Application Report
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MSP430 LFXT1 Oscillator Accuracy

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ABSTRACT

This report details 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 MSP430-specific factors influencing 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.

1 LFXT1 Equivalent Circuitry

The frequency of oscillation for a standard watch crystal for use with the MSP430 is 32.768 kHz. The actual frequency of oscillation in-system is dependent on many factors, of which often the most influential is 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 vs. the nominal value of 32.768 kHz. Figure 1 represents the equivalent circuit of the MSP4304xx family low frequency oscillator circuitry including the external elements.

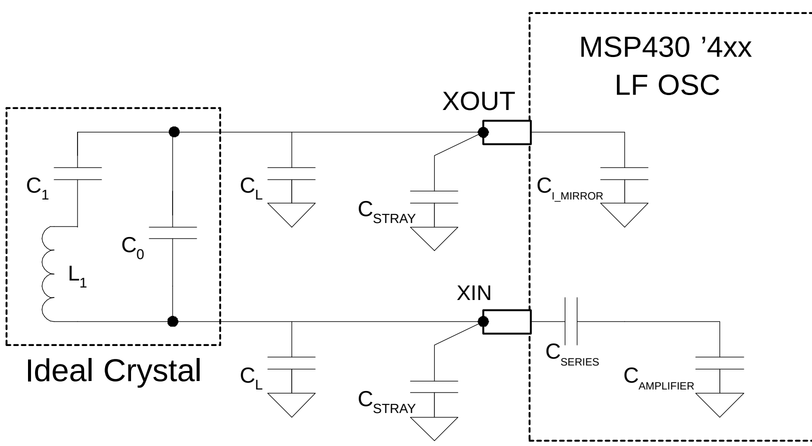

Figure 1. External Components and Internal LFXT1 OSC Equivalent Circuitry

The oscillator presented here is the MSP430F4xx family LFXT1. For simplicity, this circuit only represents the contributing factors to the loading of the crystal affecting oscillation frequency and is not intended to represent the actual LFXT1 oscillator circuitry. As shown in Figure 1, the internal load capacitance has been disabled and is assumed to be provided externally to the crystal. This is the recommended configuration when frequency accuracy is critical allowing for precision or even trimmed external load capacitances to be used. For information pertaining to the MSP430F1xx family LFXT1 oscillator refer to Appendix A.

A detailed description of each component of the MSP430 LFXT1 circuitry in Figure 1 is shown in Table 1. In addition, the typical values for each are listed along with the tolerances 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 circuitryd	3 pF	±10%
C_{I_MIRROR}	Current mirror input capacitance	100 fF	±10%
C_{SERIES}	Series capacitance used to reduce LFXT1 current consumptiond	1.5 pF	±10%
$C_{AMPLIFIER}$	Oscillation amplifier input gate capacitance	63 fF	±10%

(1) Tolerances given 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:

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

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 the equations above along with the crystal parameters from a typical crystal datasheet, 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 Microcrystal 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 boardinduced 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 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 in order to isolate the MSP430-specific tolerances.

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 tolerances of the MSP430 internal elements is approximately ±2.5 ppm based on simulated internal values where the ±10% variation is due to worst-case temperature effects and process variation. Similar calculations for a 12.5 pF crystal are given in Table 4 and Table 5.

Table 4. Upper Tolerance Calculations Using a 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

Table 4. Upper Tolerance Calculations Using a 12.5 pF Crystal (continued)

Variables				Results		
	Nominal	Tolerance			Nominal	Tolerance
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 Using a 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 as shown in 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 a varying C_L and C_{STRAY} dominate the total error when an ideal crystal is considered. In reality, tolerances of the crystal are far greater but are assumed ideal here to determine the contribution of the MSP430. 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 × 1ppm x 1×10^{-6} = ±0.032768 Hz. This translates into ~1 µsec/sec or ~ ±0.086 sec/day. Going a few steps further, over a 365 day duration, approximately 32 seconds of error will be accumulated for 1ppm of error in crystal frequency.

