Keywords: transmitter, receiver, ISM, RF, radio, quartz crystal, frequency, PCB, parasitics, load capacitance, motional, negative resistance, pulling, ppm, cut, reference oscillator, HKC, Raltron, NDK, Crystek

TUTORIAL 5422

Crystal Calculations for ISM-RF Products

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Abstract: Many industrial/scientific/medical (ISM) band radio frequency (RF) products use crystal oscillators to generate a reference for the phase-locked loop (PLL)-based local oscillator (LO). This tutorial provides a basic description of the ISM-RF Crystal Calculator, which can be used to calculate various impacts on crystal frequency accuracy and startup margin for such an LO.

ISM-RF Crystal Calculator

The ISM-RF Crystal Calculator is broken down into a number of worksheets that address various calculations related to crystal oscillators and provides reference information about crystals themselves.

Click here for an overview of the wireless components used in a typical radio transceiver.

Instructions Sheet

This tab provides a summary of the formatting conventions used on the *Calculator* worksheet, as well as brief descriptions for the other tabs.

Calculator Sheet

As noted in the *Instructions* sheet, there are two primary sections of the *Calculator* worksheet: the **Product Information** section used for data entry, and the three calculation sections showing results of the entered parameters. The **Product Information** area has three background colors used to denote different categories of data within the section. There are also particular cells (outlined in red) that require user input, thus providing the variable values used for the subsequent calculations.

The orange section contains information related to the Maxim ISM radio product for which the calculation is being applied. At the top of this section is a drop-down box that is used to select the target device for the calculations. The following rows display the device's internal capacitance (C_{INT}) related to the XTAL pins, the PLL dividing ratio, the IF frequency (for receivers), and the suggested crystal reference frequencies for 315MHz and 433.92MHz of operation. An automated macro is provided that will copy either the f_0 value down to the **Crystal Frequency** section (cell C23). (Note: macros will need to be enabled within the spreadsheet to use this functionality.)

The blue section has information regarding the printed-circuit board (PCB) and the crystal oscillator circuit. It includes an estimated value for parasitic capacitance (C_{PAR}) and two cells for entering shunt (C_{SHUNT}) or series capacitor values (C_{SER}). It is very common for designs to provide a pair of shunt or series capacitors, one for each pin, so the entry assumes that the same value is used for both shunt or series capacitors. A reference diagram is provided to illustrate the capacitor connections.

The green section shows data for the crystal itself. A pair of drop-down boxes is available to simplify crystal selection from the various vendor sheets (see the NDK Crystals, Crystek Crystals, HKC Crystals, and Raltron Crystals Sheets section below). An automated macro is also provided, allowing the user to easily copy the crystal vendor's electrical characteristics from the reference column over to the user input section. (Disclaimer: For the latest specs, please confirm with the crystal vendor's data sheet.) If the user has crystal parameters available from a specification sheet, they can be manually entered directly into the cells outlined in red. Values for shunt capacitance (C_0), maximum equivalent series resistance (ESR) (R_1), and motional capacitance (C_1) are intrinsic to the crystal design. The motional inductance (L_1) is a calculated property of the crystal system. A reference diagram showing the basic crystal model is provided to illustrate these properties. The load capacitance ($C_{L\text{-}SPEC}$) and the crystal frequency (f_0) are parameters used by the crystal vendor to target a specified operating frequency.

