Application Report

SLAA225A–November 2004–Revised August 2018

MSP430™ LFXT1 Oscillator Accuracy

MSP430 Applications

ABSTRACT

This report describes the factors that influence achievable accuracy of the low-frequency oscillator, specifically for real-time clock (RTC) applications. The intent of this application report is to provide an understanding of factors specific to MSP430™ microcontrollers (MCUs) that influence real-world achievable RTC accuracy using the LFXT1 oscillator with a standard 32.768-kHz watch crystal and present measurement data supporting the achievable performance.

The source code that is described in this application report can be downloaded from www.ti.com/lit/zip/slaa225.

NOTE: For additional information about selecting the right crystal, the correct load circuit, and the proper board layout for the low-frequency oscillator, see MSP430 32-kHz Crystal Oscillators.

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1 LFXT1 Equivalent Circuitry

The frequency of oscillation for a standard watch crystal for use with an MSP430 MCU is 32.768 kHz. The actual frequency of oscillation in a complete system depends on many factors, of which the most influential is often the crystal itself. Additional parameters including load capacitance tolerances, trace and pin parasitic capacitance, and internal oscillator circuitry capacitance all play a role in the deviation of the actual frequency from the nominal value of 32.768 kHz. Figure 1 shows the equivalent circuit of the MSP430F4xx family low-frequency oscillator circuitry and the required external elements.

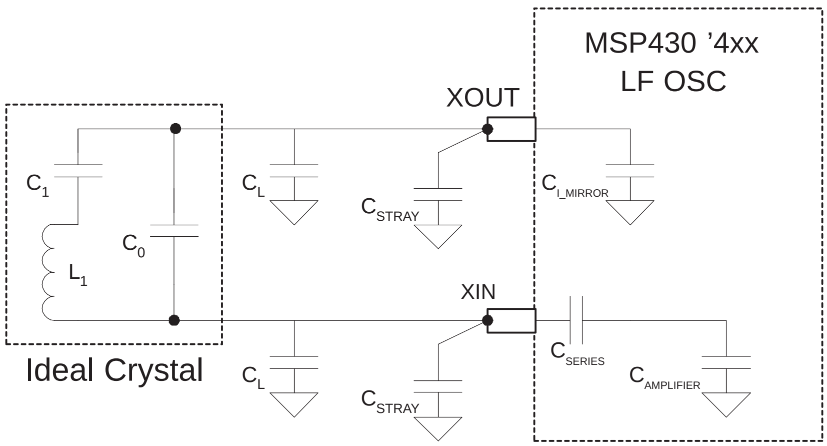

Figure 1. External Components and Internal LFXT1 OSC Equivalent Circuitry

The oscillator in this figure is the MSP430F4xx family LFXT1. For simplicity, this circuit represents only the factors that contribute to the crystal load and that affect oscillation frequency. This figure does not represent the actual LFXT1 oscillator circuitry. Figure 1 shows that the internal load capacitance is disabled and is provided external to the crystal. This is the recommended configuration when frequency accuracy is critical, because it allows for precision or even trimmed external load capacitances to be used. For information about the MSP430F1xx family LFXT1 oscillator, see Section 5.

Table 1 describes each component of the MSP430 LFXT1 circuitry in Figure 1. The typical value for each component is listed along with the tolerance as determined by design simulation.

Table 1. MSP430F4xx LFXT1 Equivalent Circuit Values and Tolerances

COMPONENT	DESCRIPTION	NOMINAL VALUE	TOLERANCE[1]
C_{STRAY} [2]	Internal parasitic capacitance including contributions from bond wires, bond pads, ESD circuitry, and the oscillator circuitry	3 pF	±10%
C_{I_MIRROR}	Current mirror input capacitance	100 fF	±10%
C_{SERIES}	Series capacitance used to reduce LFXT1 current consumption	1.5 pF	±10%
$C_{AMPLIFIER}$	Oscillation amplifier input gate capacitance	63 fF	±10%

(1) Tolerances are over temperature and process variation as determined through design-level simulation.
(2) This value also has an external contribution as shown in Figure 1. Parasitic capacitance from the PCB traces, signal interference and solder connection can all influence the final value of C_{STRAY}.

The corresponding mathematical relationships of the equations established by the circuit in Figure 1 can be used to determine the error contribution for each element to a total frequency tolerance. These equations consist of the fundamental expression for frequency of a resonant circuit:

$$f_0 = \frac{1}{2 \times \pi \times \sqrt{L \times C}} \qquad (1)$$

In addition, the parallel and series combinations of each capacitive element contributing to the total *C* term above must be evaluated. These relationships as shown in Figure 1 are:

$C_{XOUT} = C_{I\_MIRROR} + C_L$

$C_{XIN} = (C_{SERIES} \times C_{AMPLIFIER}) / (C_{SERIES} + C_{AMPLIFIER}) + C_{STRAY} + C_L$

$C_{COMBO1} = C_0 + (C_{XOUT} \times C_{XIN}) / (C_{XOUT} + C_{XIN})$

$C_{COMBO2} = (C_1 \times C_{COMBO1}) / (C_1 + C_{COMBO1})$

$f_{OSC} = 1 / \{2 \times \pi \times \sqrt{(L_1 \times C_{COMBO2})}\}$

Using these equations with the crystal parameters from a typical crystal data sheet, the effects of the different capacitive elements on the oscillation frequency can be determined. The parameters for the 6-pF and 12.5-pF versions of the Micro Crystal MS1V-T1K watch crystal were used for the calculations and testing in the following sections.