3 Experimental Results

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

In the case of the 6 pF crystal, a setup consisting of a 6 pF crystal and a socketed MSP430F437 was used. Fifty MSP430 devices were tested with no external load capacitance due to the large parasitic circuit board capacitance of the socketed setup. Figure 2 represents the test results for the ACLK output frequency with respect to the ideal 32.768 kHz output. It should be noted that the actual load capacitance provided is not of importance here except that it is near enough to the ideal to provide for a stable crystal oscillation. The point of interest is rather the variation in frequency from device to device. The results across 50 MSP430F437IPN devices are shown in Figure 2.

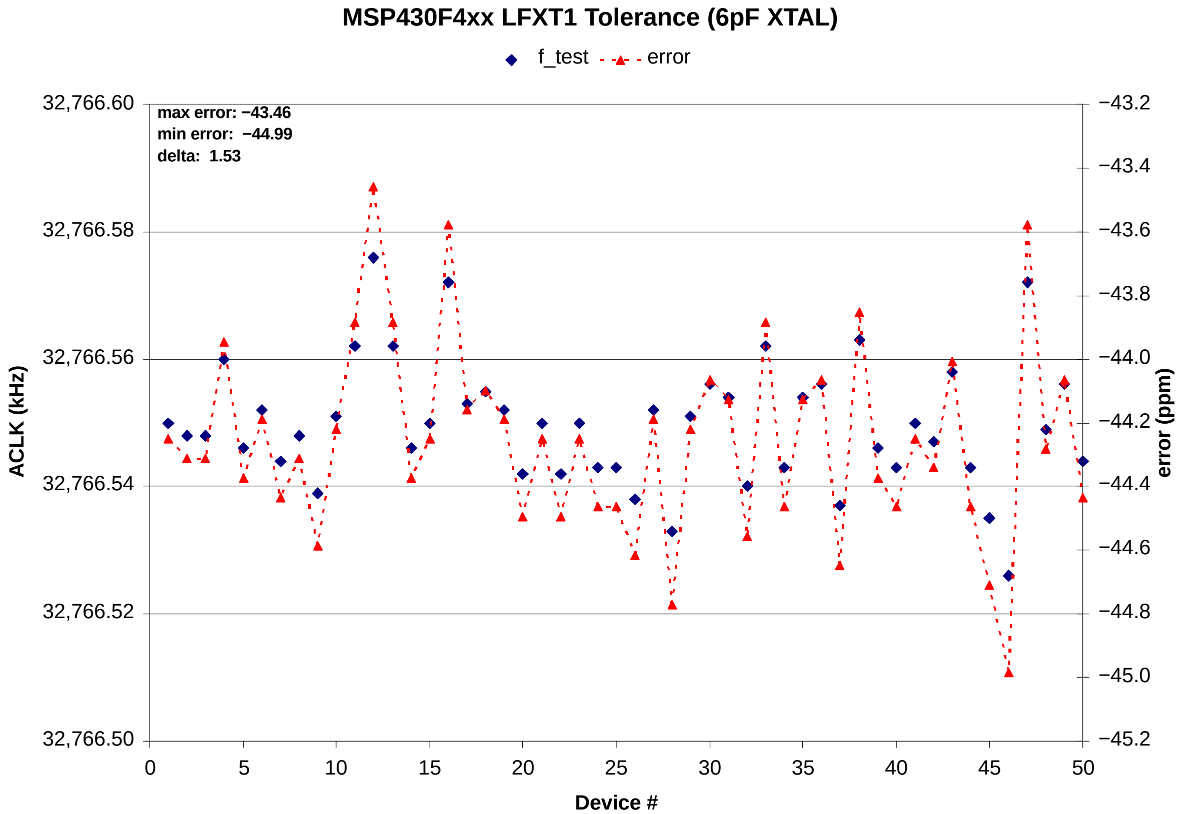

Figure 2. MSP430F437 Test Results With a 6 pF Crystal

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 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 around the nominal frequency measured of ~32766.55 Hz.

