AN-1058
Application Note

Using CBC348xx EnerChip RTC in High Accuracy Applications

Introduction

This application note addresses issues relating to overall timing accuracy of the final design of systems utilizing the Cymbet CBC34803 and CBC34813 (collectively known as CBC348xx) Self-Powered Real-Time Clock (RTC) devices. This ap note also includes tips on crystal selection.

Typical Crystal Parameters of Interest

Typical tuning fork crystals are specified in terms of:

- Load Capacitance (pF)
- Frequency Tolerance /Initial Frequency Error (parts per million = ppm)
- Series Resistance(Ω)
- First-Year Aging (ppm)
- Frequency vs. Temperature (ppm)
- Turnover Temperature, which is usually around 25 °C

In addition to these parameters, there are parasitic capacitances and inductances in the circuit board layout and assembly that need to be considered. With the exception of aging, the CBC348xx has the ability to calibrate out or compensate for all of these parameters. The lesser exceptions of Load Capacitance and Series Resistance are relatively easy to specify in the specific crystal chosen. Crystals with frequency tolerances of ±20ppm or so can easily be used, because they can be calibrated to 0ppm at initial test.

How the CBC348xx Parts Compensate for Crystal Parameters

The CBC348xx includes offset registers to allow temperature compensation for thermal drift of the crystal. The part can calibrate out all initial frequency variations at assembly test time by measuring an output clock and loading several registers in the part based on simple calculations derived from the measured time. The register values should be kept in non-volatile memory somewhere in the system to reload these calibration registers whenever system power is recovered after a shutdown. The only parameters that are not controlled are the crystal aging parameter and the crystal temperature variation, but these can be controlled at the system level if necessary. The aging parameter is typically ±2ppm to ±4ppm for the first year. Most aging occurs in the first few months of operation. See the section on temperature compensation for information on crystal temperature variations.

Factors Affecting Overall System Accuracy

The final accuracy of a timing system using a CBC348xx involves: the CBC348xx itself, the thermal use-case of the system, the crystal, and the parasitic loads that result with a printed circuit board implementation. Issues to be considered are:

1. Temperature compensation of the crystal.
2. Thermal use-case of the system.
3. Trimming the initial frequency of the mounted crystal.
4. Aging of the crystal.
5. The following selectable operating modes of the RTC offer a trade-off of power for overall accuracy:
    a. Crystal (XT) mode.
    b. RC Autocalibrate mode.
    c. RC only mode.

Temperature Compensation

Tuning fork crystals typically exhibit a temperature versus parts per million (ppm) frequency characteristic that is centered on 25°C. Figure 1 below shows a typical characteristic.

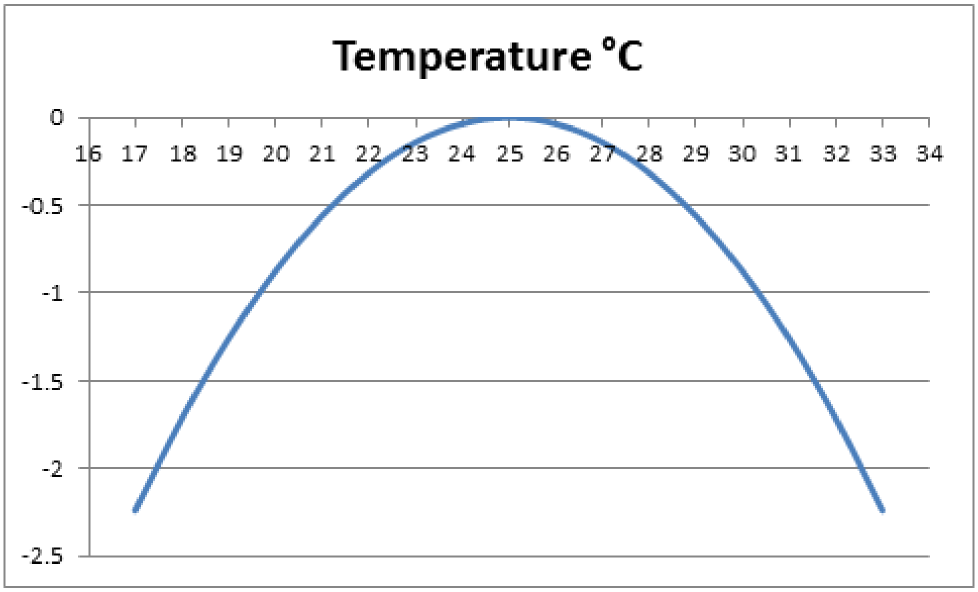

Figure 1: Parts per Million Frequency Error vs. Temperature.