NOTE: The value for L_1 was determined based on the nominal frequency of the crystal and the specifications for C_0 and C_1. Equations for C_{XIN} and C_{XOUT} were simplified to include only the ideal C_L as required by the given crystal specification. Calculation of L_1 in such a way establishes a frequency baseline for the ideal crystal to which external load contributions can be compared. Actual measurement of L_1, C_0 and C_1 for a given crystal will vary and may not represent that of the *ideal* or nominal crystal.

2 Calculated Tolerances

Using the relationships and simulated results given in the previous section, a tolerance for the frequency of a 32.768-kHz watch crystal can be calculated. Keep in mind that external board-induced C_{STRAY} values in addition to crystal tolerances and crystal temperature shift also contribute to the achievable accuracy and are not included in the following calculations. Only the internal contribution of the MSP430 MCU to the term C_{STRAY} has been taken into account.

All crystal-specific parameters (L_1, C_0, C_1) along with the recommended load capacitances (C_L) are assumed ideal with 0% variation to isolate the tolerances that are specific to the MSP430 MCU.

Table 2 through Table 5 show the error contribution of the internal MSP430 circuitry to the oscillation frequency of each crystal (6 pF and 12.5 pF). Table 2 and Table 3 pertain to the 6-pF crystal. All values are given in base units (Farads, Henrys, and Hertz).

Table 2. Upper Tolerance Calculations for Internal Elements (6-pF Crystal)

Variables				Results		
	Nominal	Tolerance			Nominal	Tolerance
C_0	9.0E-13	0%	9.0E-13	C_{XOUT}	1.5100E-11	1.5410E-11
C_1	2.30E-15	0%	2.30E-15	C_{XIN}	1.5060E-11	1.5367E-11
L_1	1.0260E+04	0%	1.0260E+04	C_{COMBO1}	8.4401E-12	8.5941E-12
C_L	1.20E-11	0%	1.20E-11	C_{COMBO2}	2.2993734E-15	2.2993846E-15
C_{STRAY}	3E-12	10%	3.3E-12	f_{OSC}	3.2767379E+04	3.2767299E+04
C_{SERIES}	1.5E-12	10%	1.65E-12		**tolerance:**	**–2.44 ppm**
C_{I_MIRROR}	1.00E-13	10%	1.10E-13			
$C_{AMPLIFIER}$	6.3E-14	10%	6.93E-14			

Table 3. Lower Tolerance Calculations for Internal Elements (6-pF Crystal)

Variables				Results		
	Nominal	Tolerance			Nominal	Tolerance
C_0	9.0E-13	0%	9.0E-13	C_{XOUT}	1.5100E-11	1.4790E-11
C_1	2.30E-15	0%	2.30E-15	C_{XIN}	1.5060E-11	1.4754E-11
L_1	1.0260E+04	0%	1.0260E+04	C_{COMBO1}	8.4401E-12	8.2861E-12
C_L	1.20E-11	0%	1.20E-11	C_{COMBO2}	2.2993734E-15	2.2993618E-15
C_{STRAY}	3E-12	–10%	2.7E-12	f_{OSC}	3.2767379E+04	3.2767462E+04
C_{SERIES}	1.5E-12	–10%	1.35E-12		**tolerance:**	**–2.53 ppm**
C_{I_MIRROR}	1.00E-13	–10%	9.00E-14			
$C_{AMPLIFIER}$	6.3E-14	–10%	5.67E-14			

NOTE: Crystal manufacturers typically define the effective load capacitance in a crystal data sheet. Electrically, load capacitors are connected serially on pins XIN and XOUT. This corresponds to a crystal-specified effective load capacitance of 6 pF, having 12 pF at each terminal of the crystal.

The theoretical tolerance of the internal elements of the MSP430 MCU is approximately ±2.5 ppm based on simulated internal values. ±10% of the variation is due to worst-case temperature effects and process variation. Table 4 and Table 5 list similar calculations for a 12.5-pF crystal.

Table 4. Upper Tolerance Calculations for Internal Elements (12.5-pF Crystal)

Variables				Results		
	Nominal	Tolerance			Nominal	Tolerance
C_0	9.0E-13	0%	9.0E-13	C_{XOUT}	2.8100E-11	2.8410E-11
C_1	2.30E-15	0%	2.30E-15	C_{XIN}	2.8060E-11	2.8367E-11
L_1	1.0259E+04	0%	1.0259E+04	C_{COMBO1}	1.4940E-11	1.5094E-11
C_L	2.50E-11	0%	2.50E-11	C_{COMBO2}	2.2996460E-15	2.2996496E-15
C_{STRAY}	3E-12	10%	3.3E-12	f_{OSC}	3.2767034E+04	3.2767008E+04
C_{SERIES}	1.5E-12	10%	1.65E-12		**tolerance:**	**–0.79 ppm**
C_{I_MIRROR}	1.00E-13	10%	1.10E-13			
$C_{AMPLIFIER}$	6.3E-14	10%	6.93E-14			

Table 5. Lower Tolerance Calculations for Internal Elements (12.5-pF Crystal)