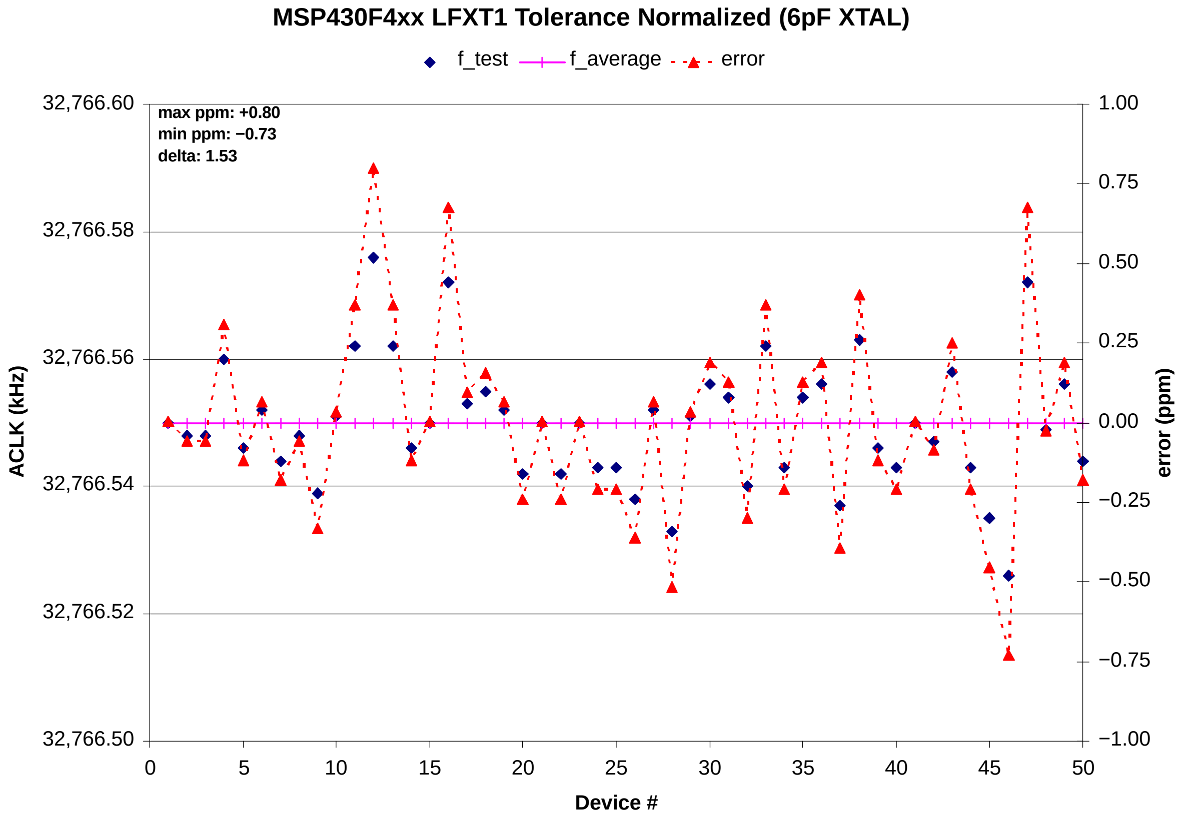

Figure 3. Normalized MSP430F437 Test Results With a 6 pF Crystal

The normalized results more clearly show the tolerance of the MSP430 from device to device. The result is less than ±0.8 ppm. The absolute error values shown 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 again with the entire setup kept at 25°C, V_{CC} = 3.0 V. The board and socket remained the same as for the 6 pF tests, however, additional external load capacitance was added (~12.7 pF at each crystal terminal) in order to provide approximately the same ACLK frequency achieved in the 6 pF tests. Again, the internal MSP430 load capacitors are configured for the lowest setting.