The most common frequency versus temperature coefficient is -0.035 ppm, but that operates on the square of the temperature delta from 25°C (thus the parabola). Notice that if the temperature is either above or below 25°C the crystal will slow down. It will never speed up. Also notice that if the temperature is always near 25°C, say 25°C ± 6.5°C, there is only a -1.5ppm error which is quite minor. 1.5ppm equates to about 47 seconds per year. The next three sections present techniques for compensating for this parabolic curve at the system level. The techniques are: a static compensation based on use-case information, an active compensation using the host microcontroller, and an adaptive compensation using the host microcontroller that requires less energy.

Use-Case Compensation

This technique requires estimation of the average temperature the system will be exposed to and compensation at final test time for the difference between the estimated average temperature and 25°C. There is no active temperature compensation in this technique after the system is initially calibrated. Because the crystal temperature profile shown in Figure 1 is a parabola that plots ppm errors versus temperature, the crystal will slow down if the temperature is either above or below 25°C. This means that the oscillator needs to be sped up at assembly time by calibrating the oscillator to a faster clock. To determine the speed of this reference clock, sum the products of the hours per year the system is expected to be at a given temperature times the ppm error associated with each temperature and divide the sum by the total hours in a year. This weighted average ppm figure will be how much to speed up the clock used for calibrating the system at test time.

Periodic Temperature Compensation Using the System Microcontroller

This technique involves using the alarm function of the CBC348xx RTC to wake the system microcontroller at preset intervals. The microcontroller then reads the temperature from its own sensor and compensates the CBC348xx RTC as follows:

Initially record (in the microcontroller's nonvolatile memory) the assembly-time calibration parameters of the system. This is used as a starting point for temperature calibration adjustments. Let's call this value OscCalOrig and it is a combination of the CMDX and OFFSETX fields of the Calibration Register. OscCalOrig is in ppm.

At periodic intervals wake the system microcontroller and measure the system temperature using the microcontroller's internal temp sensor. Calculate a running average of the temperature but don't adjust the RTC yet.

After several hours of temperature averaging, look up the ppm error associated with the average temperature in a table containing the crystal temperature parabola shown in Figure 1 and start a running average of ppm errors. Keep enough significant bits to avoid loss of accuracy – the ppm numbers are usually small. Reset the running average temperature to the current temperature so it will calculate a new average temperature in the next interval.

About twice per day look up the running average of ppm errors and set the OFFSETX and CMDX fields to the sum of the original OscCalOrig plus the signed running average of ppm Errors calculated above. This procedure will continuously converge on the actual ppm temperature error contribution your system is actually seeing in its environment.

Temperature Calibrate and Confirm

If the periodic technique discussed above requires too much power from the overall system, this technique can be used to reduce power. The technique starts much like the Periodic Compensation above whenever the clock is manually reset. It requires the system microcontroller to periodically wake up, measure the temperature, and compensate as above but it also records the average temperature in nonvolatile memory for each time period. A suggested time period is one hour which requires 24 locations to record temperature. After several days of this operation the time period is changed to a pseudo-random time period with a 24 hour mean period where the microcontroller wakes up, measures the temperature, compares it to the stored average temperature for that time period, and goes back to sleep for another pseudo-random period if the temperature is within a few degrees of the stored value. If the temperature is outside of a few degrees from the stored value the system reverts to the initial periodic technique where it generates a new temperature profile for pseudo-random comparison. This technique can reduce the number of times the host microcontroller must wake up but it assumes the temperature profile is fairly consistent from day to day.

Thermal Use Case of Final System

Different inaccuracies are present in each of the three modes of EnerChip RTC timing operation. For example, the crystal oscillator is much more accurate over temperature than is the RC oscillator by itself however more power is required. The Autocalibration RC Oscillator mode is a hybrid that provides the best combination of crystal accuracy and low power but adds some inaccuracies that may or may not affect the final system operation depending on the thermal use case. The system will be subjected to different temperature extremes for different periods of time and the amount of time the final product spends at each temperature extreme contributes a different amount of drift. It would be incorrect to rate the system's overall accuracy at the accuracy associated with the worst temperature extreme if most of the time the product sits at 25°C, where the drift is very low.

The crystal oscillator is capable of around 2-3 ppm accuracy after initial calibration to compensate for initial crystal frequency and parasitic capacitances and thermal compensation for the crystal. A procedure for calibrating the initial frequency including parasitic is given later in this paper. If the system experienced an additional 20ppm error from temperature variation for only one day per year and operated very near 25°C for the rest of the time it would be wrong to specify the accuracy at 20ppm. The real accuracy would be much closer to the 2-3ppm it was initially calibrated to.

Initial Frequency Trimming

The CBC348xx devices contain registers to compensate for the initial frequency inaccuracy and parasitic loads of the final circuit board layout and build. These registers can be loaded at run time from the product's microcomputer and the values are easily determined in approximately one second or less at test time. Trimming the initial frequency must be done with a well-calibrated timing source to assure the best operation. The algorithm for trimming will be discussed later in this paper.