Variables				Results		
	Nominal	Tolerance			Nominal	Tolerance
C_0	9.0E-13	0%	9.0E-13	C_{XOUT}	2.8100E-11	2.7790E-11
C_1	2.30E-15	0%	2.30E-15	C_{XIN}	2.8060E-11	2.7754E-11
L_1	1.0259E+04	0%	1.0259E+04	C_{COMBO1}	1.4940E-11	1.4786E-11
C_L	2.50E-11	0%	2.50E-11	C_{COMBO2}	2.2996460E-15	2.2996423E-15
C_{STRAY}	3E-12	–10%	2.7E-12	f_{OSC}	3.2767034E+04	3.2767060E+04
C_{SERIES}	1.5E-12	–10%	1.35E-12		**tolerance:**	**0.80 ppm**
C_{I_MIRROR}	1.00E-13	–10%	9.00E-14			
$C_{AMPLIFIER}$	6.3E-14	–10%	5.67E-14			

For the 12.5-pF crystal, a maximum tolerance of approximately ±0.8 ppm is calculated. This error tolerance is noticeably smaller than that for a 6-pF crystal (see Table 2 and Table 3). This is due to the ratio of the load capacitance to the other elements in the system.

Based on the equations, the effects of C_L and C_{STRAY} dominate the total error when an ideal crystal is considered. Typical tolerances of crystals are far greater, but they are assumed ideal here to determine the contribution of the MSP430 MCU. As the proportion of C_L to C_{STRAY} increases, the effects of the varying C_{STRAY} become less of a factor. This relationship shows that using a crystal with a larger C_L requirement can help to reduce the effects of MSP430 internal tolerances as well as external board-dependent parasitics.

To help put this into perspective with regard to actual error in time, for a 32.768 kHz crystal, ±1ppm of error in frequency corresponds to:

32.768 kHz × 1 ppm x 1×10^{-6} = ±0.032768 Hz

This translates to approximately 1 µs/s or approximately ±0.086 s/day. During a 365-day duration, approximately 32 seconds of error accumulate for 1 ppm of error in the crystal frequency.

3 Experimental Results

To help further quantify the tolerances of the MSP430 MCU relative to crystal frequency, lab measurements were also performed. The purpose of the measurements was to establish a tolerance for the MSP430 MCU in a controlled environment. All measurement were taken at 25°C with V_{CC} = 3.0 V.

In the case of the 6-pF crystal, a 6-pF crystal and a socketed MSP430F437 were used. 50 MSP430 MCUs were tested with no external load capacitance, due to the large parasitic circuit board capacitance of the socket. Figure 2 shows the test results for the ACLK output frequency with respect to the ideal 32.768-kHz output. The actual load capacitance is not of importance, except that it is near enough to the ideal to allow stable crystal oscillation. The point of interest is the variation in frequency from device to device. Figure 2 shows the results across 50 MSP430F437IPN devices.