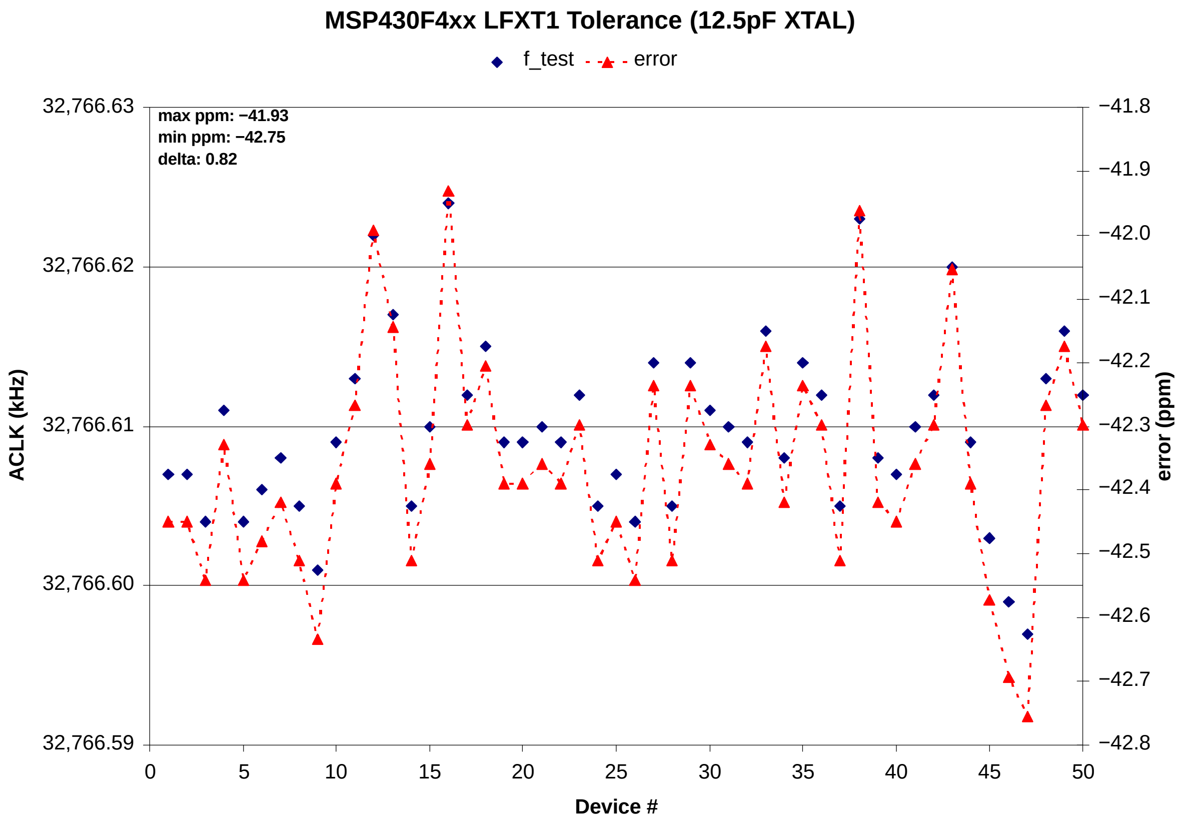

Figure 4. MSP430F437 test results with a 12.5pF crystals

From the results given in Figure 4, it can be determined that the crystal loading was again slightly more than ideal for the given setup. As stated earlier, the variation is the point of interest and is well within a ±0.8ppm range. The normalized results are shown in Figure 5 with a mean oscillation frequency of ~32768.024 Hz.