Crystal Aging

All crystals age over time. The bulk of the aging happens in the first few months of operation. Aging can be caused by matter falling off the crystal or matter falling onto the crystal. Crystal manufacturers specify aging in ppm for the first year and the numbers typically vary from ±2ppm to± 4ppm. Because the CBC348xx has no way of knowing how the crystal will age it is up to the application software to compensate for this. One could determine the difference in time when the time is re-set and calculate the amount to modify the calibration registers. Remember that aging mostly happens in the first few months of operation and so is a diminishing factor in the overall system accuracy over time.

Modes of RTC Timing Operation

The CBC348xx can operate in one of three distinct modes of timing:

- RC mode
- Crystal (XT) mode
- RC Autocalibration mode (combination of RC mode and XT mode)

Each mode has benefits and liabilities. RC mode exhibits the lowest power (35nA) but has the most jitter and inaccuracy. Crystal (XT) mode is the most accurate but requires the most power (76nA) – although this is very low power consumption for a crystal oscillator that is accurate to less than 3ppm. The RC Autocalibration mode gives the best accuracy for the power used (43nA). This mode uses the crystal to run for short periods of time to re-calibrate the RC oscillator for drift and in doing so achieves close to crystal accuracy with RC-like power. The RC oscillator is specified in the datasheet for its accuracy. The Crystal (XT) oscillator accuracy itself can be initially calibrated and thermally compensated to provide 2-3ppm accuracy. The RC Autocalibration mode accuracy is a function of both the RC oscillator, because that is the main clock, and the Crystal (XT) oscillator, because that is the reference the RC oscillator is updated to periodically. These updates occur automatically and require no intervention from the system microprocessor. Figure 2 shows the error contribution from the RC Autocalibration mode. The overall system accuracy is a function of the percentage of time the system is in each of the temperature bands. Short periods of high or low temperature don't have time to contribute much error. The Figure 2 accuracy is in addition to the base crystal oscillator accuracy.

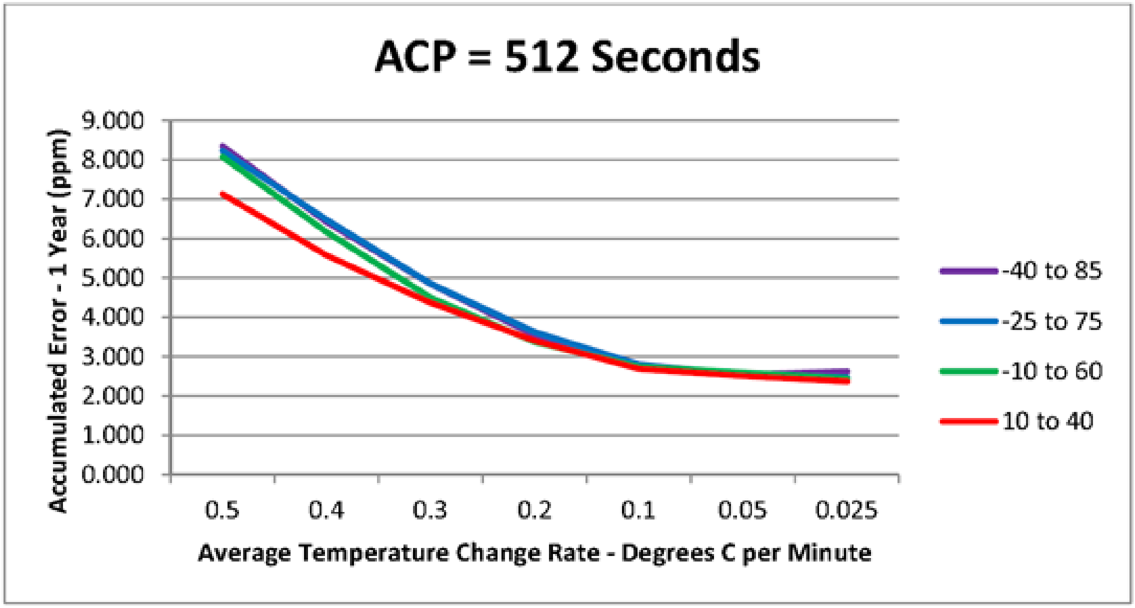

Figure 2: Autocalibration Error Contribution for RC Autocalibration Mode with Autocalibration Period of 512 Seconds.