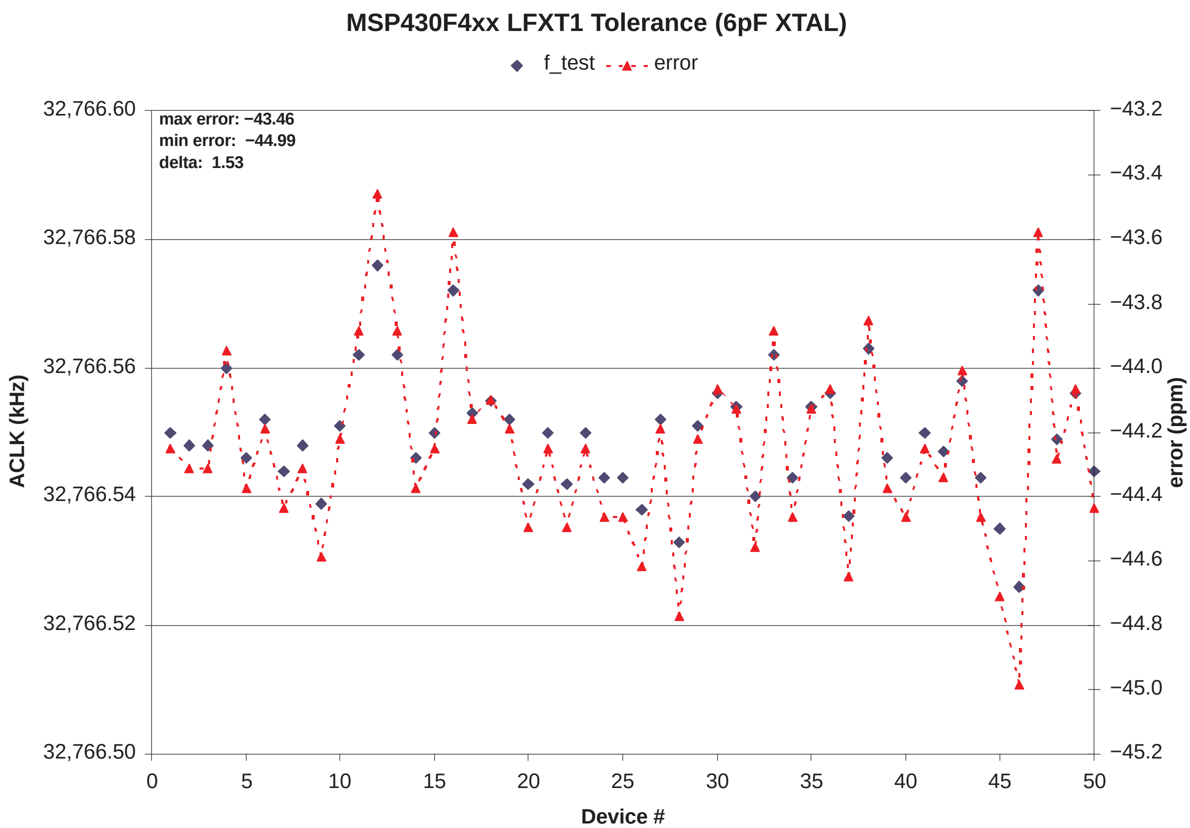

Figure 2. MSP430F437 Test Results With a 6-pF Crystal

From the results given in Figure 2, it can be determined that the crystal loading was slightly more than ideal for the given setup. This caused the crystal frequency to shift slightly below the nominal 32.768 kHz. However, as stated earlier, the variation is the point of interest, and it is well within a ±2.5-ppm theoretical range. A more accurate interpretation of the results comes from normalizing the error to the mean frequency determined in the tests. Figure 3 shows the same results normalized to the nominal frequency measured of 32766.55 Hz.

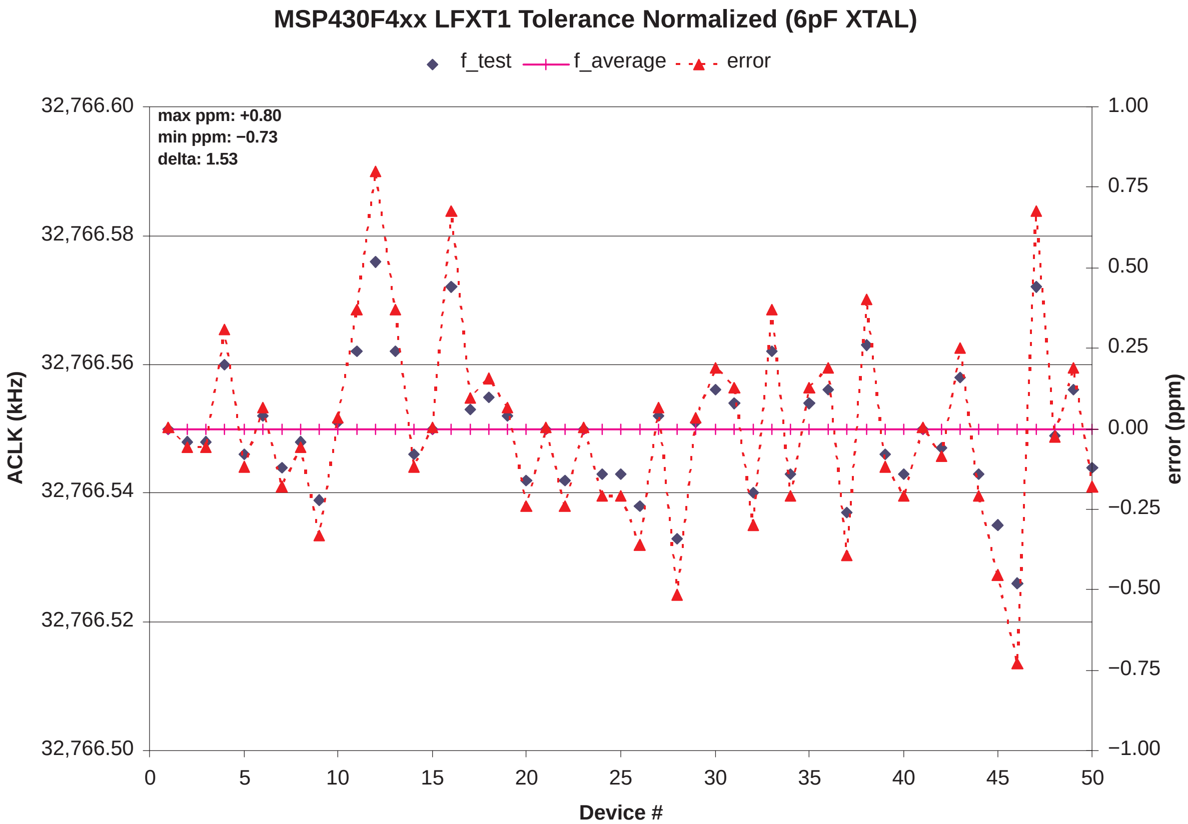

Figure 3. Normalized MSP430F437 Test Results With a 6-pF Crystal

The normalized results more clearly show the tolerance of the MSP430 MCUs from device to device. The result is less than ±0.8 ppm. The absolute error values in Figure 3 are not as important as the total distribution of the tolerance. Each individual ppm value is based on the statistical mean frequency, which may vary, however the distribution will remain consistent.

In addition, a 12.5-pF crystal was used as the source at T_A = 25°C and V_{CC} = 3.0 V. The board and socket remained the same as for the 6-pF tests. Additional external load capacitance was added (approximately 12.7 pF at each crystal terminal) to provide approximately the same ACLK frequency as in the 6 pF tests. Again, the internal load capacitors of the MSP430 MCU were configured for the lowest setting.