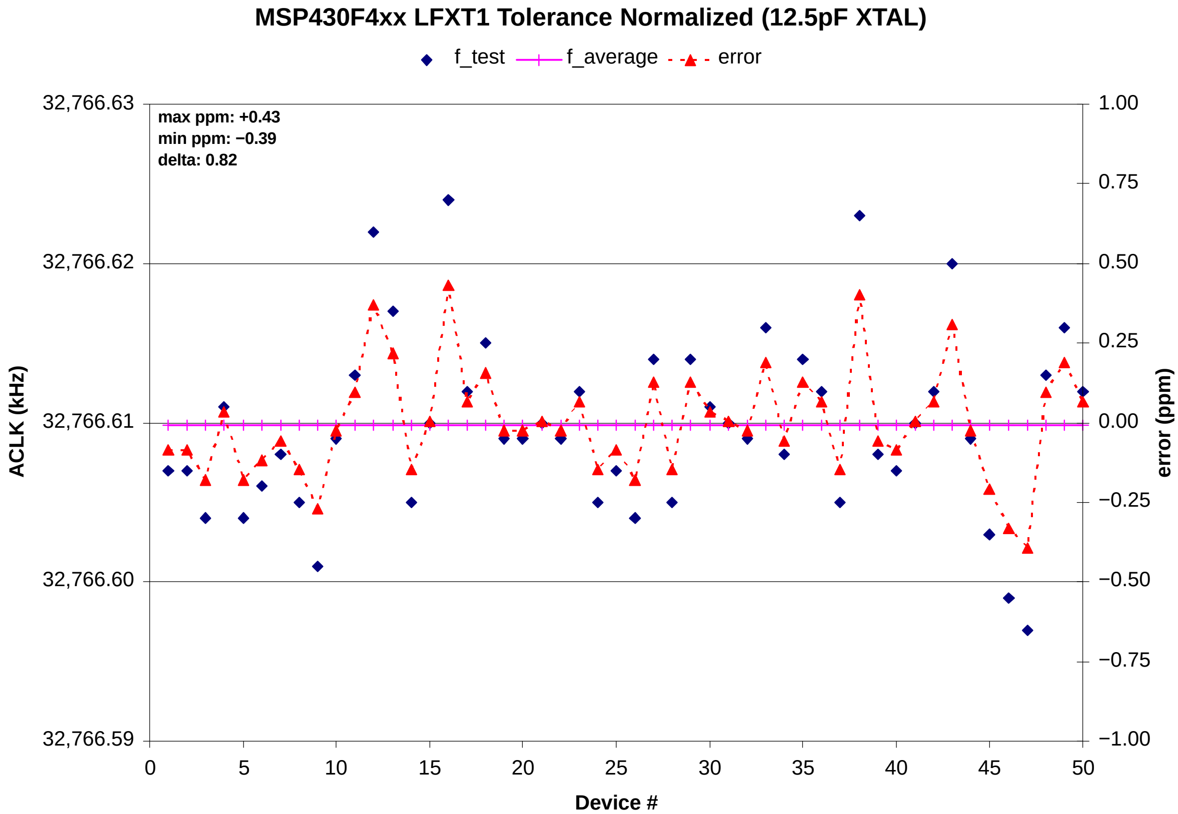

Figure 5. Normalized MSP430F437 Test ResultsWith a 12.5 pF Crystal

Again, 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.