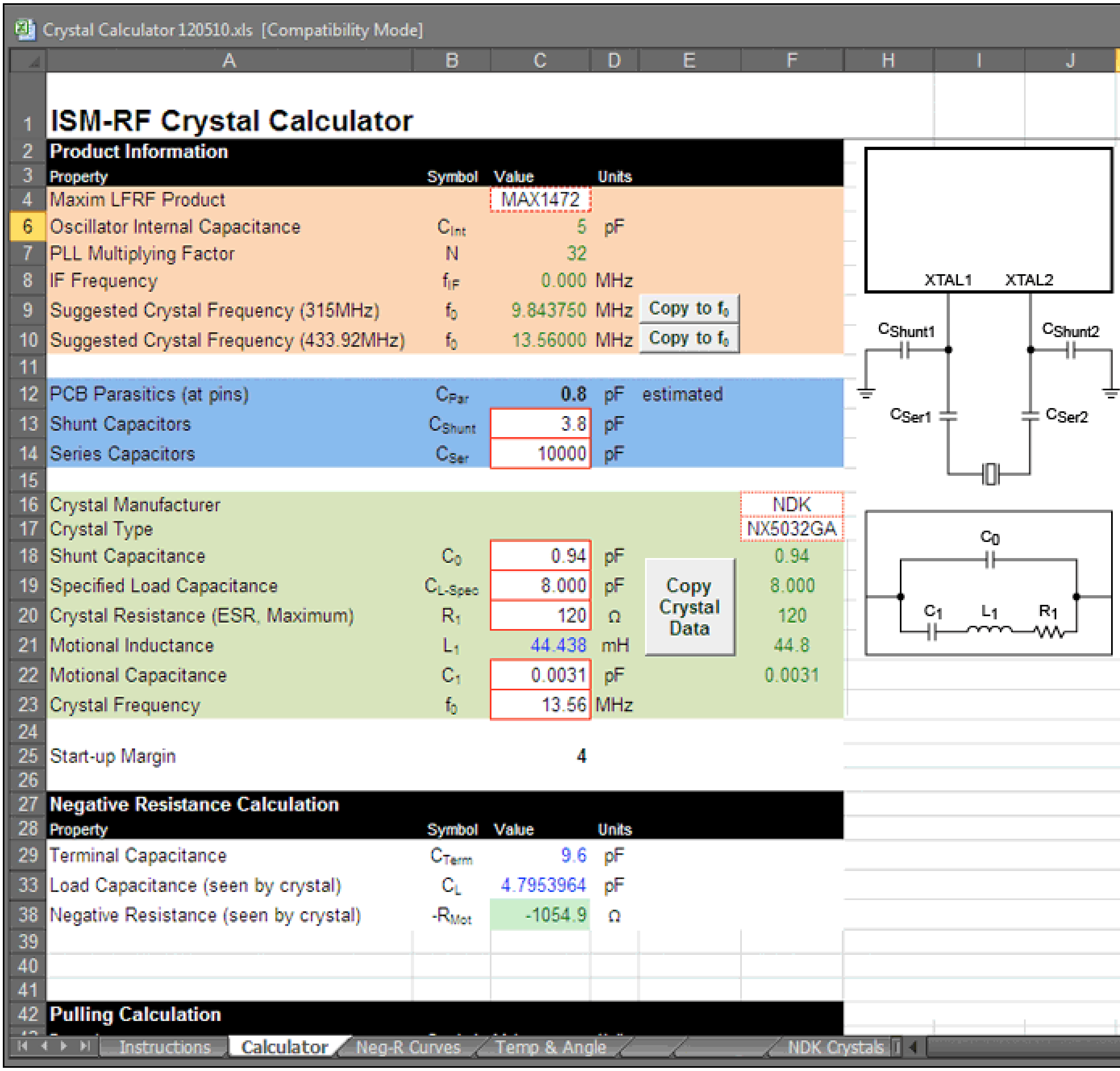

Figure 1. The Calculator worksheet.

Commonly, crystal vendors will provide a data sheet that specifies the nominal operating frequency (f_0), the tested load capacitance (C_L), the maximum ESR (R_r), and occasionally the shunt capacitance (C_0) (which is usually also a maximum parameter). The actual shunt capacitance tends to be less than half of the specified maximum, and the ESR can commonly be found at a 1/4 to 1/3 of the specified maximum. The motional capacitance (C_1) tends to be dependent on the cut angle, which is not commonly provided. Other properties such as aging and lifetime stability, storage, soldering, operating temperatures, as well as operational tolerances may be provided in a crystal data sheet. However, these are not assessed in this calculator.

The lower sections of the worksheet provide calculations for the negative resistance and crystal pulling. There is also a third calculation section specifically for the MAX1479 amplitude-shift keying (ASK)/frequency-shift keying (FSK) transmitter.