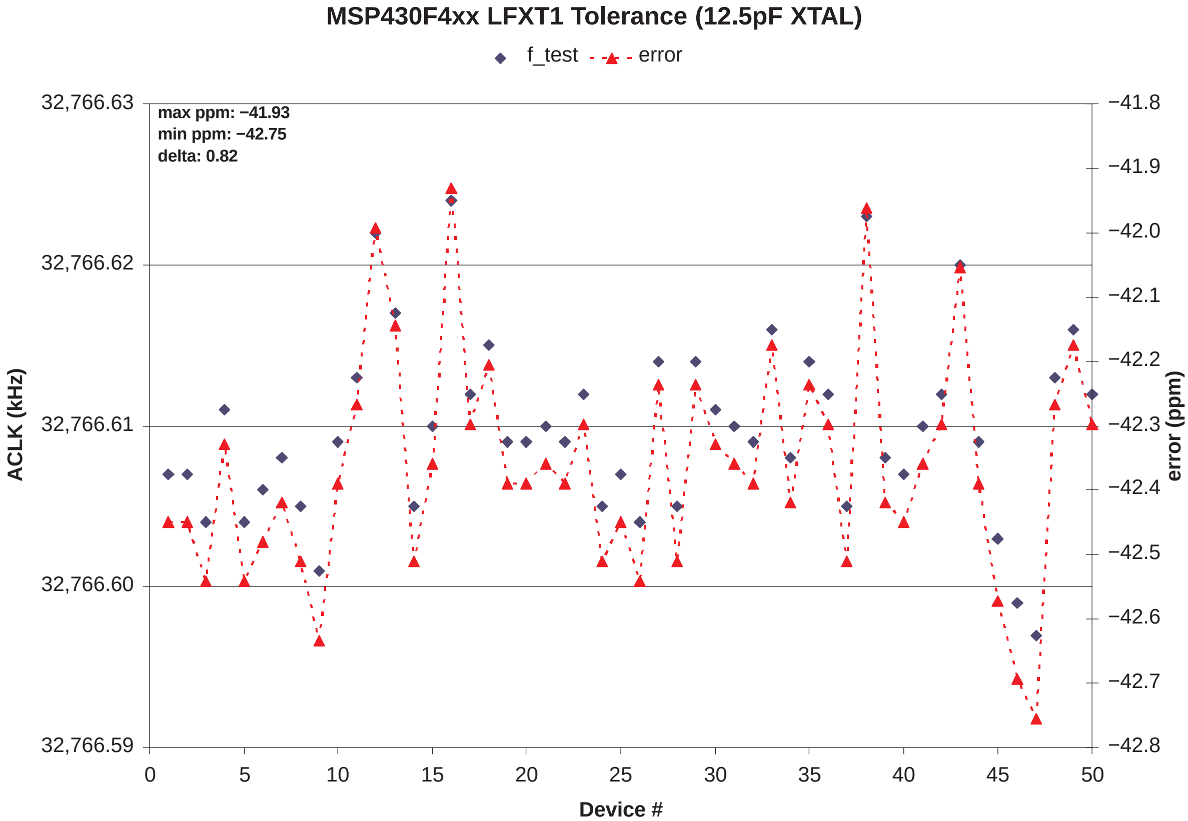

Figure 4. MSP430F437 Test Results With a 12.5-pF Crystal

From the results given in Figure 4, the crystal loading was again slightly more than ideal for the given configuration. As previously stated, the variation is the point of interest and is well within a ±0.8-ppm range. Figure 5 shows the normalized results, with a mean oscillation frequency of approximately 32768.024 Hz.