4 Oscillator Error Contributiono

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

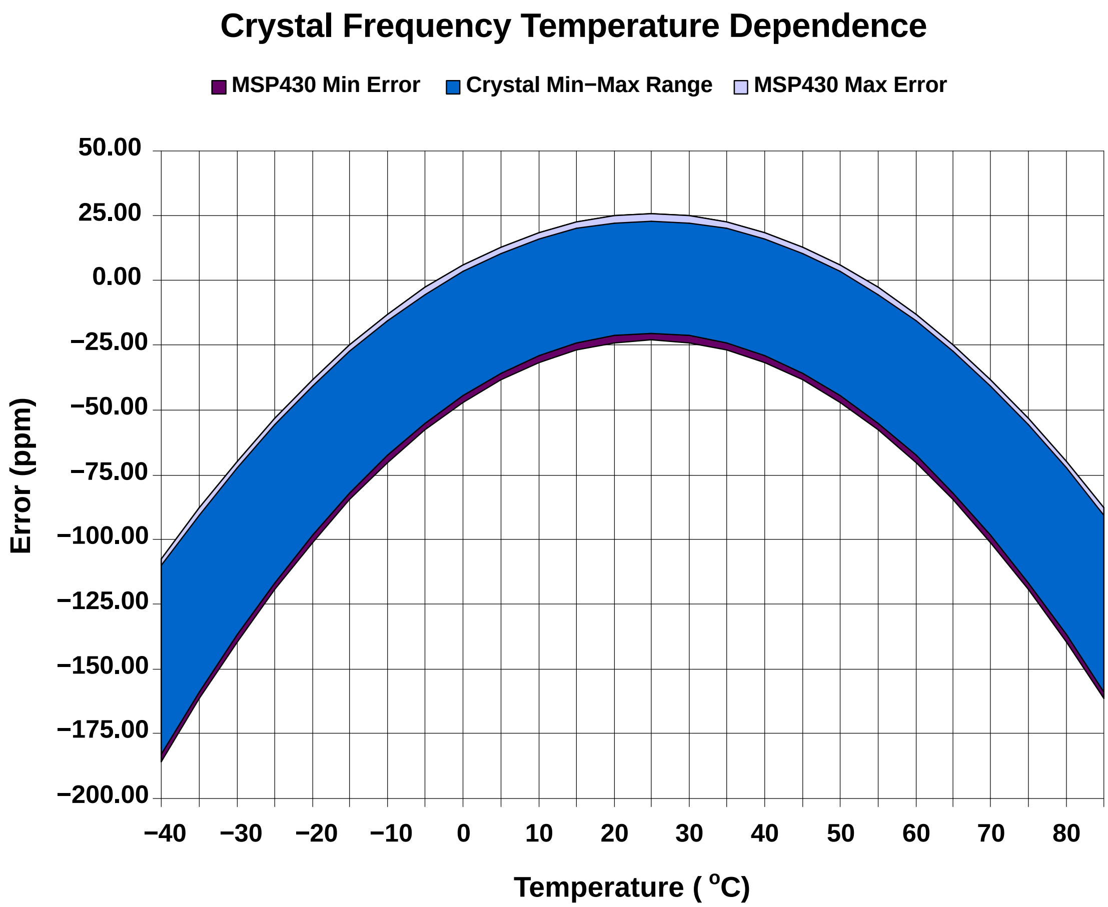

Figure 6. Combined Error for a Typical Crystal and the MSP430c

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. As can be easily seen from the figure, crystal accuracy plays a far greater role in the total accuracy of the system as compared to the relatively small impact of the MSP430.

5 Conclusion

The information presented has shown the simulation-based theoretical error contributions and supporting lab measurement data in an effort to quantify the impact of the MSP430 LFXT1 oscillator on the tolerances of an ideal 32.768 kHz watch crystal. In the wider scope of a realworld 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 does have an impact on the total tolerance of the final crystal frequency, much larger contributing factors are system stray capacitance, load capacitance tolerances and finally, the component and temperature tolerances of the crystal itself.

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

6 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, SLAU056
3. MSP430F437 Device Data sheet, SLAS344

4. MSP430F135 Device Data sheet, SLAS272

Appendix A 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 '1xx and '4xx MSP430 families both have built-in C_L, however this capacitance cannot be selected onboard the '1xx family devices. A high level representation is shown in Figure A-1.