The negative resistance calculation is used to help determine if there will be any issues associated with starting up the oscillation of the crystal. The formula for calculating the negative resistance stems from the oscillator transconductance gain, the frequency of oscillation, and the terminal capacitances:

$$\text{Negative Resistance } (\Omega) = \frac{-gm}{\omega^2 \times C_{TERM}^2}$$

In this spreadsheet the negative resistance ($-R_{MOT}$) is automatically highlighted in either green or red. The highlighted color is dependent upon the $-R_{MOT}$ value versus the startup margin multiplied by the ESR. Using a startup margin of 4, if $|-R_{MOT}|$ is < 4 × ESR, then the negative resistance will be in red. We recommend adjusting the design to provide less capacitive loading on the crystal, which in turn increases the magnitude of the negative resistance, and thus increases the likelihood of initiating an oscillation.

The pulling calculation determines how much the carrier frequency may deviate from the target, based on system design parameters. The formula for calculating the crystal pulling is based on the motional capacitance of the crystal and the actual versus specified total capacitive load:

$$\text{Pulling (ppm)} = \frac{C_1}{2} \times \left(\frac{1}{C_{T\text{-}ACTUAL}} - \frac{1}{C_{T\text{-}SPEC}} \right) \times 10^6$$

The actual carrier frequency ($f_{RF\text{-}ACTUAL}$) helps determining the effects of system on the final RF.

39				
40				
41				
42	**Pulling Calculation**			
43	**Property**	**Symbol**	**Value**	**Units**
44	Specified Total Capacitance	$C_{T\text{-}Spec}$	8.940	pF
45	Actual Total Capacitance	$C_{T\text{-}Actual}$	5.735	pF
46	Pulling (ppm)	Δf_{Xtal}	97	ppm
47	Pulling (Hz)	Δf_{Xtal}	1314	Hz
48	RF Frequency	f_{RF}	433.9200	MHz
49	Frequency Offset	Δf_{RF}	42.035355	kHz
50	Actual RF Frequency	$f_{RF\text{-}Actual}$	433.9620	MHz
51				
52				
53	**MAX1479 FSK Calculation**			
54	**Property**	**Symbol**	**Value**	**Units**
56	MAX1479 Pulling (ppm)		199	ppm
57	MAX1479 Pulling (Hz)		2692	Hz
58	Actual FSK Space Frequency		433.9620	MHz
59	Actual FSK Mark Frequency		434.0061	MHz
60	FSK Δ Frequency		44.1023	kHz
61	Actual FSK Center Frequency		433.98409	MHz
62				

*Figure 2. The **Pulling Calculation** and **MAX1479 FSK Calculation** sections of the Calculator worksheet.*

As noted, the **MAX1479 FSK Calculation** section can provide estimates of the FSK deviation based on the system design parameters. The MAX1479 uses internal switched capacitance to force the crystal oscillator to change, thus providing a means to generate FSK modulation. For further information, see the MAX1479 data sheet.

Neg-R Curves and *Temp & Angle* Sheets

Various other plots can be used to determine operational characteristics and empirical limits to the crystal oscillator. Data tables and plots are provided to visually explain these crystal properties.

The data generated on the *Neg-R Curves* sheet uses values from the *Calculator* sheet to build a table of resistance based on various shunt capacitance (C_0) and load capacitance (C_L) values (see **Figure 3a**).

The data found on the *Temp & Angle* sheet is used to depict the intrinsic relationship between temperature and operating frequency with a given angle of cut for the quartz crystal. Values on this worksheet were derived from the plots included further down on the sheet and from industry literature.

More detailed image. (PDF, 1.9MB)

Figure 3. The (a) Neg-R Curves worksheet and (b) the Temp & Angle worksheet.

NDK Crystals, *Crystek Crystals*, *HKC Crystals*, and *Raltron Crystals* Sheets

Crystal electrical characteristics are provided for various vendors on these sheets. A number of the values are used with the automated lookup feature on the main Calculator sheet. For the latest specs, please confirm using the vendor's data sheet.

Appendix: Example Calculation

This example will walk a user through the process of entering data into the Crystal Calculator workbook and will explore the results.