The Figure 2 chart shows is that the error incurred by the RC Autocalibrate mode is not much of a function of temperature band, but more a function of the rate of temperature change if the rate is higher than 0.1 degrees C per minute (6 degrees per hour). If the system is in an indoor environment near 25°C for most of the year, it is evident that the inaccuracy from the RC Autocalibrate mode in addition to the Crystal (XT) inaccuracy is around 2.5ppm, which when added to the Crystal (XT) inaccuracy of around 2.5ppm would yield a total inaccuracy of 5ppm on a one year basis. The key issues to take away from the Figure 2 chart is a blend of how much time the product stays at a low average temperature change rate and how much time it is at a higher average temperature change rate. A short time in a high temperature change rate band will not contribute much error over an entire year.

In applications where high rates of temperature change rates are expected, the system could be operated in RC Autocalibrate mode for the main part of the year to save power and switch to Crystal (XT) mode when a large or fast temperature excursion is detected by the system microcontroller.

Initial Timing Calibration Algorithm

To initially calibrate out any crystal frequency inaccuracies and any parasitic load inaccuracies, the following procedure should be run using a timing measurement device that can resolve better than one ppm in less than a half-second. This device could be a frequency counter with a good calibration, a custom circuit built on the device-under-test (DUT) board of the system tester that includes an accurate oscillator of 10MHz or better and a counter that can count how many tenths of microseconds between the edges of the clock output from the CBC348xx, or possibly the system tester itself if it can be calibrated to resolve tenths of microseconds between edges of the output clock. The procedure is as follows:

1. Set the OFFSETX, CMDX, and XTCAL register fields to 0 to make sure the oscillator is running without any calibration taking place. The CMDX and OFFSETX fields are both in the CAL_XT register. The XTCAL bits are in the Osc Control register.
2. Select the XT oscillator by setting the OSEL bit of the Osc register to 0.
3. Configure a square wave output on one of the output pins of frequency Fnom (for example 16Hz). See register SQW in the datasheet for information on how to do this.
4. Measure the pulse width of several cycles of the square wave with a resolution of better than 0.25ppm (resolve edges to 15ns or better using averaging if needed) and convert to a frequency Fmeas by taking the reciprocal of the pulse width.
5. Compute the pulse adjustment value (PADJ) required in ppm as ((32,768 - Fmeas)*1000000) / 32,768 = PADJ.
6. Compute the adjustment value in steps as PADJ / (1000000 / 2^19) = Padj / (1.90735) = ADJ.
7. If ADJ < -320 the XT frequency is too high to be calibrated. Contact Cymbet for design assistance.
8. Compensate by starting at the top of this table and proceeding down until the pertinent condition is met and set the fields XTCAL, CMDX, and OFFSETX as indicated:

If ADJ is as below	set XTCAL =	set CMDX =	set OFFSETX =
ADJ < -256	3	1	(ADJ + 192)/2
-256 < ADJ < -192	3	0	(ADJ + 192)
-192 < ADJ < -128	2	0	(ADJ + 128)
-128 < ADJ < -64	1	0	(ADJ + 64)
-64 < ADJ < 64	0	0	(ADJ)
64 < ADJ < 128	0	1	(ADJ)/2

Otherwise, XT is too low to calibrate. Contact Cymbet.

The calibration register values can be saved in nonvolatile memory in the final system's microprocessor for reloading when system power is recovered.

Suggested Crystals for CBC348xx devices

The CBC348xx should operate well with any standard 32.768kHz tuning fork crystal with 0-12pF capacitance and 0-90KΩ ESR. Some crystals that can be used with the CBC348xx are:

Microcrystal	CC7V-T1A or CM7V-T1A
Cardinal	CPSZ-A2 C1 70 -32.768 D9
Epson	C-002RX, FC-135, FC-12D, or FC-12M

Ordering Information

EnerChip RTC Part Number	Description	Notes
CBC34803-M5C	EnerChip RTC in 5mm x 5mm x 1.4mm 16-QFN Land Grid Array	Shipped in Tube
CBC34803-M5C-TR1 CBC34803-M5C-TR5	EnerChip RTC in 5mm x 5mm x 1.4mm 16-QFN Land Grid Array	Tape-and-Reel - 1000 pcs (TR1) or 5000 pcs (TR5) per reel
CBC34813-M5C	EnerChip RTC in 5mm x 5mm x 1.4mm 16-QFN Land Grid Array	Shipped in Tube
CBC34813-M5C-TR1 CBC34813-M5C-TR5	EnerChip RTC in 5mm x 5mm x 1.4mm 16-QFN Land Grid Array	Tape-and-Reel - 1000 pcs (TR1) or 5000 pcs (TR5) per reel
CBC-EVAL-12-34803	EnerChip RTC Evaluation Kit	USB based Eval Kit with CBC34803 tab board
CBC-EVAL-12-34813	EnerChip RTC Evaluation Kit	USB based Eval Kit with CBC34813 tab board

U.S. Patent No. 8,144,508. Additional U.S. and Foreign Patents Pending.

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