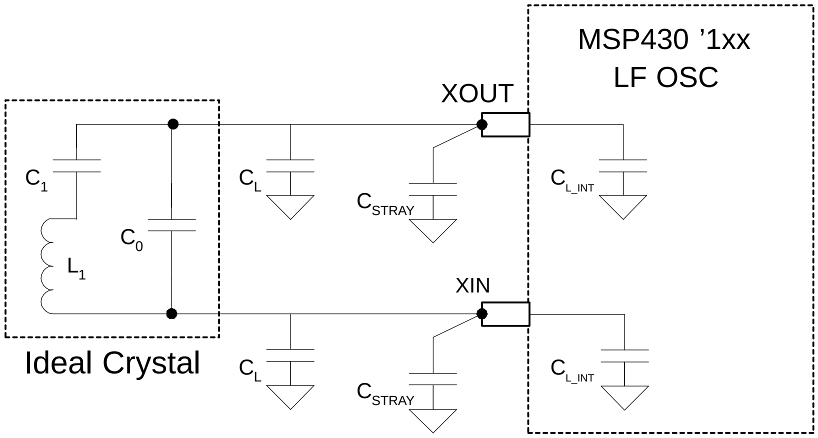

Figure A-1. MSP4301xx LFXT1 Architecture

The built-in load capacitance is denoted as C_{L_INT}. This capacitance is ~12 pF from device to device allowing for additional external capacitance to be used to trim the total C_L seen by each leg of a 12.5 pF crystal. A theoretical analysis has not been repeated for the '1xx 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 MSP430 test socket were added to the loading of the crystal.

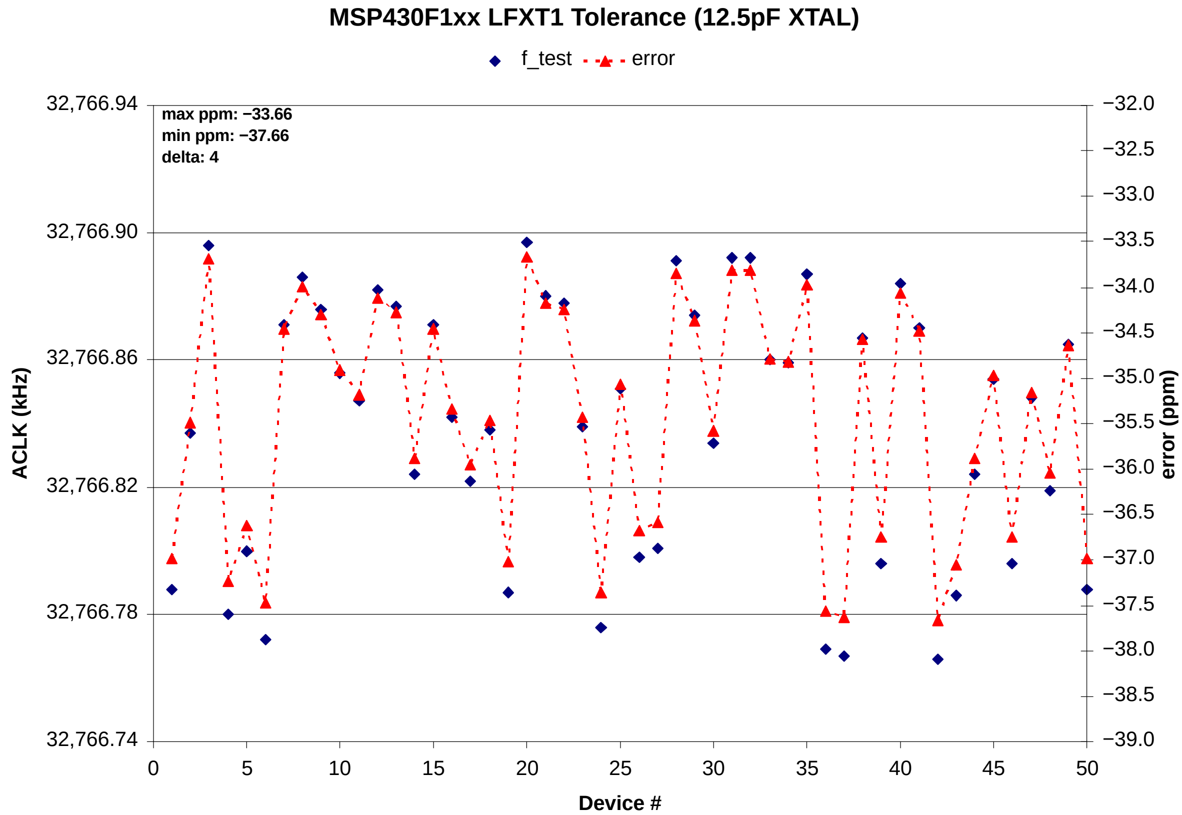

Figure A-2. MSP430F135 Test Results With a 12.5 pF Crystals

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 '4xx results, the actual oscillation frequency is of less interest than the variation from device-to-device. The normalized results are shown in Figure 6.