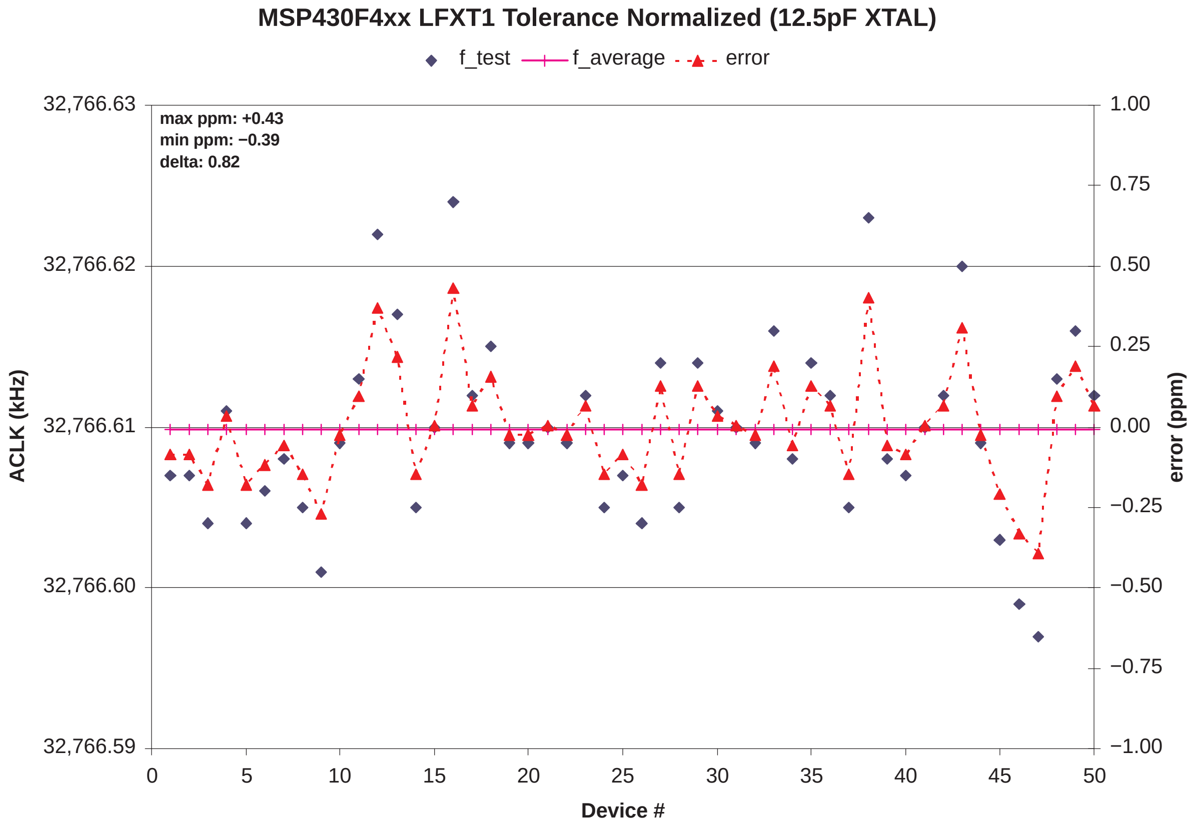

Figure 5. Normalized MSP430F437 Test Results With a 12.5-pF Crystal

The measured results correlate to the theoretical results calculated for the 12.5-pF crystal at less than ±0.5 ppm of error contributed by the device-to-device variation of the MSP430 MCU.

4 Oscillator Error Contribution

Previous sections describe how the effects of the MSP430 MCU are quite small when taking total error contributions into account as they relate to total oscillator frequency accuracy. The crystal-to-crystal tolerances and the error over temperature for a typical tuning-fork 32.768-kHz crystal dominate the total error contribution to the system. Figure 6 shows the crystal-specific error and the additive error from the MSP430 MCU as measured in the previous sections.

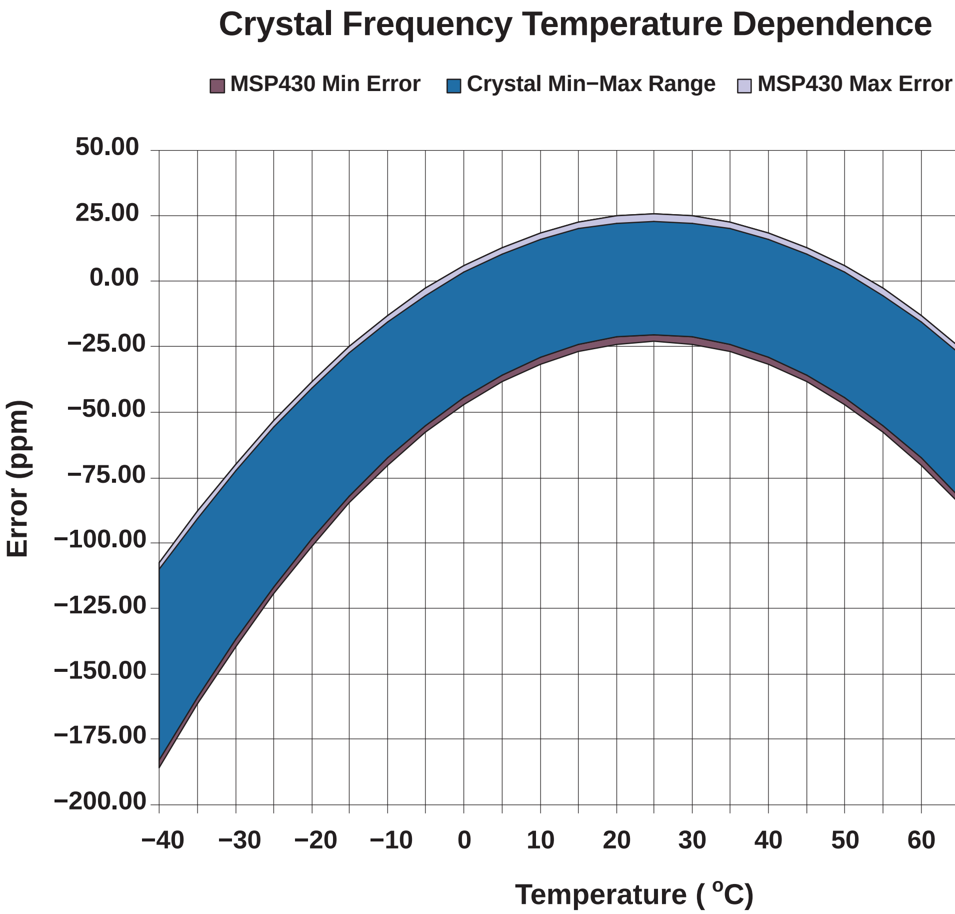

Figure 6. Combined Error for a Typical Crystal and the MSP430 MCU

The crystal error band in Figure 6 is made up of the key factors effecting crystal accuracy: crystal-to-crystal variation, aging effects, and temperature dependence for a typical 32.768-kHz crystal. Figure 6 shows that the crystal accuracy plays a far greater role in the total accuracy of the system compared to the relatively small effect of the MSP430 MCU.