1. Open the Crystal Calculator workbook and enable macros if prompted.
2. Select the ***Calculator*** tab along the bottom of the Excel® workbook.
3. Select cell C4 (*Maxim LFRF Product*), click on the drop-down arrow next to the cell, and select *MAX1473* from the list. Note that the appropriate parameters are filled in based on the list selection.
4. Click on the *Copy to* f_0 *button* next to the 13.22560MHz value. This should place the value of 13.2256 into cell C23.
5. Enter the value of 0 in cell C13 (*Shunt Capacitors*).
6. Enter the value of 10000 in cell C14 (*Series Capacitors*).
7. Select cell F16 (*Crystal Manufacturer*), click on the drop-down arrow and select *NDK* from the list of manufacturers.
8. Select cell F17 (*Crystal Type*) and choose *Custom* from the drop-down list. This should fill in the crystal values in cells F18 to F22.
9. Click on the *Copy Crystal Data* button next to the new values. This should transfer the crystal information over to the cells outlined in red to the left.
10. Scroll down and observe that the negative resistance shows -514.3 in green. (If the values do not match, check that cell C12 has the value of 0.8 and cell C25 has the value of 4.)
11. Scroll down to the **Pulling Calculation** section and check that the actual carrier frequency shows 434.0522.
12. Scroll up and enter the value of 5 for the shunt capacitors. Observe that the negative resistance has dropped to -201.0 and the actual carrier frequency has changed to 433.9616.
13. Change the shunt capacitor value back to 0 and enter the value of 3.000 for the specified load capacitance (cell C19). Observe that the negative resistance is back up to -514.3 and that the actual Carrier frequency is 433.925.

Related Application Notes

Tutorial 726, "Specifying Quartz Crystals"
Application note 1017, "How to Choose a Quartz Crystal Oscillator for the MAX1470 Superheterodyne Receiver"

Related Parts		
MAX1470	315MHz Low-Power, +3V Superheterodyne Receiver	Free Samples
MAX1471	315MHz/434MHz Low-Power, 3V/5V ASK/FSK Superheterodyne Receiver	Free Samples
MAX1472	300MHz-to-450MHz Low-Power, Crystal-Based ASK Transmitter	Free Samples
MAX1473	315MHz/433MHz ASK Superheterodyne Receiver with Extended Dynamic Range	Free Samples
MAX1479	300MHz to 450MHz Low-Power, Crystal-Based +10dBm ASK/FSK Transmitter	Free Samples
MAX7030	Low-Cost, 315MHz and 433.92MHz ASK Transceiver with Fractional-N PLL	Free Samples
MAX7031	Low-Cost, 308MHz, 315MHz, and 433.92MHz FSK Transceiver with Fractional-N PLL	Free Samples

MAX7032	Low-Cost, Crystal-Based, Programmable, ASK/FSK Transceiver with Fractional-N PLL	Free Samples
MAX7033	315MHz/433MHz ASK Superheterodyne Receiver with AGC Lock	Free Samples
MAX7034	315MHz/434MHz ASK Superheterodyne Receiver	Free Samples
MAX7036	300MHz to 450MHz ASK Receiver with Internal IF Filter	Free Samples
MAX7042	308MHz/315MHz/418MHz/433.92MHz Low-Power, FSK Superheterodyne Receiver	Free Samples
MAX7044	300MHz to 450MHz High-Efficiency, Crystal-Based +13dBm ASK Transmitter	Free Samples
MAX7049	High-Performance, 288MHz to 945MHz ASK/FSK ISM Transmitter	Free Samples
MAX7057	300MHz to 450MHz Frequency-Programmable ASK/FSK Transmitter	Free Samples
MAX7058	315MHz/390MHz Dual-Frequency ASK Transmitter	Free Samples
MAX7060	280MHz to 450MHz Programmable ASK/FSK Transmitter	Free Samples

More Information
For Technical Support: http://www.maximintegrated.com/support
For Samples: http://www.maximintegrated.com/samples
Other Questions and Comments: http://www.maximintegrated.com/contact

Application Note 5422: http://www.maximintegrated.com/an5422
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