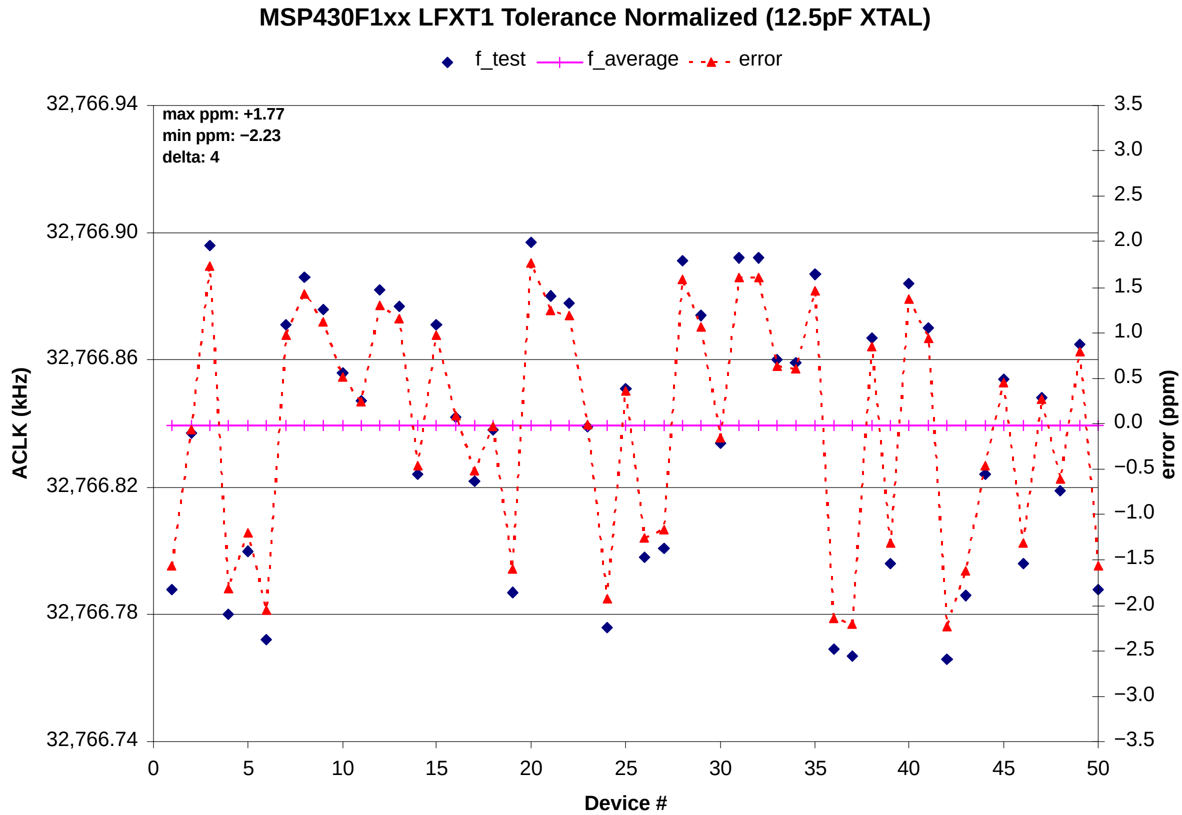

Figure A-3. Normalized MSP430F135 Test Results With a 12.5 pF Crystal

Final results for all 50 devices comfortably 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 MSP4304xx 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 '1xx 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.

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