5 MSP430F1xx Family Summary and Experimental Results

The MSP430F1xx low-frequency oscillator design differs slightly for the previously discussed MSP430F4xx LFXT1 oscillator. The most important difference is with regard to the built-in load capacitors for a 32.768-kHz watch crystal. The F1xx and F4xx MSP430 families both have built-in C_L, however this capacitance cannot be selected on the F1xx family devices. Figure 7 shows a high-level representation.

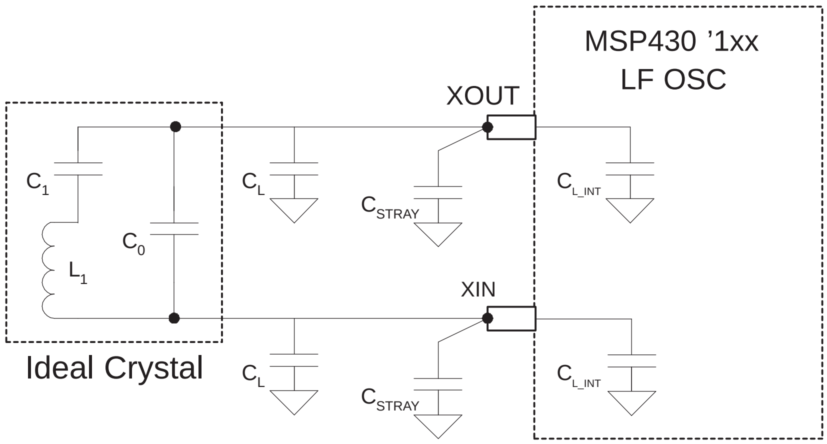

Figure 7. MSP430F1xx LFXT1 Architecture

The built-in load capacitance is denoted as C_{L_INT}. This capacitance is approximately 12 pF from device to device, which lets you use additional external capacitance to trim the total C_L at each leg of a 12.5-pF crystal. A theoretical analysis has not been repeated for the F1xx family; however, lab measurements were performed using a 12.5-pF MS1V-T1K crystal. Figure 5 shows the frequency variance from device to device for the MSP430F135. No additional external capacitances beyond the stray elements of the test socket for the MCU were added to the loading of the crystal.

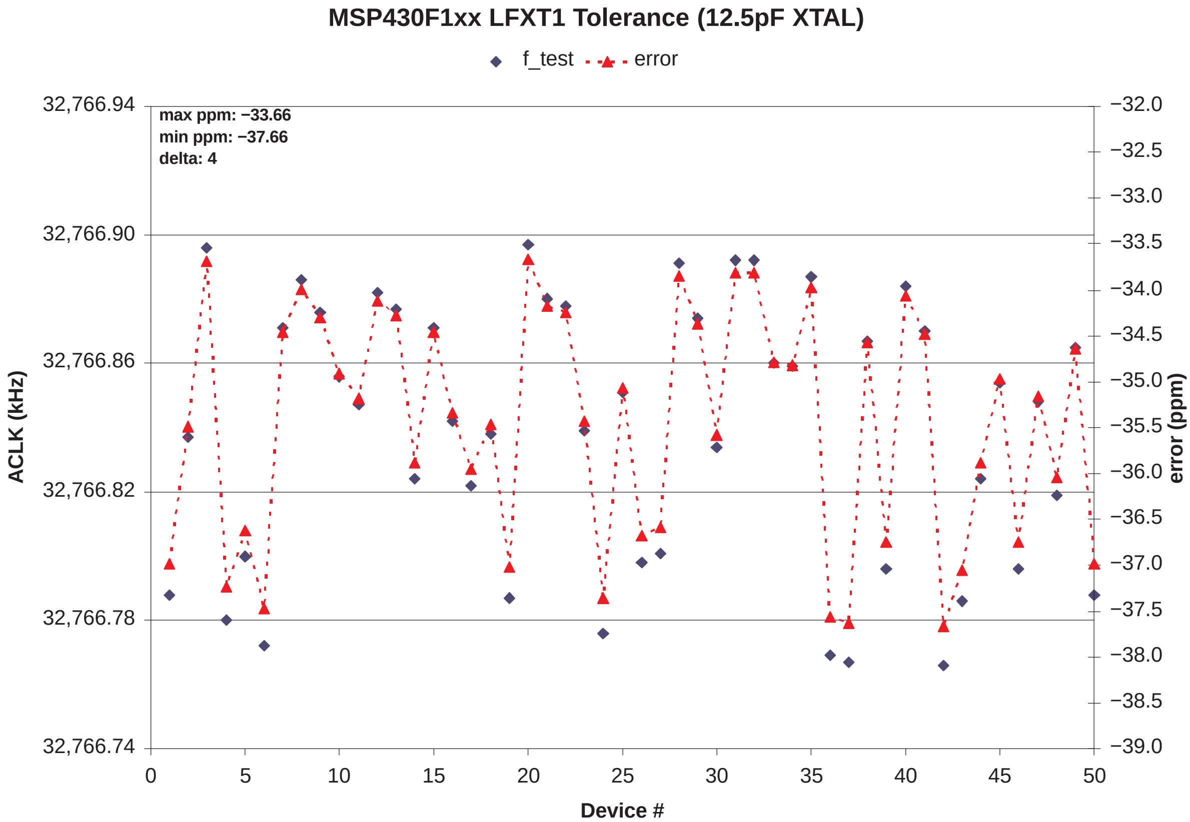

Figure 8. MSP430F135 Test Results With a 12.5-pF Crystal

As shown in the figure, the oscillation frequency is slightly slower than nominal due to a higher stray capacitance of the test socket and traces. As with the F4xx results, the actual oscillation frequency is of less interest than the variation from device to device. Figure 6 shows the normalized results.

