done during the oscillator start (Start Allowance) and it can be repeated for a running oscillator to determine when oscillation dies away (Stop Allowance).

- Start Allowance: Resistor R$_Q$ is placed in series to the crystal. The power is then turned on, and it is checked if the oscillator starts. For each new resistor value, the MSP430 must be powered down and powered up again. The highest resistor value with which the oscillator still starts is the Start Allowance.
- Stop Allowance: Once the oscillator is running, the R$_Q$ potentiometer is increased until the oscillator stops. The potentiometer can then be reduced again until the oscillation starts again. The highest resistor value with which the oscillator still runs and does not stop is the Stop Allowance.

Once the critical values of R$_Q$ are measured, the OA and the SF should be calculated to allow a judgment of the oscillator stability, as shown in Equation 4 and Equation 5.

Oscillation Allowance (OA)

$$OA = R_{Qmax} + ESR \qquad\qquad (4)$$

Safety Factor (SF)

$$SF = \frac{OA}{ESR} = \frac{R_{Qmax} + ESR}{ESR} \qquad\qquad (5)$$

Table 2 gives a qualification of the SF and is based on the experience of major crystal manufacturers. If the outcome of the investigations is a sufficient SF, then the assumption can be made that all reasonable tolerances and variations of the parameters of the oscillator externals should be covered.

Table 2. Safety Factor

QUALIFICATION OF THE SAFETY FACTOR (SF)	QUALIFICATION
SF < 2	Unsafe
2 ≤ SF < 3	Suitable
3 ≤ SF < 5	Safe
SF ≥ 5	Very safe

5 Crystal Oscillator in Production

In general, it needs to be considered that the 32-kHz crystal oscillator is an ultralow-power oscillator with very low power consumption, in the range of significantly below 1 μA. Thus, it is critical for the performance of the oscillator to maintain a certain quality and cleanness of the PCB. Also, the soldering material should be selected with respect to this. The following sections provide some basic hints at these points that should be considered.

5.1 PCB Material, Quality, and Cleaning

Beside other factors, which have been described in the previous sections and which are covered by circuit theory, optimization of the components, and layout, there is another group of factors significantly affecting the performance of the oscillator setup. These factors are the board-assembly production process and assembly quality. In the previous sections, the ultralow-power character of the MSP430 oscillators has been mentioned. Due to the optimization for the lowest possible current, the losses caused by parasitic currents can have a significant impact on the overall oscillator performance. The soldering process, dependent on the used flux material, leaves more or less critical residues on the PCB surface. Especially in applications with a long lifetime and under unfavorable conditions, like high humidity and fast temperature cycles that possibly cause humidity condensation on the printed circuit board, process residuals are critical. The process residuals can lead to a decrease of the insulation of the sensitive oscillator signal lines towards each other and neighboring signals on the PCB. High humidity can lead to moisture condensation on the surface of the PCB and, together with process residuals, reduce the surface resistivity of the board. Thus, it is strongly recommended to carefully select the materials for the soldering process and use clean PCB material for the assembly process and cleaning afterwards, if needed, especially when the factors described above apply.

5.2 Soldering and Contact Impedance

When soldering, there are basically two different types of flux material. There are water-soluble flux materials, which must be cleaned off after the soldering process by appropriate cleaning processes, and there are "no clean" flux materials on the market. For specific cleaning procedures, refer to the solder-paste manufacturer's recommendation for the specific soldering paste and flux. Even when using the "no clean" products in ultralow-power applications, PCB cleaning is recommended to achieve maximum performance by removing flux residuals from the board after assembly. The flux residuals on the board can cause leakage current paths, especially in humid environments.

In general, reduction of losses in the oscillator circuit leads to a better safety margin and, thus, also increases performance and reliability. To keep the losses in the oscillator circuit as low as possible, it is critical to keep contact impedance as low as possible.

The MSP430 package is qualified against JEDEC Std 020 to withstand the specified maximum peak reflow temperature allowed at certain moisture sensitivity level (MSL). This is the maximum allowed reflow profile. The solder-paste supplier usually supplies a suggested reflow profile that is within the JEDEC Std 020 maximum range. Thus, the JEDEC recommendations for the soldering profile for devices and the recommendations of the soldering materials supplier should be carefully followed, to achieve high reliability and quality solder joints.

If the MSP430 package is to be exposed to any reflow temperatures after the liquid cleaning process, the board with the mounted MSP430 package should be baked, to dry out the part prior to the following reflow process. In this case, the devices must be baked according to the JEDEC Std 020 (24 hours at 125°C) before processing through an additional solder-reflow step or performing a rework soldering.

5.3 Environmental Influences, Temperature, and Humidity

A very important aspect is the increasing ESR at higher ambient temperature. Increasing ESR means additional losses, thus, the safety margin of an oscillator setup decreases with higher ambient temperature. As long as the safety factor test has shown good results, as classified in Table 2, and the crystal is being used in the standard industrial temperature range, the application should work safely.

On the other hand, temperature cycles, especially fast temperature cycles combined with high ambient humidity, can result in condensed water on the PCB. Together with soldering residues, dust, and other board contaminations, which can easily happen in applications with a lifetime of several years and non-air-proof housings, this may decrease the insulation of the oscillator signals towards each other and towards neighboring signals on the PCB. Thus, it is a good practice to introduce a protective coating of the crystal, the attached externals, and the MSP430 oscillator pins, to preserve the parameters and performance of the oscillator over many years of operation in the field. If this recommendation is not followed, a continuous degradation of the oscillator performance can occur and should be taken into account.

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