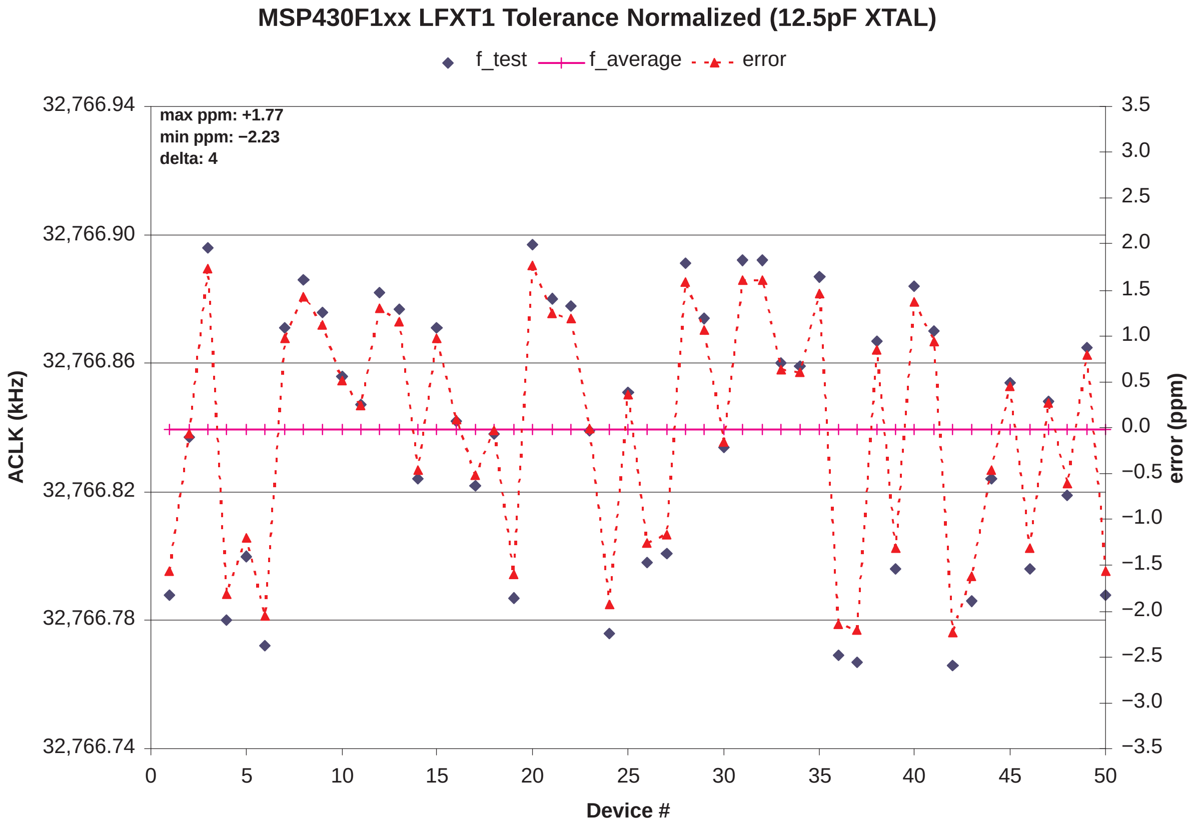

Figure 9. Normalized MSP430F135 Test Results With a 12.5-pF Crystal

Final results for all 50 devices fall within a ±2.5-ppm span, with a maximum measured delta of approximately 4 ppm. This is a larger variation across the test samples versus the 12.5-pF MSP430F4xx test results but still remains very small in comparison to the variation due to the crystal itself. The greater variation due to the MSP430F1xx is directly attributable to the larger internal C_L contribution of the built-in F1xx load capacitors for the oscillator. This built-in capacitance reduces the ration of external load to internal load causing the slight variation from device-to-device to play a more significant role in the total C_L as seen by the crystal.

6 Conclusion

This application report has presented the simulation-based theoretical error contributions and supporting lab measurement data to quantify the effect of the LFXT1 oscillator on the tolerances of an ideal 32.768-kHz watch crystal. In the wider scope of a typical system, additional contributions to frequency tolerance include external noise influences, design and layout parasitic effects, and crystal-to-crystal variation. While the internal circuitry of the MSP430 MCU does have an effect on the total tolerance of the final crystal frequency, much larger contributing factors are system stray capacitance, load capacitance tolerances, and the component and temperature tolerances of the crystal itself.

By understanding the contributions to the total error for a watch crystal in a RTC application, the designer can take measure during application development and testing to compensate for those errors. RTC timing errors, once understood and identified, can be corrected in hardware and or software enabling characterization-based tuning or even system-by-system calibration during production.

7 References

1. Micro Crystal MS1V-T1K 32.768 kHz Tuning Fork Crystal data sheet, Ver 2.2, 10-2003
2. MSP430x4xx Family User's Guide
3. MSP430x43x, MSP430x43x1, MSP430x44x Mixed-Signal Microcontrollers data sheet
4. MSP430F13x, MSP430F14x, MSP430F14x1 Mixed-Signal Microcontrollers data sheet

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from November 8, 2004 to August 3, 2018	Page
• Editorial changes throughout document	1

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